Dynamics of technology innovation and diffusion with emphasis on wind energy

by

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Abstract

This thesis takes an interdisciplinary look at wind energy innovation and diffusion through a historical case study and system dynamic quantitative model. The former uses a framework known as actor-network-theory (that allows technical as well social forces to shape historical outcomes) and applies it to an in-depth case study of the history of the technology throughout several époques. Rather than simplifying the story of the technology into a case of winners and losers, as past studies have done, this work demonstrates the complexity of the history of wind technology where many individuals in different countries, companies and national governments, all play a key role in both direct and indirect development of the technology. Without the confluence of activity from these different groups across time and space, the story of wind energy would be very different. In particular, the history shows how the technology develops and diffuses in different regions at different times in different eras, but that traces of each époque survive into the next so that the overall history of wind energy technology has some continuous threads and an accumulation of global learning. This perspective serves as a basis for the development of a system dynamics model of wind energy development and deployment. The model examines the interplay of technology innovation and diffusion dynamics where markets for the technology are local but innovation and learning is global. Wind energy for electricity generation has overcome significant volatility in local markets over the last several decades thanks to the global aggregation of demand from different countries at different times. At the same time, the persistent presence of a market somewhere in the world at any given time has allowed continuous innovation and technology learning to take place. Looking forward, these local and global feedbacks for innovation and diffusion have important implications for the further development of technology and its ability to become a prominent global source of electricity generation.
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Introduction

Despite over 100 years of technology development, wind turbines (machines for producing electricity from the wind) are still an emerging technology for electricity generation — especially when discussing their integration into the overall electric grid system. Wind turbines developed for electricity production in the late 1800s and enjoyed widespread use for rural applications by the 1920s. However, the centralization of electricity production in the mid-20th century led to the displacement of wind turbines in all but the most remote locations. The oil crisis reversed this trend, fostered a new era of innovation, and opened a window for integration of wind turbines onto the electric grid from the late 1970s onward. Still, introduction of intermittent electricity generation has produced concerns over grid stability. Early attempts for grid integration required either class-action suits from local communities or top-down government support for federally managed utility grid projects. In the 1980's, support for the technology waned, and the industry experienced cases of widespread bankruptcy. In the subsequent decade, wind turbines development rebounded in many European countries and after 2000 in the US and across the globe. Most recently at the end of the first decade of the new millennium, wind energy deployment is experiencing rapid growth in some countries and stagnation in others. The overall history of wind energy's diffusion into the electricity generation market is tumultuous with many ups and downs.
Some would argue that the industry has finally become self-sustaining. At the same time, wind turbines still rely upon considerable government support and issues of grid integration, local resistance to development, and other factors challenge overall diffusion of wind energy technology.

As with many large-scale technical systems, the issues at hand are not purely technical in nature, and involve significant sources of uncertainty and many complex relationships. Firstly, social, political and economic considerations as well as the historical inertia of the technology and system development are important. Secondly, analysis of current challenges to wind turbines deployment as well as integration into the electric grid will provide insight into how different policies and strategies may affect the innovation and diffusion of WECs technology going forward. In particular, given the technical, economic, social and political context and uncertainties, how will wind energy technology and associated markets evolve in future years? In order to address this question, we need to take several steps. This thesis takes a dual approach of first deconstructing the story of wind energy development from a historic case-study perspective and reconstructing the story in the form of a quantitative system dynamics model. Firstly, within this context, we will explore in-depth through case study the various factors and relationships affecting the innovation and diffusion of wind turbines. In particular, I use “actor network theory” to understand the complex and non-linear nature of wind turbines development. Actor network theory, or ANT, is an analytic tool from sociology/sociology of
science and technology studies treats both people and technologies as actors and mediators within a socio-technical network. Secondly, I construct a model based on theory as well as casework in order to create a model of historical and potential wind turbines diffusion. With the model, I study a variety of policy implications.

0.1 Backdrop: Industrialization and Technological Change throughout the 19th and 20th Centuries

The 19th century saw a great deal of social change and a corresponding increase in the role of technology in many aspects of society. The industrialization of Europe, North America and the world over involved a wide variety of social change, invention and innovation. Leading scholars on the topic of modernity and technology have made such bold claims as “technology made modernity possible” (Brey, 2003, p. 33) and that “technology may be the true distinctive feature of modernity” (Misa, 2003, p. 8). This rise of prominence of technology in the human experience was evident in many of the major inventions and innovations of the 19th and early 20th century and, in particular, in the rise of the large-scale complex technical systems from agriculture to energy to transportation and even the manufacture of consumer goods. A large body of work has chronicled the development of these technologies and systems in the past (Smith, 1980; Hounshell 1984; Cronin, 1991; Noble, 1977; Hughes 1983, 1990, 1998). It was during this era that the United States transformed to be not as “nature’s nation but as technology’s nation” (Hughes, 1990). Scholars have written about what exactly it means to be “technology’s nation” and cite general characteristics of the “modern era” include the following: order and regularity, rationalization and specialization, as well as systems, centralized planning and control (Hughes, 1990; Misa 2003). As we will see, these themes are relevant to the development of large-scale electric-grid systems and wind electricity generation, in different periods, can either be juxtaposed against the centralized and ordered grid systems or be a source of reinforcement to them.

0.1.1 Technologies of modernization

Many technologies exemplify these traits such as those for creating standards and classifications (Bowker and Star, 1999; Scott, 1998; Smith, 1977; Cronin, 1991). Technologies of measure and standard provide the backbone by which a modern state can intervene in the affairs of its population and organize its environment. Scott uses evidence of how mapping and surveying technologies could lead to the orderly planning of entire cities in the new world such as Chicago or reconfiguration of cities in the old world such as Paris (Scott, 1998). The modern state with a highly interventionist orientation toward the affairs of its public relies on technologies of classification and standardization. The influence of technology on order and regularity is not limited to affairs of the state. Cronon’s treatment of the rise of Chicago shows how certain novel technologies combined, such as the grain elevator, the railroad system and the telegraph, enabled the formation of a centralized and standardized market for grain with varying levels of quality (Cronon, 1991). The processing of the grain in bulk and at greater rates, the shift from grain in solid bundles to liquid flows, required a uniform set of standards for grain quality and a classification system coupled with the use of the above-mentioned technologies. The use of technology for grain elevators and sorting enabled a system of classification that at the same time affected the speed and manner of the technology’s application. Another key technology for order and regularity that influenced the making of modern America was the creation of interchangeable parts.
Many identify the technology of interchangeable parts and the creation of the “American System” of production as a fundamental enabling technology leading to mass production (Hounshell 1984). The creation of specialized machines for milling, lathing, and drilling materials and the introduction of gauges increasingly led to uniformity in production processes for complex products such as military weapons (Smith, 1977). This ultimately led to the creation of interchangeable parts and the spread of the American System beyond the military to products such as sewing machines, bikes and even automobiles (Hounshell, 1984).

Beyond standards and classifications, however, the development of critical infrastructure systems throughout the 19th and 20th century reshaped the natural landscape of the United States in a direct way – showcasing technology’s ever-growing prominence across nature’s nation. Various treatments of the making of industrial America highlight the critical role of infrastructure in enabling modernization. For instance, Cowan’s work on American technology looks at “transportation revolutions” as a central theme in the creation of large civilizations from Rome to the United States (Schwartz-Cowan, 1997). Prior to the introduction of toll and public roads, canals, steamboats and railroads, the US was largely segregated into pockets of production especially for the Mid-Atlantic States (Schwartz-Cowan, 1997). The creation of integrated systems of transportation allowed for the unification of these disparate regional economies into a larger whole that could be more easily ordered and regulated. Similarly, the growth in use of electric power across the country displaced the use of heterogeneous sources of power from human labor, water, wind, and coal for a huge number of applications (Hughes, 1983). The spread of the electric power across the country led to a fully integrated and centralized system. This in turn led to needs for standardized machinery, measures and order and to further planning and centrally controlled infrastructure (Hughes, 1983; Nye 1992). Growth of physical infrastructure led to the development of large integrated and centralized systems for modern America.

Looking more closely at manufacturing, another key role of technology in the making of modern America was the development of mass production. In large part, the development of mass production had to do with the minimization and mechanization of the human role in production processes. Firstly, the introduction of interchangeable parts and specialized machines of production meant that less skilled labor was needed during parts of the production process (Smith, 1980). Mechanization of more and more pieces of the productive process displaced the skilled craftsman of the pre-modern era. Specialized machines practically ran themselves with operation by young adults and children (Smith, 1980). Complex tools and rationally organized production replaced the machine shop with its artisan owners and apprentices, and the new system partitioned craftsmen into roles of managers, engineers and laborers (Noble, 1977; Smith, 1980). Even more, those who found themselves in the unfortunate role of unskilled labor were also subject to processes of mechanization. The human increasingly became a one with the machine in a system of production and use (Aitken, 1960; Mindell, 2002). The human laborer was becoming a specialized component of the overall system. Taylor’s immortal words, “in the past man has been first; in the future the system must be first” are exemplary of the new modern perspective of rationalization, specialization, centralized planning and control (Aitken, 1960). The final step in the process, the introduction of the conveyor belt technology and the advent of the era of mass production, represented the integration of the technologies of order, regularity, rationality and
The introduction of mass production was the end of the beginning of the modern era, signaling its maturity and preeminence for the 20th century. While rationalization and specialization were key themes of the modern era as early as the time in which Marx was writing (Rosenberg, 1982), mass production would certainly represent the culmination of these processes through maximum partitioning of the manufacturing process leading levels of productive output at a scale not previously seen. The bringing together of gauges, specialized machinery, timing and scientific management, and the like formed a network of enabling technologies for mass production and modern processes of order, regularity, rationalization and specialization.

0.1.2 Large Complex Technical Systems

Large complex technical systems in modern America represent a spectrum from those with minimal human roles in operation (such as the physical infrastructure systems listed above) to systems which are primarily social but are aimed at the creation or use of complex technologies (such as the Manhattan project) (Hughes, 1990). The word “systems” applies to a broad range of collections of technologies. Hughes uses the systems metaphor to look at the creation of such dissimilar entities as the electric grid, mass production, the Manhattan project, MIT’s SAGE computer project, the Atlas intercontinental ballistic missile project, Boston’s Big Dig, and the internet (Hughes 1983, 1990, 1998). While certain of these projects invoked a systems perspective, the systems they created were in some cases more technical (physical infrastructure) and some cases more social (organizational infrastructure). The enabling technologies described in the preceding paragraph were a preamble to the creation of these large complex technical systems in the 20th century. The creation of these systems also left an imprint on industry, politics and society. The growth of large-scale technical systems complemented the cultural and institutional transition to modernity (Brey, 2003) by embodying and promoting many of the characteristics of the era such as those described above: order, rationalization, and systems. In addition, the systems gained both momentum and inertia (Hughes, 1990) as they grew leading to a feedback of influence over not just industry but also politics and society as well.

0.2 Scholarly Response to the “Machine Age” and the Modern Era

In the 20th century, as the onslaught of new technological artifacts and the rise of large-scale complex technical systems would come to overwhelm traditional social structures under the umbrella of “industrialization”, academics keen on studying the human experience would start to ask questions about the relationships of these technologies and technical systems with society. A series of works beginning in the 1930s focused on trying to understand the relationship of society and the human experience to its technical creations. Each of the early bodies of work were a harbinger or even a catalyst for a flood of scholarly work exploring the topics in depth from a variety of perspectives – all seeking to understand further the intricacies of the relationships between society and technology. In particular, they group along several lines relating to a variety of academic disciplines from the history, philosophy and sociology of technology to economics, economic history and the management of technology and innovation.

0.2.1 History, Philosophy and Sociology of Technology

Mumford’s Technics and Civilizations in 1934 began to ask a variety of questions about the critical role of technology in industrial society. Writing in the midst of the Great Depression, Mumford challenged the
idea of progress and the modern era as an outcome of the machine age. Instead, he saw the machine as a tool of the institution of capitalism and the social incentive structures as the critical causal factors for the machine age. Timely for the era, Mumford's writing is pro-communism and emphasizes the need to harness the machine for the will of the people rather than the capitalistic bourgeois. The book breaks with the trend to overemphasize the complex technologies of the industrial era as the essence of the machine age and for the first time puts forth a debate questioning the essence of technology: are human social progress and its resulting social institutions a product of technological advancement or is technological advancement a product of societal development? While today there seems to be a confluence of scholars who find some middle ground to be the most likely answer — that there is a bi-directional causal relationship between societal and technology development — there are still proponents of both more extreme positions. In general, these different perspectives fall under the headings of technological determinists on the one hand, social constructivists on the other hand, and in between are various labels under the general theme of co-construction of science and technology.

0.2.1.1 "Hard" Technological Determinism
Very few proponents of "Hard" technological determinism as described by Smith still exist. From this viewpoint, technology has autonomous agency to affect change in social, economic, political and cultural processes (Smith and Marx, 1994). The idea that the railroads or other technology caused the industrial revolution and the modernization of America represents a hard technological deterministic viewpoint. This is in contrast to a more "soft" view that various technologies were enabling factors as part of a number of cultural and institutional factors that altogether led to the making of modern America. In the hard view, technological change necessarily induces societal change. A few notable scholars classified, with qualification, under this umbrella are Langdon Winner and Robert Heilbroner. Heilbroner is a harder determinist than Winner whose work is similar to that of systems theorists or co-constructionists. Heilbroner's article "Do Machines Make History?" and his follow-up article on "Technological Determinism revisited" (Heilbroner, 1967; Smith and Marx, 1994) notes that machines change the material conditions of human existence. The conclusions he offers are somewhat open-ended but he does recommend, counter to the social-constructionist view, that scholars make efforts to generalize the ways in which "technology exerts effects on society" (Heilbroner, 1994). Bimber's article in the same volume recognize the potential for technology exerting agency on society due to unintended consequences: the notion that effects of technological change are uncertain and thus are partially autonomous (Smith and Marx, 2004).

Winner, on the other hand, in some ways does not appear as staunch in his views as Heilbroner but aspects of technological determinism do surface in his writings. For instance, his view of technological drift is analogous to Bimber's view of unintended consequences associated with technology (Winner, 1977). Winner is also openly critical of the social construction paradigm that he sees as biased towards the social as well as elitist for their focus on relevant interest groups (Winner, 1993). In his article "Do Artifacts Have Politics?" Winner initiated a debate with social constructivists surrounding the autonomy of technology and the ability of technology to embody political values (Winner, 1997). The article's argument concerning such technologies as nuclear power is that they mandate political structures due to their complexity and thus are intrinsically political (Winner, 1997). Perrow's work on nuclear power
and other large complex technical systems with critical risk and safety issues supports Winner's claim. It
acknowledges that the complexity and uncertainty inherent in some technical systems means that
accidents are in fact a "normal" part of their operation and thus they will always require certain
organizational structures to deal with these perennial issues (Perrow, 1999).

0.2.1.2 Social Construction of Technology

Such views of technological determinism are enticing and were prevalent during the "Machine Age"
prior to the writings of Mumford and the creation of science and technology studies. However,
concurrent with a general backlash towards technological enthusiasm and progress, the school of social
construction of technology gave rise to an opposing paradigm in which technology is the result and not
the cause of social processes. A foundation for this school of thought is in Kuhn's writings on scientific
paradigms (Kuhn, 1962) and in Mumford's original and subsequent work on society and technology
(Mumford, 1934). While Mumford recognized the interrelationship between society and technology,
Kuhn's main insight was the recognition that knowledge and science was essentially a socially
constructed process (Kuhn, 1962). In his mind, "normal" scientific investigation depended on a common
paradigm within which scientists could operate and this paradigm extended beyond just a set of
theories or tools to an overarching social community of scientific activity (1962). This work inspired the
field of social studies of knowledge and subsequently the empirical program of relativism and
subsequently, the social construction of technological systems (Bijker, Hughes, and Pinch, 1987).

Common to this "paradigm" for studying the history of technology are the role of relevant social groups,
interpretive flexibility and closure (Bijker, Hughes, and Pinch, 1987). The advantage of this paradigm is
its recognition, in contrast to technological determinism, that social groups exert influence over the
creation of technology. It implies a plurality in the creation of any technology with any given instance of
the technology a result of the preferences of the relevant social groups.

In a sense, the technology is constructed via an evolutionary process of variation and selection with the
relevant social groups acting as the decision-makers in each subsequent step (Bijker, Hughes, and Pinch,
1987). However, the program leaves out one very important aspect of the evolutionary theory: that of
mutation. Mutation is analogous to the unintended consequences of Bimber, disruptive innovations of
Schumpeter, or technological drift of Winner. In addition, in evolution, an autonomous organism adapts
to its environment. In contrast, in the social constructionist view, external forces of social groups cause
technology to adapt. Still, the social construction view is attractive from the viewpoint that technology
only exists as a process of human creation. Technology is created from the natural world by social
world. Pfaffenberger argues that treating technology from a neutral or deterministic viewpoint
inappropriately fetishizes the technology (Pfaffenberger, 1988). He agrees instead with Noble that any
technology is not a causal force on society in and of itself. Instead, technology is "humanized nature" or
"hardened history" such that any causal influence that technology exerts on society today actually is just
a medium by which social groups that created the technology indirectly inflict change on society
(Pfaffenberger, 1988). In other words, since technology is created from the natural world by individuals
and social groups, then any agenda embodied in the technology is just an artifact of the agenda of the
social groups that created it in the first place.
Various authors have applied this paradigm to the evaluation of actual histories of technology including Bakelite (Bijker, 1987), intercontinental ballistic missiles (MacKenzie, 1990), the internet (Abbate, 2000) and bridge building (Kranakis, 1997). Each author presents a convincing argument for why social forces were responsible in shaping the technology of interest. Central to these arguments is the recognition that different social agendas give rise to different instances of the technology. For instance, Abbate shows how military objects of system survivability and academic objectives for interactive and shared computing resources independently influence the concept and design of packet-switching (Abbate, 2000). Kranakis showed how inductive and deductive scientific approaches were used to design suspension bridges and the relative approaches led to very different realizations of the technology (Kranakis, 1997). By demonstrating the contingent nature of creation and design of technology, these authors make a strong case for the social construction of technology.

0.2.1.3 Co-Construction of Society and Technology: Systems Theory, “Soft” Technological Determinism, and Actor-Network Theory

Co-construction of society and technology considers the mutual influence of society and technology (Misa, 1994). In general, technology has some degree of autonomy and agency but it is never independent nor does it by itself determine change in society. Thus, co-construction is as an umbrella for systems theory, “soft” technological determinism and actor-network theory.

In terms of philosophy of the relationship between technology and society, Thomas Hughes originated what we now call a “systems” theory for the history of technology (Hughes, 1990). Similar to the vein of social construction of technology, Hughes recognizes the important roles of various actors and social groups (such as independent inventors, the state, and industry) but at the same time he acknowledges certain aspects that are more congruent with technological determinism such as momentum, inertia and the role of reverse salients (Hughes, 1990). In this way, systems theory falls in between the social construction and technological deterministic viewpoints. Thus, it has the advantage of recognizing social influence in the creation of technology while still allowing for a degree of determinism. This determinism surfaces in the form of momentum and inertia especially in the case of large-scale complex socio-technical systems. Exemplary systems from this view are the electric power grid as well as the military-industrial-academic complex forming and various systems engineering projects (Hughes, 1990, 1998). These systems are neither wholly technical nor social, but together in one large combined system, they develop momentum towards invoking subsequent change both internally and externally, and they also develop inertia that resists change imposed from external sources. While such a theory is extremely useful in assessing large-scale complex socio-technical systems, for individual technologies, systems theory may not be the most appropriate tool.

Separating this particular approach into its own category is difficult. Most of those scholars, Winner, Bimber, Heilbroner and Perrow, would more likely fit into the category of “soft” rather than “hard” technological determinism. All of the above authors would probably recognize the importance of the larger context of society, the economy and politics in terms of any influence that technology would exert of any of the other spheres. The advantage of this approach is similar to that of systems theory: the importance of technical as well as social, economic and political factors is important in the study of history. These different factors exert mutual influence upon one another. Compared to systems theory
as just described or co-construction of technology as discussed in the next section, this approach does
not have as fully developed a body of theory nor methodological approaches.

Actor-Network Theory is the most recently developed approach for the analysis of the history,
anthropology and sociology of science and technology. Several scholars including Callon, Law and
Latour have championed this approach. The main difference of this approach to others intermediate
approaches that we have seen, such as systems theory or soft-determinism, is the denial of any stable
social or technological structure. In Latour’s Reassembling the Social, he criticizes the social
construction school for and even traditional schools of sociology for erroneously assigning agency to
something that does not exist: the social (Latour, 2005). From his view, the social is not a cause of
anything but the interrelationships between influencing agents or actors. The interactions of actors and
their network of relationships form technology. Therefore, technology cannot embody the social. It is a
physical entity that develops agency and independence once created and thus becomes another actor in
the network: exercising influence on the rest of the actors to which it is connected. Law’s work on
heterogeneous engineering corroborates this view by seeing the network as a juxtaposition of social and
natural or technical components; the network is a mixture of heterogeneous elements that exert mutual
influence (Law, 1987). However, both Latour and Law are concerned of the overuse and misapplication
of actor-network theory. Latour sums up the perspective by saying that actor-network theory should
consist of many actors, many mediators and few intermediaries whereas social construction is likely to
involve a few actors, many intermediaries and a few mediators (Latour, 2005). However, Latour admits
that in certain cases, a stable social reference frame is not out of the question. He compares this to the
case of relativity: where networks are slow to change, they can have some fixed social structure, but this
is not the case for most societies and most technologies of scholarly interest.

Each of these three methods of systems theory, “soft” technological determinism and actor-network
theory ascribe a different level of autonomy to technology as an entity affecting society and a different
mode of interaction between the two realms of society and technology. Their allowance, however, at all
for a technological realm puts them in a distinct category from social constructivists. At the same time,
their emphasis on the social separates them from the “hard” technological determinists.

0.2.2 Economics, Economic History and the Management of Technology and Innovation

Just as Lewis Mumford began to question the role of technology in society from a historical and
philosophical perspective, his contemporaries in the general fields of economics and economic history
began to do the same. In Inside the Black Box: Technology and Economics, Nathan Rosenberg captures
much of this scholarly history in his historiography of technical progress (Rosenberg 1982). He divides
areas of work in studying technical progress into the rate of technical progress, direction of technical
progress, the diffusion of new technologies and the impact of technical progress upon productivity
growth. The first two topics deal with the general theme of technological innovation with the former
focusing on cultural and social explanations for technical progress and the latter focusing more on
market explanations for technical progress. The below discussion will group the two under the same
topic of studies of technological innovation as would befit associated current academic disciplines and
scholarly work. The third and fourth categories of diffusion of innovations and the role of technology in
economic growth are ones well represented today by the characterization ascribed to them in Rosenberg’s work.

0.2.2.1 Technology and Economic Growth
The harbingers to the role of technology in economic growth, as Rosenberg points out, are Simon Kuznets and Joseph Schumpeter who both emphasized the critical role product innovation in overall economic growth (Kuznets, 1930; Schumpeter, 1939; Schumpeter, 1942). In particular, the impact of Schumpeter’s work has developed momentum throughout the last century and into the present. As Rosenberg points out, Schumpeter saw the radical innovation and invention as processes of “creative destruction” were key to economic growth such that the critical problem for the state is to understand the creation of new industries and the destruction of old industries (Rosenberg 1982). Schumpeter published his major works, similar to Lewis Mumford, during the Great Depression and thus his work, similar to that of Mumford, was almost a taking stock of the current state of affairs following the unbridled and overwhelmingly rapid progress of prior decades.

Many theorists and the general scholarly community did not readily accept Schumpeter’s ideas and as Rosenberg notes, many critics cited a large quantity of examples of continuous technological innovation throughout history. Indeed, it was Keynes and his General Theory of Employment, Interest and Money published in 1936 that would guide macroeconomic policy of the state for the coming decades without the explicit inclusion of technology. Similarly, neoclassical growth models beginning with Robert Solow’s work in the 1950s also omitted technology from having an endogenous role – though it did allow for an exogenous change in technology to impact the overall gross domestic production function (Solow, 1956). Though technological progress did affect the long-term rate of economic growth, the ability to affect this rate within the growth model itself did not exist. Economists at the time did however start to pay more attention to the role of technology following Solow’s study and a similar study by Moses Abramovitz (1957) which similar to a study by Solow, found that economic growth was largely explained by the “residual” after accounting for resource use from labor and capital (Abramovitz, 1957; Solow, 1956; Rosenberg, 1982). Although this residual could account for a variety of factors, technological change and improved productivity of resource use was a key component that began to capture the attention of many economists working in growth theory.

Thus, economic growth models began to evolve to incorporate “endogenous technological change” in a number of ways and led to the creation of endogenous, internally derived, growth models beginning with the work of Paul Romer in 1986. Technological change, and the residual from Solow’s model, becomes endogenous – driven by the savings rate, depreciation and population growth (Romer 1986, Lucas 1988). This approach, however, takes economic growth theory to the other extreme: i.e. technological change is now entirely endogenous versus entirely exogenous. The work of Philippe Aghion and Peter Howitt resolves this issue by reviving the work of Schumpeter in their highly cited paper “A Model of Growth through Creative Destruction” (1992). This work introduces a stochastic component to the process of technological change and innovation while still allowing for endogenous impacts on innovation through the research investment activity of the economy. Subsequent work has explored a variety of growth models that allow for some endogenous representation of technical change and exogenous effects through shocks and stochastic processes (Aghion and Howitt, 2006).
particular, economic literature surrounding economic models and climate policy analysis has leaned upon this foundation of endogenous growth theory and expanded upon it (Kohler, 2006). Since climate-economy models have a significant interest in technological change, the work is highly relevant to understanding how policy decisions will affect use and innovation of technologies and thus have downstream impacts on the overall climate. Using primarily microeconomic-based computable general equilibrium (CGE) climate-integrated models, learning curves and other phenomena are captured (Kohler, 2006). Developing such models and overall economic growth models accounting for endogenous technological change is a topic with significant active research due to its relevance in the domain of climate-economy modeling, development economics among other sub-disciplines of economics.

0.2.2.2 Sources and Drivers for Technological Innovation
Another topic of particular interest to the economic community as well as the management of innovation is the study of not just the impact of technology on economic growth but also a better understanding of the causal factors that impact how technological innovation occurs. Such an understanding is important to the overall modeling of endogenous technology change in economic growth models but also to management and industry interested in economic performance at the firm level. As mentioned, Rosenberg distinguishes between the rate and direction of technological change and cites both cultural and market forces, respectively. In his discussion on cultural and societal aspects of the rate of technological change, he cites the work of historians such as Lynn White, David Landes, Joseph Needham and others who look at the rate of technological progress in different cultural and political contexts (Rosenberg, 1982). The authors cite such characteristics as religion, political and legal structures, enlightenment, rationality and the role of science (Rosenberg, 1982). Though such work emphasizing broad generalizations about society and their impact on technological change is less prevalent as a current theme for exploring differences in innovation across different states, literature on national innovation systems continues along this vein of work in looking at drivers such as factor endowment, natural resources, macroeconomic phenomena and government policy. Work on factor endowment and natural resources lends itself both to econometric study which can look explicitly on how these factors affect production functions as well as case work such as Hughes’ use of the concept “reverse salient” to explain the direction of technological change in the early 20th century (Hughes, 1983). This type of work is closer to Rosenberg’s second theme concerning the direction of technological innovation. In particular, the bulk of literature from the management of innovation and econometrics studies of innovation are part of this tradition.

While economic growth models maintain some stochastic nature to technological change, literature on innovation attempts to explain better, how these apparently stochastic changes in technology come about – so that they might better be modeled or strategically controlled by a firm or state. The classic model of innovation is a linear process that is an outgrowth of a research and development process including such steps as basic research, applied research, development and commercialization. This perspective of R&D driven innovation is associated with the development of large R&D based organizations in the early 20th century (Hughes, 1990).
The underlying driver in such models of innovation is “technology push” where the firm invests in research and development resulting in innovation pushed out to and absorbed into the market. On the other hand, by the 1960’s, researchers began to challenge the linear model. Jacob Schmookler’s *Economic Sources of Inventive Activity* (1962) first laid out the idea of technological change driven by the demands of society and not the other way around. This approach to innovation referred to broadly as “demand pull” has received significant attention over the last several decades by a number of researchers looking at various concrete forms of demand-side drivers for technological change (Mowery and Rosenberg, 1991; Nelson 2000). On the other hand, Eric von Hippel’s work on user innovation attempts to resolve the push-pull dichotomy by emphasizing that the perspective of whether an innovation is demand-side or supply-side depends on who is the main benefactor of the innovation (von Hippel, 1988). In so doing, he identifies another driver of technological change based on user innovation where from the demand-side; it is often the users of the technology who are responsible for technology innovation rather than the supplier of the technology (von Hippel, 1988). Studies of user innovation are a predecessor to the significant body of literature focusing on open innovation (von Hippel, 2005; Benkler, 2002). In open innovation, the user base becomes expansive, as in the case of Open Source software (Benkler, 2002) which has significant impacts on the rate and direction of technological change.

The literature on innovation is rich and goes well beyond the above discussion. Two sub-topics of particular interest to this thesis are the dynamics of innovation related to technology diffusion and path dependency/dominant designs. We treat these two topics in more detail in the following sub-sections.

0.2.2.3 The Diffusion of Technology

Once a technology reaches the point of commercialization, it still has a risk of failure in adoption by the market. The topic of diffusion of technology has long been of interest to social scientists and theory in the area is substantial. In general, there are two basic types of diffusion models – economic models focusing on economic aspects of technology diffusion and social models focusing on social aspects of technology diffusion. While there is early work emphasizing both types of models, Rosenberg’s discussion of scholarly work emphasizes those models that would generally fit into the threshold model though he pays some attention to studies on social factors influencing technological diffusion. In particular, Rosenberg highlights the work of economic historians such as Marc Bloch who looked at how legal and economic conditions affecting the availability of labor influenced the rate of diffusion of the water mill (Bloch, 1935). Such work is representative of a threshold model with variance for local economic conditions that affect the economic viability of different technologies. On the other hand, he does mention the work of scholars such as David Landes and others who site the immigration of labor as
a source of technological diffusion that deviates from a purely economic explanation (Landes, 1969). Still, the emphasis of Rosenberg’s treatment of technology diffusion is on the economic model that focuses on economic factors as the main determinants for the adoption of a product or technology. The pioneering work often cited for the threshold theory of technology diffusion is that of Zvi Grilich who used an econometric approach to understanding how different expectations of profit returns to adoption of hybrid-corn could explain the variation in time lag to adoption of the new corn technology across different regions (Griliche, 1957). This led to a strong tradition in the economic study of technology diffusion using econometrics to assess what economic factors are most prominent in influencing technology diffusion processes. Scholars such as Edwin Mansfield performed a significant number of econometric studies of the diffusion process as a function of the expected profitability of the innovation and an inverse function of capital investments required (Mansfield, 1961; Rosenberg, 1982). Other economic explanations cited in Rosenberg for affecting technology diffusion include the price and availability of input factors to innovation use (i.e. resource endowments, Temin, 1964) or environmental conditions to use such as complex topography. In both cases, the conditions affected the economic viability of the innovation and are of the economic type of diffusion model. While Rosenberg notes that economic historians did place an emphasis in particular on immigration as a source for technology diffusion, other social factors affecting technology diffusion are not discussed. In fact, Rosenberg’s inspection of technology diffusion from the lens of economics ignores entirely what some might consider the bulk of technology diffusion literature stemming largely from the tradition of rural sociology.

For an explicit treatment of the social processes in technology adoption, one must turn to its roots in anthropology and sociology. For that body of work, Everett Rogers has provided a comprehensive review in his Diffusion of Innovations (1995). Interestingly, even in the fifth edition of his book, Rogers does not cite any of the econometric literature relating to technology diffusion including the seminal work of Zvi Griliches and related work of Edwin Mansfield. Roger’s work focused entirely on the social forces underlying diffusion of innovations and thus highlighted one of the trends in this literature – the division between sociology and economics in the treatment of technology diffusion. For Rosenberg’s part, even though he highlights the work of Griliche on hybrid-corn diffusion as a catalyst for econometric studies of technology diffusion, he does not mention the equally critical work also on the diffusion of hybrid-corn that was done some 15 years earlier by Bryce Ryan and Neal Gross (Ryan and Gross, 1943). On the other hand, Rogers cites this work as “the most influential diffusion study of all time” (Rogers, 1995, p. 31). From the perspective of social models of technology diffusion, Ryan and Gross’s study of how the process of diffusion of hybrid corn differed between two Iowa communities was indeed the foundational piece of work that catalyzed a large number of studies on social diffusion processes first in rural sociology but eventually in many other disciplines including communication, education, public health, among others (Rogers, 1995). In their work, Ryan and Gross established the standard research method for diffusion studies to follow where they interviewed adopters of a technology with respect to time of adoption, communication channels from where they heard about the technology, and the impacts of the adoption (Ryan and Gross, 1943). The study built on earlier work by anthropologists but differed in the use of formal surveys later coded for use in quantitative analysis (Rogers, 1995). Their main findings included the role of communication channels at various stages in the
diffusion process including salespersons as a first point of awareness while interpersonal networks proved to be more influential with respect to the decision to adopt. From this study, and the many that followed, Rogers and others have concluded, “[d]iffusion is fundamentally a social process” (Rogers, 1995, p. 35). In general, as with the findings of Ryan and Gross, these social models of diffusion rely on social contagion as the main factor influencing adoption. In terms of a formal model representing this social contagion process, the key insight came from recognizing the parallels between the spread of disease and the decision to adopt a technology in a given population. Frank Bass first formally developed this connection in a quantitative model of diffusion of technology that relies on infectivity/performance of a technology, population size, and social interaction among individuals in the population (Bass, 1969; Sterman, 2000). The basic “Bass model” of diffusion has become especially prominent in marketing and used substantially in System Dynamics studies of technology diffusion processes (Homer, 1987; Sterman 2000; Milling, 2001).

![Bass type diffusion model implemented in System Dynamics Vensim software (Sterman 2000)](image)

Related to the Bass model of diffusion are “network models” of diffusion that focus on critical mass in a population as a precursor to widespread diffusion of a technology. As Rogers notes, while the seminal work of Ryan and Gross pinpointed the importance of communication channels and in particular the importance of local networks of communication between neighbors, they did not fully recognize the importance of the characteristics of communication networks in influencing diffusion processes. This work was spearheaded by Mark Granovetter in 1985 when he published his work on the “strength of week ties” (Granovetter, 1985; Rogers, 1995). The work established that while ones local communication network is influential in the decision to adopt, it is those weak links across networks that are particularly important in widespread communication and overall diffusion throughout a population (Granovetter, 1985). In contrast to the aggregated form of the system dynamic / Bass model of diffusion, “network models” of diffusion emphasize the network structure and aspects of different types of individuals in those networks in influencing the diffusion process. Aspects related to network structure such as weak ties, centrality, positional and structural equivalence, the heterogeneity of network agents and their thresholds to adoption based on various economic and social preferences, and the relationships between individuals in a network influence the adoption process (Valente 1995).
Much current research has gone on to exploring various aspects of network models in relation to the diffusion of innovations (Valente, 1995; Rogers, 1995; Rahmandad and Sterman, 2004).

Still, the network models above remain purely in the social modeling tradition and the link to economic modeling is wanting. One particular contribution from the network modeling work is the introduction of the “threshold model” that was pivotal as a precursor for bringing together the disparate traditions of economic and social models for diffusion of innovations. The “threshold” models posited that individuals in a population were heterogeneous in the degree to which they could be influenced to adopt a new technology by their social engagements (Granovetter, 1985). Thus, certain individuals with low thresholds would adopt when only a few other individuals in their network had adopted while others would wait until most everyone in their network had adopted an innovation. While not directly combining economic and social factors of influence, the allowance for heterogeneous preferences of individuals translates easily to a diffusion model where both social and economic factors play a role. Such “mixed-influence” models have been loosely defined as those models which combine internal and external influences to adoption and thus give rise to the traditional “S-shaped” adoption curve (i.e. the Bass model) (Mahajan and Peterson, 1985).

Still, Mahajan and Peterson’s treatment of this model (as well as Rogers, 1995) focus on external and internal influences via social processes of communication rather than, for instance, the internal economic preferences of a would-be adopter of the innovation. Generically, however, the Bass model and larger category of “mixed-influence models” have been adopted by various scholars to model diffusion processes where both economic and social factors influence the adoption process. However, a better term for such models would be “socio-economic” models of diffusion since their unique characteristic is the combination of social and economic factors influencing the innovation adoption and diffusion process. An early such socio-economic model was completed by Edwin Mansfield in his 1961 work on Technical Change and the Rate of Imitation. Highlighted by Rosenberg for his attention to the role of profitability and capital investment associated with new technologies, this work also attributed a third factor for adoption – that of imitation when a significant number of competitors adopted a technology which he termed “bandwagon effects” (Mansfield, 1961).
0.2.2.4 Path dependency, dominant designs and technology standards

Bringing together the two broad areas of studies in technology innovation and technology diffusion is the topic of path dependency and associated topics of technology competition, dominant designs and technology standards. Though often used interchangeably, there are subtle differences in the definitions and range of applications for the terms “dominant design”, “path dependency” and “technology standards”. Whereas path dependency implies that the current state of an artifact depends on its previous states or its history (David, 1985; Arthur, 1989), dominant design implies that single technology architecture has obtained dominance in the marketplace (Utterback, 1975). Such dominant designs could be the product of an ergodic or non-ergodic (path dependent) process, though the literature on dominant design reflects the understanding that typically no single technology is objectively superior to another. The lack of an objectively superior technology implies that the market dominant technology architecture is likely then dependent on a probabilistic set of events for its success. However, there is another school of thought, stemming largely from the field of economics, that though short-term or weak path dependency may be present, in the long-term prevailing social, economic factors will ultimately determine the “best” architecture, and thus ultimately there is an objective and ergodic (path independent) dominant design (Liebowitz and Margolis, 1990; Garud and Karnoe, 2001).

Related to this, the concept of technology standards often appears in the same general literature group as that of dominant designs and path dependency. Technology standards, which can be either de facto, voluntary or regulated (Hsieh, 2007), may determine and influence the dominant design for a technology but it is arguably not synonymous with the concept of dominant design. Technology standards as defined by David and Greenstein (1990) are “a set of technical specifications adhered to by a stakeholder, either tacitly or as a result of a formal agreement.” We could define technology standards in a different manner and interpret them to mean a larger or somewhat different set of concepts, but for the purposes of this review, we apply the widely accepted David and Greenstein definition. Given this definition, it is entirely possible that a set of technical specifications could influence the path of technology development and the selection of a dominant design or architecture. However, firstly, this implies an acceptance of the concept of path dependency that is ultimately debatable. Secondly, depending on the strength and the scope of the technical standards, competition among architectures could still be possible. Thus, though related, the concept of technology standards is distinct from dominant design that is a distinct but related concept to path dependency.

We find ourselves yet again, as so many times in academia, with a three-circle Venn diagram, each of which slightly overlaps and at the center an intersection of all three concepts. Path dependency implies that historic processes influence the current state of a technology. The end state for this path will be a path dependent dominant design or the natural end-result of optimized innovation processes. This dominant design is a de facto standard for a technology and may or may not embody product or operational standards as well.
Path Dependency

Many scholars recognize that path dependency as a concept has been around for some time. Path dependency is where current and future development of a technology is limited by its historical development— for example, once standardization has taken place it becomes very difficult to move to a new configuration that is fundamentally different. In fact, some noted scholars particularly from the field of economics are critical of the body of research on path dependency as not adding novel insight (Krugman, 1979). This is largely due to the fact that the concept of increasing returns, which can give rise to path dependent behavior for a technology, has been used in economics literature from the early 1900's and even before (Mishra, 2007). Similar to path dependency, increasing returns, returns to scale, or economies of scale imply that the more a firm sells of a product, the cheaper it is to produce that product and this can lead to in many cases a stifling of competition and a monopoly in the extreme. Krugman's own work highlighted the role of increasing returns for international trade in the 1970's. However, despite these facts, the general area of path dependency pushed the boundaries of returns to scale far beyond the production function. In 1985, Paul David published a still controversial article on the topic of the path dependent process of adoption for the "QWERTY" computer keyboard configuration. In that paper he defined a path-dependent process as the "a sequence of economic changes... one of which important influences upon the eventual outcome can be exerted by temporally remote events, including happenings dominated by chance elements rather than systematic forces" and in particular he applied it to a specific configuration of a technology: the computer keyboard. In 1989, Brian Arthur demonstrated a formal model of path dependency using the probabilistic "Polya-Urn" process. The generic model he proposed for two competing technologies only required that there be some benefits to adoption of one technology based on the historical adoption of that technology. Through this process, one technology would ultimately gain market dominance over the other and that technology would be "locked-in" going forward.

Since then, a substantial amount of research has identified a wide-range of potential factors that could lead to path dependent of one technology over another including: intellectual property, contractual commitments and durable purchases, learning curves for both users and producers, search costs for information about alternative products, economies of scale and scope, switching costs, reputation and brand name, and a variety of network effects including complementary technology development / availability, standards in technology and interoperability, and loyalty programs (Shapiro and Varian...
A number of scholars have demonstrated various formal models of these factors’ influence on path dependence such as Katz and Shapiro (1986, 1992, and 1994), Lieberman and Montgomery (1988), Schilling (1988), Farrell (1986), and Spence (1981). More recently, scholars have considered the augmentation of increasing returns models with the additional role of underlying network structure (Lamberson 2009). While network effects as mentioned above account for the role of increasing returns on a global level, they do not take into account the role of underlying network structure. As noted by Lamberson, 2009, this oversight has led to the common misconception that where increasing returns are present, “winner-takes-all” market outcomes develop. This in turn has led to an emphasis on “get-big-fast” strategies that may or may not be effective given a particular network structure for a market. The key results from these studies demonstrate how local bias or localized increasing returns (Lamberson, 2009) can lead to scenarios where a diverse market share is liable to persist even when traditional global increasing returns are present. Models that take into account local preferences due to network structure can account for a much wider array of market phenomena for the diffusion of innovations (Valente, 1995).

In addition, a body of empirical work has also surfaced to show examples of path dependency in the development of technology. The most famous case includes David’s original work on the QWERTY keyboard, but there are a number of other examples demonstrated among different disciplines. From the history of technology perspective, Cowan’s work on the development of nuclear technology presents an argument that the prevailing nuclear technology in the United States, light-water reactor technology, may be inferior to other forms and dependent on a number of chance and socially motivated historical processes (1990). In the management of innovation literature, the arguably most famous case involves the competition between the VHS and Betamax home video recorder platform technology (Carlsson, 1991). Many argue that in addition to being first to market, Sony’s Betamax technology was “superior” to the later entrant, JVC’s VHS technology (Cusumano, 1992). As previously discussed, the path dependency argument has been applied to many cases historically as well as to modern day cases involving a number of recent technologies such as computer operating systems (Microsoft versus Apple) and high-definition disk players (Blu Ray vs HD DVD) (Arthur, 1996; Flaherty, 2004).

As a final note however, many have contested whether path dependent processes ultimately lead to the dominance of an “inferior” technology. Recognizing that historic processes are important, scholars have challenged the idea that an “inferior” technology could dominate a market – especially in the long-term. As previously noted, the work by Liebowitz and Margolis directly challenge the notion of “hard” path dependency by saying that even if an inferior technology could gain some short-term advantage, it would not persist in the end (1994). In other words, Liebowitz and Margolis argue that technology “lock-in” is a temporary phenomenon at best. They argue explicitly against the case of the QWERTY keyboard by attacking a number of the positions in David’s original argument and making another case that the differences between the QWERTY and Dvorak keyboards are trivial at best. This notion of the end game of a path dependent process brings us directly to dominant designs.
Dominant Designs and Technology Standards

Utterback and Abernathy (1975) to describe the eventual trend towards one dominant technology for the market first proposed the term “dominant design” in the work. Initially, there is a lot of product innovation and many competing products but eventually, the market settles and a dominant design emerges. From that point on, innovations tend to be on the processes involved with bringing the technology to market rather than with the actual product itself. Many studies have built upon this idea including work by Christensen, Suarez and Utterback looking at firm entry and exit based on the development of dominant designs (1998) and Christensen’s work on disruptive innovations. A dominant design in essence is a de facto standard. However, a dominant design also encompasses a broader range of standard categories since the application of voluntary or regulated standards could also influence the process leading to the adoption of a dominant design. At the same time, though a de facto standard necessarily implies a dominant design exists, the application of voluntary or regulated standards do not absolute lead to the establishment a dominant design.

Similarly, the research on technical standards does bare some overlap with that of dominant designs and path dependency, but it also has its own scholarly tradition. In the preceding discussions, we gave several examples of research relevant to technology standards in particular the empirical work on path dependency demonstrating cases such as the QWERTY keyboard and VHS home video systems that demonstrate how certain technologies became de facto standards. In addition, there is substantial overlap at the intersection between literature on diffusion and path dependency in which market selection processes eventually result in a de facto standard or dominant design. However, literature on technology standards looks more broadly at other forms of technology standards and different ways in which standards can affect innovation and diffusion processes. Various typologies of standards exist in the literature (Cargill, 1997; David and Greenstein, 1990; Grindley, 1995; and Hemenway, 1975) as well as the standards setting processes. Work by Hseih 2007 sought to integrate these typologies into one overarching typology resulting in a matrix of standards and their associated standard setting processes.

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<td>Dimension 1</td>
<td>Product,</td>
<td>importance</td>
<td>Quality /</td>
<td>guidance,</td>
<td>Basic, product,</td>
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<td>compatibility</td>
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<td>Conceptual /</td>
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<td>De facto,</td>
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0.2.2.5 Intersecting themes in technology studies
The above review highlights a myriad of approaches and themes within technology studies from a variety of disciplines. Many of these approaches and themes overlap disciplinary boundaries from
economics to the history and sociology of technology to the management of innovation and strategy. The approach of this thesis, as previously mentioned, is to use both a bottom-up and a top-down approach to the study of innovation and diffusion for a particular technology: wind energy conversion systems. In the first part of the thesis, we will use a case study of the history of the technology to explore a bottom-up understanding of innovation and diffusion processes for wind turbines. In the second half of the thesis, we will construct a model of wind energy innovation and diffusion and use it to ask top-down questions regarding the influence of different policy scenarios on the future development and adoption of the technology.

0.3 Organization of Thesis

0.3.1 Section 1: An Actor-Network Theory Study of Wind Energy Conversion System Innovation

Latour pioneered the approach of Actor-Network Theory to open the black box of scientific investigation in Science in Action. More general than just actor-network theory, co-construction of society and technology considers the mutual influence of society and technology (Misa 1994). Thus, co-construction is an umbrella for systems theory, "soft" technological determinism and actor-network theory. In general, technology has some degree of autonomy and agency but it is never fully independent nor does it by itself determine change in society. Wind Energy Conversion Systems present a prime candidate for analysis via actor-network theory. The technology does not comprise a complex system, as would be appropriate for a systems theory approach (Hughes, 1983), though it is integrated into and therefore exerts mutual influence on the electric grid. Wind energy technology has been under development for over 100 years, and during that time, various technical and social forces have influenced its development. At the same time, its political role is ambiguous. The set of agents involved and their interrelationships are numerous. The influence that these varying agents impose upon wind energy technology as well as of wind energy technology in turn on the other technologies and actors are ambiguous. Actor-network theory lends itself towards the analysis of such a complex history of wind energy technology especially given the numerous sources of competing interests and intermediaries from both actors as well as other technologies.

Prior treatments of innovation in the wind industry, as will be discussed in subsequent chapters, have invoked various theoretical paradigms from political theory to technological trajectories. The various approaches do not explicitly assign agency to either human or technical actors but there is an implicit assignment to each depending on the study and theme of interest. Chapters 1-5 of this work are dedicated to the development of an ANT interpretation of the history of wind energy technology. Chapters 1-4 focus on historical context and early wind energy innovation. Chapter 5 provides an ANT approach to wind energy innovation in Denmark and the United States in the 1970s and 1980s. This work will investigate the role of agency from both sets of actors at once in order to provide a more holistic perspective on the multiple factors that influenced the historical evolution of wind turbine technology. In addition, it will take a deeper approach to studying the "technical" aspects of the history of wind energy technology that have received less attention in previous studies than the social aspects of development. This will itself be a contribution to the domain of the history of wind energy technology.
In chapter 5, we use ANT in the casework on wind energy innovation to explore the theme of technology as mediator. With this approach, we will revisit some of the debate that has evolved over the last few decades concerning the philosophy of technology and explore the question of “just how empty is the black box?” The contribution of this area of work focuses on the history and sociology of technology. This thesis will explore the role of science and technology and the evolution of the actor-network intertwining human, technological and scientific actors in the innovation of wind energy technology. Via this approach, we will explore co-evolution of science and technology. In particular, we will explore the role of co-evolution as it relates to path dependency and the dynamics of innovation. This body of work will primarily contribute to the discipline on the management of innovation.

0.3.2 Section 2: A System Dynamics Model of Wind Energy Diffusion
The second section of the thesis and chapter 6 constructs a system dynamics model of wind energy. The model backbone is a mixed-influence diffusion model with its main feedback loops involving technology dynamics of diffusion and innovation. The central feedback includes an overall potential resource that depletes as wind projects develop on different sites. Beyond this are various relationships related to overall industry development – on both a local and global level. The local level involves the acquisition of knowledge and local development capacity. The global level involves technology innovation dynamics (learning curves) as well as industry growth dynamics related to turbine supply.

The wind energy model involves both theory as well as information derived from the case study work on historical development of wind energy. The chapter will also provide an overview of the model including a presentation and discussion of the key structures and equations in the model. We present and assess the model performance in comparison to historic case data. This work will contribute to the diffusion modeling literature in general and the system dynamics literature in particular by bridging a local diffusion model representation for technology commercialization with a global innovation model.

The last portion of the chapter will explore policy scenarios and their impact on wind energy development using both the model with and without grid integration. A discussion of the political economic aspects of the findings will account for the viability of different policies. The contribution of this section will be primarily in the policy domain as it relates to wind energy technology.

0.4 References


Section 1: An Actor-Network Theory Approach to Understanding the Development of Wind Energy

The development of Wind Energy Conversion Systems (WECS) have been treated with many analytical lenses – some popular accounts (Gipe 1995, Maegaard et al 2009), some interpretations of political theory (Van Est 1999), several within the vein of innovation theory (Karnoe and Garud 1999, Garud and Karnoe 2003, Christensen 2009, Nielsen 2010), and still others within the field of history of technology (Heymann 1998, Serchuk 1996). Both of the two main accounts in the treatments of history of wind energy, by Heymann and Serchuk respectively, focus on the implications of different “social” approaches to the development of the technology. The former is a comprehensive work looking at the cross-country development of the technology while the latter contrasts the activities of two groups in the US: the federal wind program and small entrepreneurs. However, the “social” structure of the different groups explains relative successes and differences of the development programs and this analytical technique is not compatible with an actor-network treatment (Latour 2005). The social characteristics and definitions of successes and failures are presupposed and the specific causal relationships are then deduced by historical analysis rather than inductively building the social out of the historical development. The other non-ANT feature of these two histories is the passive role the technology itself plays in each work. While both authors allow for a “voice” from wind energy (the selection of technology by the actors influences the results), the technology is still passive.

The very central role that the technology plays in these works would suggest it has more agency than the prior work allowed and would serve as a mediator in the development process (Latour 2005). This work, then, seeks to be fair to all the different actors and networks in the history of wind energy development by providing to the extent possible a voice for each – for those who have traditionally been considered “successful”, for those who have traditionally been considered “failures”, and most importantly to the very wind energy technology itself. Wind energy technology has been under development for over 100 years and during that time various technical and social forces have influenced its development. The set of agents involved and their interrelationships are numerous. Actor-network theory lends itself towards the analysis of such a complex history and with this new analytical lens, we highlight new insights that may contradict or add to the earlier treatments of wind energy technology development. Even Latour admits that a stable social reference frame is not out of the question. He compares this to the case of relativity: where networks are slow to change, some fixed social structure can be ascribed to them, though this is not the case for most societies and most technologies of scholarly interest. One can extend this argument to encompass the larger socio-technical networks in which a particular actor-network of analysis exists. A larger socio-technical network that changes very slowly can encompass a smaller actor-network that both develops and eventually ceases to exist all while the larger network remains stable. The political climate of the day that heavily influences technology development at any given time may be seen in many cases as exogenous to that development process even though that political climate is the embodiment of actor-network activity at a very large scale and over a longer period. In addition, certain aspects of history (actors and actor-
networks) persist in some form from long ago providing important context for the history of any technology. Current actor-networks are like a slow motion picture with shadows following behind them of their predecessors and previous forms. Within the history of wind energy, actor-networks that were the nucleus of the modern wind industry were mobilized in the 1970s. However, important elements from earlier social and technical developments merit consideration before moving to that analysis. These include both technological and social histories: innovation and diffusion of wind energy technology up to the 1970s as well as various political, economic, and social movements prior to that period. To provide structure, we break down the history of wind energy technology into a series of époques. The below table provides an overview of the different époques of wind energy technology development and adoption.

**Table 0-1: Wind energy technology époques**

<table>
<thead>
<tr>
<th>Époque</th>
<th>Period</th>
<th>Locations</th>
<th>Core technology</th>
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<tbody>
<tr>
<td>Wind mills époque 1</td>
<td>Ancient civilization</td>
<td>Initially Asia and Europe and diffused globally</td>
<td>Horizontal- and vertical-axis windmills connected to a shaft to deliver mechanical power</td>
</tr>
<tr>
<td>Wind mills époque 2</td>
<td>18(^{th}) through the 19(^{th}) century</td>
<td>Initially the United States and diffused globally</td>
<td>Multi-vane windmills popular for irrigation and other mechanical uses</td>
</tr>
<tr>
<td>Early wind electricity</td>
<td>Late 19(^{th}) through early 20(^{th}) century</td>
<td>Europe and the United States</td>
<td>Adaptation of existing technology to connect to electric generators</td>
</tr>
<tr>
<td>generation systems</td>
<td></td>
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</tr>
<tr>
<td>Wind chargers</td>
<td>Early through mid-20(^{th}) century</td>
<td>Predominantly the United States and also Europe and elsewhere</td>
<td>Propeller-style wind charger with electric generator</td>
</tr>
<tr>
<td>Large-scale wind turbine</td>
<td>Mid-20(^{th}) century up through the 1960s</td>
<td>Europe and the United States</td>
<td>Large modern wind turbines (mostly prototypes)</td>
</tr>
<tr>
<td>turbine demonstrations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern wind turbines</td>
<td>1970s through present day</td>
<td>Europe and the United States and now global</td>
<td>Initially small wind turbines that were standardized and scaled up to over time</td>
</tr>
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</table>

Firstly, technologies to harness the wind for power production have existed since ancient times and two distinct periods reflect windmill technology for mechanical power production. In reality, the first period
is divisible into several sub-époques. Secondly, there is the introduction of the first machines to use wind energy for electricity production (the first windmill dynamos). These machines more-or-less adapt the mechanical systems for use in electricity production. In the third époque, inventors create the first machines designed specifically for wind generated electricity production – wind chargers. As the wind charger era is winding down, several actors make the first attempts at large-scale electric-grid-compatible machines, though most of these are prototypes. Some of these machines have important influence in the final époque of modern wind turbine technology. In each époque, we will explore the role of the technology and physics behind the technology in affecting the development and innovation processes. At the same time, we will explore how different social processes affect the technology evolution and in particular, places where human agency molding the technology in specific ways leads to variation in the technology.

References


1 Early development of wind energy technology (from ancient times through the 19th century)

This chapter deals with the first two époques of wind energy for power production through windmills. While there is not a lot in common between gigantic wind turbines today and earlier windmills, a brief look at the technology from its earliest origins through the 19th century will show how some core features of current machines persist through history. As we will see, some of these features include the dominance of the horizontal-axis upwind rotor configuration, the general use of lift force over drag to produce rotation (even before the physical understanding of lift and drag forces existed) and the important role of controls in the technology's development. In addition, we will see how the technology development occurred in a collective process, over time and in various geographic locations, and how the technology diffused to different regions and adapted for different needs. The diversity of approaches to the technology highlights how different frames of reference and contexts shape the design and influence innovation. At the same time, the existence of common threads in the technology development over time support the argument that technical and physical factors also have a role to play in shaping the technology's path.

1.1 Wind Energy in Ancient Times (from Wind Gods to Conceptualizing Wind at Work)

The sun's radiation is the dominant source of energy for life on earth whether we use it directly, or allow it time to transform into surface heating, forms of motion such as wind and waves, or evolve into plant life. Even fossil energy depended largely on the sun's radiation to become the concentrated form that we extract today for use in heating, electricity and transportation. To create wind, the celestial power of the sun reaches different regions of the earth with different intensities causing variance in heating of the surface from the poles to the equator. The temperature gradient results in a pressure gradient (buoyancy forces) causing air to flow and create winds. The earth's rotation then provides the Coriolis force (apparent deflection of objects moving perpendicular in a rotating frame of reference), which combined with pressure gradients lead to large-scale atmospheric circulations. The combination of the large-scale movement caused by the pressure gradients and the Coriolis forces result in the creation of three convection cells and associated wind belts in each hemisphere.
From there, the winding curves and varied topography of the earth transform the wind into a highly volatile creature with formidable power capable of destroying the most robust of man-made structures – literally capable of moving buildings and mountains. We recognize this power today in the hurricanes and tornados that terrorize the human built-environment. We notice it when flying across the country and experience uncomfortable levels of turbulence. We welcome it when we are strolling along a path on a hot summer day.

Ancient civilizations recognized the amazing power of wind and even attributed it the status of gods. Perhaps the most commonly associated deity of wind is Aeolus, the ruler of the winds in Greek mythological accounts. Homer’s Odyssey famously portrayed him as the keeper of the winds and provided Odysseus with both means to travel home to Ithaca via the westerly winds as well as the temptation in the form of the other three (northerly, southerly and easterly) winds locked in a bag that when released would ultimately keep Odysseus from his home (trans. 1998). Aeolus controlled the Anemoi who were also Greek wind Gods but for particular directions: Boreas (north), Eurus (east), Notus (south), and Zephyrus (west) as well as the minor winds Kalkias (northeast), Apellotes (southeast), Livas (southwest), and Skiron (northwest). Each directional God was associated with certain characteristics that one might naturally attribute with such winds – the westerly winds of Zephyrus were associated with spring and growth while the northerly winds of Boreas were associated with violent storms and winter (Lloyd 1968).
These Gods of wind were mighty and imposed their will upon each civilization in both positive and negative ways. While Greece’s Boreas brought cold winter winds from the north, he was also a savoir during one battle of Athens against the Persians, whose fleet sank due to winds sent by Boreas. Other ancient societies that supported polytheism also tended to identify Gods associated with the winds from the Hindu God Vayu to the Aztec God Ehecatl.

The principle role of wind in ancient civilizations, however, extended beyond religion to contemporary philosophy and understandings on the essence of life. Ancient societies went beyond mythology to try to understand the world around them and the classical elements formed a cornerstone of this understanding. While the type and variety of elements that were seen as essential or foundational to life differed by society, many did include a representation of wind either in and of itself or as air. The presence of wind as a classical element or foundation for life dates back even to ancient Babylonia which explicitly named wind as one of the five elements along with earth, fire, sea and sky. Later on, the Greek’s would also include wind among the essential set of elements of nature or phases and states of matter. Indeed, wind, or air, was one of the five classical elements of Ancient Greece along with fire, earth, water and “aether” or quintessence (the “fifth essence” - a celestial element associated with the air of the Gods).
Similar categorizations existed from India to Tibet and from China to Japan. Indeed, the Hindu God of the wind Vayu was also the name for the air or wind element in the creation of all human life. These elements were fundamental to both matter as well as energy in life and ancient societies found ways to use each to their respective advantages. Ancient societies recognized the power and utility of the wind and invented technologies to take the mysterious force, element, aether and harness it for the benefit of humankind.

Wind energy was early adapted for use by ancient civilizations notably in ships (as with the westerly winds that carried Odysseus towards Ithaca or the northerly winds that sunk the fleet of Xerxes). While the history of wind energy use for maritime propulsion is a long and interesting one, the scope of this work centers around wind energy for electricity production. For a detailed history of sailing technology, Gilfillan’s Inventing the Ship provides an excellent account (1935). The utilization of wind’s power on land lags the first maritime uses by a lengthy amount of time. The exact origin of the windmill, the predecessor to modern wind electricity generation, is a subject of debate. The oldest windmills developed concurrent with the development of large-scale agricultural systems and the ancient civilization of Greece, Rome and Persia (Wailes, 1968; Vowels, 1930; Bathe, 1948; Sheperd, 1994; Lucas 2006). Often cited as the origin of the windmill is a description by Hero of Alexandria in his 2nd century B.C. Pneumatics that mentioned the use of a windmill in powering an altar organ (Vowels, 1930). Vowel’s “Inquiry into the Origins of the Windmill” studied various versions of Pneumatics including five Greek manuscripts, two Greek printed texts and translations in Latin, French, Italian, German and English (Vowels, 1930). After his in-depth review of the texts, he cast significant doubt on the notion that Hero’s windmill was anything more than an abstract notion in the Pneumatics texts. Firstly, he noted that the terminology used in the original texts “anemourion” was not part of contemporary Greek vocabulary, and British author Dr. J. G. Greenwood only later translated it as “sail of a windmill” (Vowels, 1930). Vowel’s notes also that the interpretation of the word “anemourion” could also be a wind vane and not necessarily the sail of a windmill. Anemourion did exist as a city of Greece though any association with windmills is unlikely and it is more likely that the windy nature of local gave rise to its name. In addition, a Roman contemporary, Vitruvius, documented a variety of mechanical devices for power including watermills but makes no mention of windmills (Vowels, 1930). Various interpretive drawings over time in different scholars’ translations tried to establish what the design of Hero’s windmill would look like (Vowels, 1930). The Greek text did identify however some mechanism by which wind was used to provide a force that would eventually lead to operation of a “piston or plunger”
for the organ such that the account is likely the earliest written attribution of wind being used to supply energy for terrestrial purposes (Vowels, 1930).

Later historians give more credence to Hero’s design siting the work of Schmidt (1899), which included a waterwheel depiction of the entire system with a peg driven connection to the piston (Needham, 1965; Lewis, 1993). The scholarly community has accepted this diagram as following the original manuscript illustrations (see figure below). However, Sheperd’s review of the same work that builds upon that of Drachmann notes that the more complex design was actually interpretive just as with the various interpretations cited by Vowels (Drachman, 1961; Sheperd, 1994). A cruder version of the rotor also depicted in Schmidt 1899 and supposedly drawn from the original manuscripts (also shown below) removes the more complex attributes of the piston mechanism as well as the perspective drawing that would have been absent in the first century B.C. Thus, the drawings such as Schmidt’s and other earlier interpretations use the textual description of the machine rather than the original manuscript illustration that was apparently more rudimentary. The illustration by Schmidt is the most accurate interpretation of the text to date and Drachmann demonstrates how Schmidt’s machine tied to the manuscript descriptions. He also notes how all of the early manuscripts contain near identical texts and illustrations that support the authenticity of the windmill altar organ as created in Hero’s original *Pneumatics* text.
Despite the authenticity of the machine, there are a few aspects of the design that has lead historians to question the viability and practicality of the machine. Sheperd makes a few notes about potential design flaws in Hero’s description regarding the ability to turn the device in the wind (Drachman, 1961; Sheperd, 1994) and the “peg-driven tripping and return motion (in lieu of a crank)” which would require “a very rapid oscillating movement of the piston” (Sheperd, 1994, p. 6). As Sheperd (1994) points out, Hero’s windmill organ, unlike many of the other machines in *Pneumatics*, of Hero was a small toy model or more likely meant to be a concept than a common machine of the times.

1.2 Horizontal (vertical-axis) windmills

Thus, for concrete evidence of windmills with ties to current times and technology, one will have to wait several more centuries. Many historians have sought to pinpoint the origins of the two common types of windmills invented in the last two millennia: the horizontal (vertical-axis) windmills of Persia and the vertical (horizontal-axis) windmills of Western Europe (Vowels, 1930; Bathe, 1948; Wailes, 1968; White,
1962, Needham, 1965). Lucas (2006) provides the most recent account and attempt to reconcile the different perspectives over the origins of each type of windmill and their subsequent regional and international diffusion. Lucas performed an extensive research project on the ancient origins of various types of milling technologies from the hand mill to the beast mill to the compartmented waterwheel to the vertical and horizontal watermill and then finally to tidal and windmills (Lucas, 2006). He suggests, similar to other historians, that windmills were an extension of compartmented waterwheels and millwrights developed them due to special geographic circumstances for sites where waterpower was inaccessible and wind was abundant. The mountains of ancient Persia, current-day Iran, are home to such a region where wind is plentiful and water scarce. Therefore, it is no surprise that there exists a good amount of documentation and archeological evidence of windmills in this region at very early dates (anywhere from 7th century in a popular history told centuries later to eyewitness accounts in the 10th century A.D.) (Vowles, 1930; Bathe, 1948; Lucas, 2006). The region of Seistan in ancient Persia and modern day Iran is home to modern and historical accounts of horizontal windmills. This region was described by one early Arab scholar al-Mas’udi as “... the lands of winds and sand” where the “wind drives mills and raises water from the streams, whereby gardens are irrigated” (Ali al-Mas’udi in 956 as quoted in Sheperd, 1994). Some scholars have historically attributed a link from Hero’s windmill alter organ to the horizontal windmills of ancient Persia based on the knowledge that Greek works were known to contemporary Arab scholars (Vowels, 1930) but such accounts are largely absent from more recent histories. Other interpretations have linked Tibetan prayer wheels to the introduction of horizontal windmills in eastern regions of Persia where some interaction between Tibetan culture and Muslim culture would have been present (White, 1964). Lucas’ (2006) notes the lack of any concrete evidence for either the account.

However, there is some evidence that Greek or perhaps Roman technology did influence the invention of the Persian horizontal windmill through its watermill counterpart (White, 1964; Lewis, 1993; Sheperd 1994). Lucas’ (2006) accounts of the origins of the watermill include early invention of vertical-wheeled watermills in the first century B.C. with horizontal-wheeled watermills appearing only later and with conflicting stories of origin (Lucas, 2006). The earliest concrete evidence of these horizontal-wheeled watermills comes from in Palestine and Tunisia in the third or fourth centuries during the late Roman Empire though scholars often refer to them as “Greek” watermills (Lucas, 2006). Bathe dates the origin of the horizontal watermills in Greece as far back as first century BC (Bathe, 1948). The importance of the horizontal-wheeled watermills is their similarity to early Persian horizontal windmills. There are a number of factors that make the horizontal windmills of Persia quite different from their watermill counterparts. Firstly, as depicted by al-Dimashqi and scholars who have sited him (Bathe, 1948; Sheperd, 1994; Lucas, 2006), the construction of the rotor blades were sails made of cloth as opposed to the wooden blades of watermills. While it makes sense that millers would not use bellowing sailcloth in the harsh conditions of river and tidal environments, the innovation of using sail clothes by Persian millwrights is evidence of their unique tradition. Secondly, Persian windmills are “draft mills” whereby walls or shutters prevent wind flow except through apertures (Bathe, 1948). In absence of a mechanism to orient the blades parallel to the incident wind flow on their recovery stroke, the machine design must shield the blades from the flow so they do not provide resistance to further rotation.
Still, there are many features of horizontal watermills that make them quite similar to the earliest Persian windmills. Firstly, there is the horizontal configuration of the windmills similar to the “Greek” waterwheel. Secondly, horizontal watermills had the millstones overhead (above the water surface or flow). Sheperd notes that the earliest accounts of Persian windmills, the detailed descriptions and sketches of al-Dimashqi at the end of the 13th century, describe that the milling stones were placed above the rotor (Sheperd, 1994; Lucas, 2006). From an intuitive perspective, it seems odd to place the heavy millstones and devices above the rotor; al-Dimashqi’s drawing shows a 13th century Persian windmill next to an image of a “Greek” watermill. This is evidence of the possible earlier influence of watermill technology on Persian windmill technology (Sheperd 1994). In the crude drawing from al-Dimashqi, the bottom stone rotates under the upper stone for milling purposes.

![Figure 1-VI: Left: "Greek" style watermill (from Lucas, 2006, p. 35); Right: Persian horizontal windmill (after al-Dimashqi from Sheperd, 1994, p. 8)](image)

Indeed, as the technology evolved, later accounts of the windmills all showed the milling stones housed below the rotor. From an engineering perspective, the location of the milling stone below the rotor would have been advantageous for the stability and loading of the rotor structure – the added force of gravity and potential imbalances would have placed large loads on the rotor shaft likely leading to failure. A natural innovation, if the “Greek” watermill theory is accepted, would be to move the rotor above the milling stones so that the structure did not have to support the stones in addition to the aerodynamic loads to which it were subject. Images from windmills still in use in the 20th century in Iran are evidence of the more modern configuration.
In addition, Lucas describes how horizontal waterwheels found in regions of limited water supply incorporated the use of a funnel to direct water and make it more powerful when affecting the rotor blades (Lucas, 2006). There was a specific name for the chute technology in Arabic: an arubah (Lucas, 2006). Again, one may hypothesize that ancient Greek, Roman or perhaps Persian societies introduced ancient watermill technology and then water-poor regions by Persian communities adapted the technology to early horizontal windmills. Horizontal watermills were in common use in Iran into the 20th century and there is evidence that were similarly common as early as the 7th century A.D. (Harverson, 1993). According to Harverson, the last Sasanian king before Persia was conquered by Islam was murdered “by tradition in a mill” in 651 A.D. (Harverson, 1993, p. 150). He also discusses the presence of the arubah or drop-tower that was essential to providing water supply to the mill and was a standard component of such Persian and modern-day Iranian mills (Harverson, 1993). Thus, from the perspective of social models of diffusion along the lines of Griliche and Bass, the technology of the watermill diffused throughout ancient Greece, Rome and Persia. As it diffused, however, innovations were necessary to adapt the technology in particular to regions without significant bodies of water flow – thus the particular contribution of the arubah by Persian millwrights. To borrow from Thomas Hughes (1983), millers had to overcome the “reverse salient” of operating without access to strong consistent flows of water. Finally, in water-scarce regions, such as Seistan, where desert sands were kings and winds were Gods, the technology finally had to adapt to the use of wind rather than waterpower. Eventually, this led to the recognition of the need for certain innovations such as placing the milling stones underneath the rotor of the windmill. However, detailed accounts of the technology of such early horizontal windmills are scarce themselves and much more investigation into the specifics of their evolution over time might help to evaluate this hypothesis of “Greek” watermill diffusion and adaptation to the Persian horizontal windmill. A study similar to Harverson’s “Watermills in Iran” for windmills would indeed be a worthwhile contribution to the overall history of horizontal windmills.
The diffusion of the horizontal windmills by several accounts spread further east from ancient Persia to various Arab countries and eventually to China. However, the horizontal windmills of China in the 17th century had sail wings without any draft technology (Needham, 1965; Bathe, 1948). The sail wings were open to the wind, and a rope attached to the next sail's post held them taught when the wind was incident upon them. During the recovery, the rope would slacken so that sail would be parallel with the wind flow (Needham, 1965; Sheperd, 1965). Needham traces early discussion of windmill to eastern China along the silk road where Chinese traders may indeed have come into contact with Arab windmills of the near east (Needham, 1965). Needham identifies one early account from the year 1219 to coincide with the visit of a Chinese statesman Yehlu Chhu-Tshai, patron of astronomers and engineers, to the Samarqand region of modern day Uzbekistan which mentioned that “the stored wheat is milled by the rushing wind” (quoted in Needham, 1965, p. 560). The description of Persian style windmills with sail cloths and four directional apertures is found in later work by Chinese scholars commenting on their presence both in Samarqand as well as in Herat (in modern day Afghanistan) (Needham, 1965). Thus, Needham supports both the notion that Persian style windmills diffused throughout much of the Arab world from their introduction in the early centuries A.D., but also that this technology was also the basis for the later introduction of horizontal windmills to China. At the same time, however, Needham shows evidence of how introduction of the technology into a new culture or social frame of reference allowed the technology to take on its own unique character: namely through removal of the aperture configuration and introduction of the fore-and-aft rigged sails based on Chinese junks (Needham 1965). The technology was likely adapted from Chinese ship technology with imperfect information about the actual construction of Persian windmills (Needham, 1965) or it occurred as the result of an innovative process by which the performance of non-draft configurations were found to be superior to those that used the draft technology.

![Figure 1-VIII: Chinese windmill with sail wings and string attachments (from Needham, 1965, p. 560)](needham_1965_560)
In general, the technology of the horizontal windmill evolved and adapted in different geographic locations and for different applications. While Western Europe and the United States spent considerable effort on innovations for vertical windmills, there was also significant attention paid to their horizontal windmill counterparts. For instance, between 1680 and 1870, 94 patents were approved in England concerning sails of windmills or smoke jacks and of these 55 were concerned with the horizontal configuration (Hills, 1994). Many of these patents were concerned with how to improve the overall control of windmills. Much of the unique character that differentiates windmill designs are associated with the types of control used in windmill operation for automating wind mill orientation towards and away from the incident wind direction, braking the system in extreme winds, and controlling the amount of wind energy absorbed by the rotor. Bathe’s work on horizontal windmills distinguishes between two types: shrouded (or shielded) windmills such as the Persian windmills and articulated windmills such as the Chinese windmills. The main distinction between these two designs is the mechanisms by which they control the direction of wind flow onto the rotor. However, there are a large number of mechanisms to accomplish this control in either case. Bathe (1948) surveys a wide variety of types for each from the earliest mills to innovations developed into the 19th century. In the case of shrouded windmills, a fixed wall on one side or a two or four-sided wall with apertures could direct the flow such as in the case of the Persian windmills. However, any number of walls could encapsulate a vertical access turbine so long as the mechanism protects the recovery motion of the blades from incident wind flow. For instance, in 17th century France, one inventor provided a mechanism whereby one moveable wall or screen would protect one-half of the rotor from the wind (Bathe, 1948). On the other hand, another 17th century France inventor suggested the use of an external structure with a myriad of slightly overlapping louvers, or angled shutters, that would direct the wind towards the blades (Bathe, 1948). The inventor apparently borrowed the idea for this technology from such windmills that were common in both Portugal and Poland, so called “Polish windmills.” An Englishman named Stephen Hooper in a 1777 patent (Hills 1994) suggested a similar invention. Additional innovations where suggested such as using sliding panels moderating wind flow through a given aperture – which would result in control of the amount of wind impinging on the rotor vanes (Bathe, 1948).

For articulated windmills, no walls were necessary but the blades were required to move in and out of the plane perpendicular to wind flow through various types of automatic control mechanisms such as folding vanes, shuttered vanes, hinges, or pivots (Bathe, 1948). Interest in these types of mills extended across the Atlantic and into the 18th and 19th centuries in both Europe and the United States. Some of these “inventions” were reminiscent of the Chinese style articulated windmills such as an 1898 invention of a Nebraskan resident using rope hinges to orient the rotor blades during each phase of rotation (Bathe, 1948). Other inventions concerning articulated horizontal windmills included even more complicated mechanisms described by several patents filed in the 19th century. During this period, inventions concerning the use of hinged shutter vanes automatically controlled by a governor also targeted braking and control of wind flow (Bathe 1948). For a comprehensive review of these various mechanisms, Bathe’s work provides detailed descriptions and corresponding illustrations of each type. Some added discussion will follow in the section on comparisons between horizontal and vertical windmill technology.
1.3 Vertical (horizontal-axis) windmills

Vertical windmills, in which the rotor turns around a horizontal axis, have their own history. A natural extension of the diffusion of technology story, that Greek waterwheels diffused north and influenced the invention and diffusion of Persian horizontal windmills is that the horizontal windmills of Persia and surrounding Arab nations diffused west into Europe and eventually led to the development of the vertical windmill in medieval Europe. However, the historical evidence of such a diffusion path is scarce and there seems to be a discontinuity in the history of windmill innovation. Scholars have indeed suggested this very idea on numerous occasions (Bathe, 1948; Vowles, 1930; Lewis, 1993). These accounts have included the suggestion that Crusaders may have brought knowledge of such mills back with them upon their return home (Bathe, 1948). Bathe pinpoints the first “authenticated” mention of a windmill in France in 1105, which corresponds to the end of the first crusades (Bathe 1948). However, scholars have since discredited this reference to a French windmill at such an early time. The cited document was a forgery written almost a century later (Wailes, 1960). While direct evidence of a link between the crusades and windmill technology diffusion remains speculative, other theories also linked Persian windmills to later Western European vertical windmills. Lucas discusses the two theories of Vowels and Lewis. The former suggests Viking traders brought the technology west from Russia while the latter suggests that the technology diffused via Byzantium with complementary influence derived from Hero’s windmill powered organ (Vowels, 1930; Lewis, 1993; Lucas, 2006). Lucas notes that neither of these two theories demonstrates strong evidence of their claims. However, he notes that the fact that Arabic writers of the 10th century who referred to windmill technology also discussed a “wind-powered fountain apparently derived from Hero’s anemourion,” which supports part of Lewis’ theory (Lucas, 2006, p. 106). This provides evidence of the first link of Hero’s early technology to Persian windmills rather than direct evidence of the influence of the Persian windmills on vertical windmills.

Moving away from the theory of transfer of technology from the near east, Wailes and others have suggested that the invention of the windmill in Western Europe was an independent invention based on the Vitruvian waterwheel common at the time (Wailes, 1968; White, 1964; Sheperd, 1994). Earlier, we mentioned Vitruvius as an early scholar who documented Roman and Greek machines and mechanics. He did not mention any windmill technology, but he did provide a significant treatment of watermill and waterwheel technology. The so-called “Vitruvian” waterwheels were vertical in orientation. Vitruvius provided a detailed description of the undershot watermill (example shown below) and archeological evidence for such mills date back as far as the 1st century A.D. (Lucas, 2006).
Figure 1-IX: Above: Vertical "Vitruvian" style waterwheel with "Vitruvian" cog-and-ring gear mechanism to translate the horizontal to vertical motion (Lucas, 2006, p. 35). The mill is an "undershot" configuration since the arrow is point to the water being oriented to impinge on the rotor blades from below thus causing the wheel to spin in the reverse direction to the incoming flow; Below: vertical windmill rotor with "Vitruvian" cog-and-ring gear (left) and one of the earliest known illustrations of a vertical windmill (a postmill) from 1270 (Shepered, 1994, p. 13).

In particular, the general use of gearing and the configuration of the waterwheel around a horizontal-axis are two particular technological ties to the vertical windmill. The Greeks used such gearing since at least the first century B.C. in clocks astronomical clocks and other instruments (Lucas, 2006). Vitruvius' watermill depiction also described the gearing since it is a necessary technology for overall function of the mill (translating the vertical spinning motion of the wheel into horizontal spinning motion necessary for milling). Earlier Persian windmills did not need such complex gearing by using a horizontal rather than a vertical configuration. Horizontal (vertical-axis) windmills are arguably simpler in construction and operation and that would make their adoption more likely. The basic physics behind operation of such a turbine require only the recognition that wind can apply a force that pushes an object and a basic understanding of wheels and axles for milling operation. Thus, the engineering involved with horizontal and vertical windmills is distinct enough to support different traditions. Similar to the shared knowledge and experience of the Chinese and Persian windmills, however, it is possible that the basic knowledge
and idea of using wind to provide power for milling was made known to Europeans from experiences in the Crusades or trading activity and this was enough to inspire the translation of the vertical windmill from their well-known vertical watermill technology.

Regardless of whether the vertical and horizontal windmill traditions are independent, the historical evidence surrounding the appearance of records of windmills in Western Europe appears abruptly at the end of the 12th century. While no records have been verified for windmills before 1180, dozens of accounts have been confirmed both in England and France as well as Flanders and Belgium in the period between 1180 and the early 1200s (Lucas, 2006). The notion that such mills were spontaneously invented and then adopted over such a wide geographic range is one reason to suspect that the technology pre-existed these early accounts. However, the novelty of the technology at the time is evident in a few particular accounts concerning the taxation of profits associated with the productive work from the mills used for grinding grains. A papal decree from before the 12th century mandated the taxation of windmills just as any other mill (Lucas, 2006). The fact that the church identified a need to formalize taxation of windmills is evidence of their contemporary invention. Milling tithes during the period were a significant source of income for the church and a new un-taxed milling technology would have posed a threat. In 1191, there is an account of an argument between a Dean Herbert who built a windmill on his property for grinding corn and an Abbot Samson who demanded the community tear down the windmill (Hills, 1994). Dean Herbert promised that he was planning to use the mill only to grind his own corn, but in the end, the mill was demolished. In Britain during that time, the wind was a free resource, unlike the water controlled by the riparian owners through which the water passed (Hills, 1994). While this was not true of all medieval societies—the Dutch did in fact tax use of the wind—it has significance for the adoption of the technology. If wind were free in Britain, then it would have a distinct advantage over other milling technologies since it avoided costly taxes paid to the state and church. The primary food source in medieval Britain was bread, and as the population rose quickly between the end of the 11th and the onset of the Black Death in the mid-14th centuries, milling technologies were important in producing enough food for the population (Hills, 1994). Hand, horse, water or wind could accomplish milling. The latter two provided economies of scale. Waterpower had its advantages in terms of overall productivity as well as consistency – it was available, for the most part, when needed. Wind power, though, had its own distinct advantages. Firstly, there were specific regions where water was scarce. In particular, there were regions such as along the east coast of England, where water was less plentiful and windmills were more prevalent (Langdon, 2004). Wind power, unlike waterpower, is available to some degree everywhere. Thus, the combination of initially tax-free use of wind energy combined with specific regional scarcity of water would have promoted the early adoption of the technology in certain parts of England.

It is no surprise then that the majority of accounts concerning early vertical windmills as well as the earliest vertical windmill installations have been found in England (Lucas, 2006). The key technologies to enable the development of these mills were three-fold: 1) the vertical rotor connected to a 2) gearing mechanism translating the horizontal-axis rotation to vertical-axis rotation and 3) a mechanism for orienting the rotor towards or away from the wind depending on its direction of movement and the need to either operator or brake the rotor. The former two were well known in Western Europe at the
time from their origins with watermill technology as described above. The latter technology was unique to windmill technology and more specifically to vertical windmills. As mentioned, four walls with apertures often encapsulated horizontal windmills of the near East that allowed the wind to turn the rotor under a variety of wind conditions. Through various innovations, the need for the walls were removed as in the case of the Chinese windmills which used taught ropes and “jibing” of the sails on the recovery turn (Needham, 1965; Sheperd, 1994). However, vertical windmills had the rotor affixed to one side of an enclosed structure housing the gearing and milling equipment and thus needed to be oriented into the wind in order to function. Millers initially accomplished this by rotating the entire structure to face the wind by use of a giant tail pole as illustrated in the figure above (Sheperd 1994). There is little information to suggest whether the very first mills had such a tail pole or whether millers discovered the need for it after constructing the first several. Only the foundations of early post mill structures have remained to present day (Lucas, 2006). The illustration from 1270 clearly delineates a tail-pole or tail beam attached to the structure distinguished from the support beams at the foundation implying that such technology was common to vertical windmills by at least the late 13th century. By that time, windmills existed in several countries including England, France, Flanders, Belgium, Crusader Syria, Netherlands, Pomerania, Denmark, and Bohemia (Lucas, 2006). As far as is known, all of these early windmills featured the common “post mill” configuration. This type of vertical rotor mill is distinguished by the fact that the entire mechanical system of the mill including the rotor, gearing, milling and auxiliary equipment is all mounted inside of a structure / “post” that is rotated into the wind for operation and out of the wind to shut down. Several scholars have sought to describe the detailed operation and mechanics of these windmills (Langdon, 2004; Lucas, 2006).
Figure 1-X: A large post mill from Sussex, where several of the earliest windmills have been discovered (Walles, 1960, p. 23); Notice the ladder / tail-pole in the back of the structure that has wheels on which the structure rotates. Notice the fantail on the back structure that would automatically orient the structure into the wind that was not invented until several centuries after such mills had been in use.

Langdon, as summarized and expanded upon by Lucas (2006), provided an in-depth treatment of the technical challenges in early post mill design as well as various innovations from the 12th century going forward. Each of the basic components including the rotor, gears, shafts and bearings, milling stones, auxiliary equipment, and tail-beam had various configurations and used a variety of materials. The rotor was connected to the main shaft, or “windshaft,” which was connected to the gearing mechanism – a large spur gear, or cog-wheel, on the windshaft connected to a cage, or lantern-pinion gear, on the millstone shaft, or the “upright shaft” (Sheperd, 1994; Langdon, 2004; Lucas, 2006). Millwrights initially constructed the assembly just as if it were an inverted vertical watermill assembly with right-angled gearing that turned the upper millstone (Lucas, 2006). Even the gearing configuration of a spur gear connected to a cage gear was typical of contemporary watermill technology. This again lends supports the influential role of watermill technology on early vertical windmill designs.

As the technology evolved, however, the drivetrain assembly incorporated certain modifications. Gears evolved from rectangular pegs to shaped wooden cogs to iron cogs to eventually cross-helical gears (Sheperd, 1994). In addition, later machines had the orientation of the main shaft shifted away from a right angle to the upright shaft to allow for tilt of the rotor upwards. Early arguments speculated that
the transition to a tilted shaft supported overall “balance” of the structure (Wailes, 1954), but Sheperd suggests that the primary value of the tilt is similar to the rationale in modern day wind turbines: it provides for additional clearance of long rotor blades (1994). The force of the wind on the blades induces thrust that pushes the blade tips towards the tower; modern wind turbines designs adhere to standards for minimum blade clearance (International Electrotechnical Commission, 2005). The longer and more flexible the blades of the rotor are, the more likely the thrust may lead to a “tower strike.”

While coning the blades forward can also reduce the likelihood of tower strikes, this mechanism does not seem present in the account of windmill technology development. All examples of later windmills exhibited an incline of some amount (approximately 10 degrees) (Sheperd, 1994). While the incline would also shift some of the load of the overall rotor structure across the main shaft towards the tail beam providing the added “balance” Wailes refers to, Sheperd notes that this introduces additional design challenges. The gearing as well as support structures including beams and bearings all would need to be adjusted to accommodate the incline of the shaft which would result in more complex loading of each of these components. Thus, Sheperd suggests that the tail beam was the main mechanism to provide balance to the structure and the main reason for the introduction of a titled rotor was for tower clearance as suggested earlier.

Another method of addressing the problem of tower strikes used in modern wind turbine technology includes coning of the blades away from the tower; however, accounts of such mechanisms are not present in histories of windmill technology (Sheperd, 1994; Lucas, 2006). This potentially may stem from the fact that the assembly of the rotors themselves was quite simple – the rotor typically had a configuration of four blades (sometimes six) that were constructed of “two long timbers or sail-yards... mortised in the shape of a cross to the end of the mill axle” (Lucas, 2006, p. 119). Such a configuration would have provided a good amount of strength against the loading of the rotor by the wind. For modern turbines, the use of individual connections of blades at the hub results in strong loads at the root of the blade which result in a major source of concern in the overall design process (IEC 2005). Shifting to a coned rotor, if conceived of for early or late windmill technology, would have made the two crossed-timber rotor configuration more challenging. The following figure provides a depiction of an advanced windmill with detailed listing of components in Brill, England, built in 1686 and later restored to its original form (Freese 1957 as described and illustrated in Sheperd 1994).
Figure 1-XI: Detailed diagram of a fully developed post mill (in Sheperd, 1994, p. 21 after Freese 1957)
Beyond the major assembly of the rotor, drivetrain, millstones and auxiliary equipment, the support structure including the housing and foundation was critical to the technical viability of the overall system and evolved overtime as well. Lucas refers to Thomas Hughes’ notion of the “reverse salient” to describe the innovation process of the support structures for vertical windmills. In particular, Langdon’s review of windmill technology found that failure of the central post on which the entire structure turned was a critical challenge faced by early millwrights (Lucas, 2006). Sheperd describes this problem in modern mechanical engineering terms noting that the structure was subject to large overturning moments from the wind thrust. The structure’s weakest point with respect to this overturning moment would have been at the interface of the post structure with the central post that supported it and where the post interfaced with the foundation of the structure. Thus, inventors developed a series of foundation designs for support of the central post over the years from burying the post in the ground to the use of a crosstree and struts buried in the ground, to eventually the use of the crosstree and struts position on stone or brick piers (Lucas, 2006). The illustration above shows the fully developed foundation design using brick piers and a crosstree with the central post connected to them via a tongue and groove joint and quarter bars bracing each side of four sides of the central post.

Even with the most advanced design as described above, the central post and foundation still would be subject to significant loads. Attempts to remedy this might involve using a very large and strong central post such as from an oak tree of considerable age (Sheperd, 1994). Another method of addressing limitations associated with the heavy loads is to reduce the overall weight of the structure that the central post needs to support. A variation on post mills called “hollow post mills” that have been documented in fifteenth century Netherlands, Belgium and France were one way to address this (Lucas 2006). The “paltrok” style post mill found across Eastern Europe provided another mechanism for this by moving the support beams to the perimeter of the structure so that the weight of the overall post structure spread across a much larger area (Langdon, 2004). However, the durability improved even more by reducing the orienting structure to only the top portion of the mill. Such mills known as “tower mills” were very similar to post mills but only the cap of the tower would rotate into the wind. A tower constructed from brick or stone would contain the milling equipment and the cap of the tower rotated into and out of the wind as needed with a tail beam as before. Such mills “cost around twice as much to build as a post-mill [but were] far more durable” (Lucas, 2006, p. 122). In addition, due to their solid construction, such mills could be built on the walls of towers and castles allowing the rotor of the mill to reach higher overall winds (Lucas, 2006). Generally, scholars assumed tower mills evolved at least a few centuries later than post mills perhaps in the Mediterranean where significant documentation of such windmills exists from the fifteenth century (Lucas, 2006). Recent work in the area has found that accounts of such tower mills date back to at least the fourteenth century and even to thirteenth century England (Langdon, 2005). The account by Langdon and Watts provides convincing evidence of a tower mill constructed in Dover, Kent, England in 1294 (Langdon, 2004). Whatever its initial inception, certainly this technology descended from earlier post mill technology. The superiority of the tower mill in terms of withstanding the thrust from the wind, however, did not lead immediately to their replacing older post-mill technology; post mills would continue to be the most prominent form of windmills in England until the late seventeenth or eighteenth century (Lucas, 2006). From a perspective of economic models of diffusion, the extra cost associated with building tower mills may have prevented them from
overtaking the post-mill if they were either not affordable or did not provide a significant enough return on their investment. Certainly, given the rapid proliferation of post mills in England during the 13th century, one would not expect a general lack of awareness or diffusion of information about such mills across the country. However, perhaps the pre-existence of post-mill technology impeded this process. Indeed, the average lifetime of a post-mill may have directly contributed to the slow adoption of tower mill technology in England where such mills were common unlike in the Mediterranean where post mills had not experienced significant development during the 13th century.

The technology of these tower mills was such that several survived and were in use into the 20th century. The key distinguishing feature from the post mill was the rotating cap atop a fixed tower. This

Figure 1-XI: Dutch tower mill with dual millstones (Sheperd, 1994, p. 23)
cap initially rotated on the tower by the use of greased wooden blocks sliding on a curb but eventually evolved to use iron tracks and rollers (a roller-bearing) so that overall friction of movement was minimized (Sheperd, 1994). Aside from the cap itself, the tower mill configuration allowed for several other innovations: a taller overall structure to access faster winds at higher heights, longer blades, and more internal room within the structure to provide for grain storage or even for living quarters for the millwrights and their families (Shepherd, 1994). In addition, inventors introduced several controls innovations for tower mills. Control for windmill operation was an engineering challenge both for horizontal as well as vertical windmills and resulted in a variety of innovations through the entire history of each technology. In particular, however, just as with horizontal windmill innovations for articulated windmills, the 18th and 19th centuries featured significant innovative activity with respect to control of vertical windmills. As with horizontal windmills, the general types of control involved in windmill operation were for automating windmill orientation towards and away from the incident wind direction, braking the system in extreme winds, and controlling the amount of wind energy absorbed by the rotor. Such technology development was arguably even more important for vertical windmills.

Firstly, regarding orientation of the windmill, Edmund Lee of England introduced an innovation in the mid-18th century with a “fantail” (Sheperd, 1994). As mentioned, early windmills used a tail pole to orient the windmill towards the wind for operation and away from the wind to protect the machine during extreme conditions. The fantail, however, allowed for the automation of this task for the purposes of orientation into the wind. This fantail was oriented perpendicular to the rotor plane, was significantly smaller than the main rotor, and contained six or more of small blades. If wind was blowing perpendicular to the main rotor, then, this fantail would turn and provide power to gearing which would turn the tower mill cap or the entire post mill until the fantail was perpendicular to the wind (and thus the wind would be directly incident on the main rotor). The previous picture of a post mill includes an image of such a fantail. Such automatic systems for “yawing” the turbine into the wind are present in wind turbines today though their form is substantially different.

In addition, braking and control of the amount of wind flow were two interrelated areas of innovation that also followed rather late in the development of vertical windmill technology. Windmills can have a number of different mechanisms for braking and control of wind flow that include both aerodynamic braking and flow control on the rotor as well as mechanical braking on the driveshaft. In addition, “yawing” the windmill into and out of the wind is another way of controlling the amount of wind flow to the blades. Finally, use of cloth sails for the rotor blades and allowing for their furling, or rolling up, either partially or fully under different wind conditions, was another way of controlling the aerodynamic forces experienced by the rotor. While the earliest mills supposedly were slatted boards for blades, later windmills would use cloth sails. Different types of rotors were prominent depending on the region. In the Mediterranean, rotors eventually developed a sort of inverted wind rose type configuration inspired by the rigging of local ships (Hills, 1994). Hills hypothesizes that a shortage of heavy timber in the Mediterranean region inspired the design where triangular-shaped pieces of canvas were attached at their leading edge to a spar around which they could be wound in high winds. Hills (1994) notes that the aerodynamic design of such a rotor was advantageous since it resulted in a lower tip-speed-ratio. This resulted in high efficiency at low-speeds and reduced the likelihood of over-speeding (Hills 1994).
Northern Europe favored rotors with four to six blades typically constructed of slatted-wood covered in cloth sails that a mechanism could draw back, "furl," manually and eventually automatically in high winds (Drees, 1977; Langdon, 2004). In the 18th century, various mechanisms to automate this process were introduced including "spring sails" with hinged wooden shutters rather than sail cloth, "roller-reefing sails" which used a long "striking rod" to simultaneously open or close each individual sail element, and various other improvements (Sheperd, 1994). Such shutters acted as aerodynamic brakes by creating drag that would cause the rotor to stop rotation (Sheperd, 1994).

Scholars suspected, however, that the earliest mills lacked both the cloth sails as well as any kind of aerodynamic or even mechanical braking mechanism (Langdon, 2004). Millwrights introduced mechanical braking systems in the fourteenth century to Flemish windmills and subsequently to other types of mills (Langdon, 2004). The system consisted of a large wood band that nearly encircled the large cogwheel that the rotor would drive and this in turn connected to a hinged beam drawn down and caught by a lever in order to produce a strong grip of the brake on the cogwheel—prohibiting rotation (Langdon, 2004). Scholars have suspected that early English windmills from the 13th century operated without any braking system as some French post-mills did even into the 20th century (Langdon, 2004). Later windmills would use an automated mechanism to brake under extreme winds that consisted of a heavy ball resting on top of a circular pedestal would shake under high winds and ultimately fall to activate the brake. There are many innovations in windmill controls for both horizontal and vertical configurations and a comprehensive review of this topic in particular does not exist.

1.4 Comparison of horizontal and vertical machines

By the nineteenth century, vertical (horizontal-axis) windmills diffused across much of Europe and eventually the world while use of horizontal (vertical-axis) windmills was still prevalent in the near and Far East. Once can compare these technologies across a number of dimensions in terms of both cost and performance. The horizontal windmills are considered to be generally less complex and less costly than their vertical counterparts are but also do not have nearly the same degree of overall power performance. We will briefly describe the reasoning for the performance difference.

The physics of operation of historic vertical windmills are fundamentally different from those of historic horizontal windmills. Early horizontal windmill rotors are literally "pushed by the wind". Their blades move in the same direction as the incident wind (drag force). On the other hand, vertical windmill rotors respond to wind flow with rotor movement perpendicular to the incident wind direction (lift force). In a lift-driven wind turbine, the pressure difference above and below the rotor blade or sail causes the rotation of the blade. While those comparing horizontal and vertical windmill technologies did not have an understanding or knowledge of these forces, they could recognize the difference in performance between a drag-type horizontal windmill and a lift-type vertical windmill. As early as 1659, an Englishman who found that made a comparison between the two types:

"The first sort (being perpendicular), are the most usual and best, being commonly used in Corn mills. The other sort call'd horizontal sayles, are of little use, and lesse worth; they will move, but not equaling the strength of one horse..." (Bathe, 1948, p. 11)
Millwrights made various hypotheses for this difference in performance. In the mid-18th century, John Smeaton carried out a series of experiments to understand the “optimal” design of sails and rotors for vertical windmills. Firstly, he adapted and improved upon the “whirling-arm” test machine originally invented by Benjamin Robins in the early 1740’s to explore air resistance for projectiles (i.e. cannonballs) (Anderson, 1997). Just 15 years after Robin’s work was reported, Smeaton was using an adaptation of the whirling-arm (which included a rotating miniature windmill rotor) to investigate forces associated with windmill operation and how variations in windmill design might affect performance (Anderson, 1997; Smeaton, 1759).

The device by which he measured performance of the rotors also led to a formula for force exerted on an object’s surface by moving air; however, he did not have a thorough understanding of the principles of lift and drag and their interaction as scientists would begin to understand in the late 19th century (Anderson, 1997). In addition to his experiments on the performance of vertical windmill rotors, he also compared the overall performance of vertical and horizontal windmills. His conclusion was that the orientation of the blades were not important, but it was the fact that only part of the horizontal windmill which was exposed to the wind at a given time that made the machines tend to underperform their vertical counterparts by a factor of 8 or 10 (Bathe, 1948). It is true that while for a horizontal machine each blade is simultaneously working to deliver power while only half of the blades on a vertical machine are working to provide power at any given time. However, due to advances in aerodynamics, we now understand that the primary advantage of historic vertical windmills over historic horizontal windmills is the use of lift by the former and drag by the latter. The word “historic” here is important since modern-day wind turbine technology includes horizontal (vertical-axis) machines that also operate using lift over drag as the principle force inducing rotation.

![Figure 1-XIII: Direction of different type of forces acting on an airfoil](http://en.wikipedia.org/wiki/File:Aeroforces.svg)

Much of modern understanding about optimal rotor design for vertical windmills surfaced through empirical development of the technology from the 13th through the 19th centuries. Modern notions of rotor solidity, non-linear blade twist, leading-edge camber and fractional-chord position of the main spar were present on windmills of the 17th century (Drees, 1977; Hills, 1994).

In particular, the location of the main spar or blade stock at ¼ the chord, the aerodynamic center and center of gravity, is important to minimizing twisting moments on the blade and thus supports overall structural reliability (Drees, 1977). As noted before, structural reliability of vertical windmills was a challenge. The center post and support structure, prior to the development of the tower mill, was subject to strong loading that led to various failures and improvements of the support structure design.
The horizontal windmill, on the other hand, did not need to be oriented towards the wind, so the design of the support structure was less critical. In addition, the horizontal windmill, as mentioned previously, did not require gearing of any sort in its simplest form that implies fewer moving parts subject to loading and breakdown. The main structural challenge for horizontal windmills was the connection at the root of the rotor to the millstones. Similar to modern vertical-axis windmills, torsion on the shaft would have required sturdy designs to avoid failure, but this design challenge would seem far less difficult to address than those facing vertical (horizontal-axis) windmills with all of their design complexity.

From a cost perspective, Bathe postulates that horizontal windmills would have been cheaper and easier to build than vertical windmills since one could easily attach such a system to an existing barn or other structure (Bathe 1948). He describes the differences:

"There can be no comparison drawn between the elaborately equipped and permanent structure of the English or Dutch mills and those built on the horizontal [vertical-axis] principle, but they were cheaper to maintain and operate and did not require experienced millwrights to build them, so it is not surprising that this type of windmill found much favor in continental Europe during the 18th century. Farms were poor and isolated and the proprietor could, by erecting such a simple contrivance, often placed on the roof of his barn, take care of his small seasonal milling requirements to good advantage." (Bathe, 1948, p. 7)

In terms of versatility of applications, millwrights used windmills to grind grain, pump water, full cloth, and even saw wood (Baker, 1985; Righter, 1995). While less prevalent for industrial milling applications than their watermill counterparts, some mention of windmills for the use of the above applications was present for both horizontal and vertical windmills. Richard Hills provides a review of several types of agricultural and industrial applications of windmill technologies. Windmills for water drainage were common in both the Netherlands as well as England where flooding was hazardous in areas near or below sea level (Hills, 1994). Use of windmills for pumping water would be a critical technology in the settlement of the western United States as will soon be discussed. In addition to milling and water pumping, however, the industrial era found use for windmills in providing power for a number of applications from sawing wood, processing oil and dyestuffs from raw materials, grinding flint, crushing chalk, fulling cloth, and even stamping paper pulp (Hills, 1994). The use of wind power for these applications essentially required reconfiguration of the stones for different purposes such as pressing and crushing seeds or turning the rotary motion of the driveshaft into reciprocating motion via a camshaft to produce the action needed for stamping and sawing (Hills, 1994).

The repertoire of industrial activity for the vertical windmill before the development and proliferation of steam technology was quite extensive as noted above; the same, however, was not necessarily true for horizontal windmill technology. This may have resulted from the fact that horizontal windmills were not as common in northern Europe where industrial activity was growing, but it may also be due to the earlier mentioned limits in efficiency of such mills that rely on drag forces over lift for movement. However, vertical windmills did find some use for industrial applications as well. One prominent manufacturer of horizontal windmills in Iowa near the end of the 19th century touted them with such taglines as “the Favorite of every one who has seen or used it”, “Runs with Lighter Wind” and “Is Never Injured by Storms” apparently meant to juxtapose the technology against its vertical counterparts.
The potential uses of the technology include grinding grains, pumping water, and even sawing wood. However, the poor performance of drag-driven horizontal windmills would have likely made them less attractive for industrial applications than vertical windmills. Regardless, the main applications for both types of mills included grinding grains and pumping water.

1.5 American windmill technology
The function of windmills for pumping water would lead to their adoption and innovation for use across the Great Plains of the United States and ultimately lead to the invention of the so-called “American windmill.” Early colonists brought windmill technology across the ocean with them from Europe of both post-mill and tower-mill configurations. The early settlement of Jamestown in modern-day Virginia was home to the first windmill in U.S. soil in 1621 (Righter, 1995). Early New Amsterdam, founded by Dutch colonists, featured several tower windmills and windmills in New England were prevalent for use in industrial purposes such as sawing wood (Righter, 1995). Post-mills were common in coastal and island regions where winds were quite plentiful especially in the fall and winter months when grinding grain was most needed. In addition, windmills were an important component of the growth of the salt industry in the late 18th century (Torrey, 1976). The build-up to the American Revolution resulted in the loss of various imports from Europe and the Caribbean including salt that was not an indigenous industry up to that time (Bowman, 1969). Salt was of course an important source of general nourishment for food but also played a key role in the fishing industries for preservation of cod and mackerel. Captain John Sears apparently began using windmill technology to pump salty water from the cape into wooden vats that would evaporate in the sun and leave residue of salt behind (Torrey, 1976). The “saltworks” that sprang up during the revolutionary era peppered the Cape Cod and the Long Island Sound regions for several decades after and led Thoreau to describe the windmills as “huge turtles” and others to refer to Long Island Sound as “windmill country” (Torrey, 1976). Thus, windmills played an important role as the young nation of the United States began to take shape.

Soon, though, the introduction of steam engines and eventually electric machinery eclipsed the importance of windmills for industrial activity in the northeast. Just as the prevalence of windmills in the northeast had declined, there use would gain a foothold in western states where winds were strong and water was often scarce. Famous historian of the “Wild West” Walter Prescott Webb claimed that along with the railroad, barbwire and the “six-shooter”, windmill technology enabled settlement of many more of the “parched places” of the west and supported the expansion of the cattle industry (Righter, 1995). So necessary to Prairie life were windmills that Cowboys were claimed to have a saying that “Nebraska was no place for a woman unless she could keep a sod house tidy, shoot a snake, and climb a windmill” (Torrey, 1976, p. 101). Large ranches in particular, had an abundance of windmills to provide water for their livestock. At the turn of the century, payments for cattle were adjusted to per pound rather than per head basis such that long treks to watering holes were not economically desirable (Baker, 1985). Large ranches had windmill water pumping stations every few miles, such as the three million acre famous XIT ranch with over 500 windmills scattered across it (Hills, 1994). Beyond providing water for crops, livestock and settlements, the windmill was itself an enabling technology of the railroad system since it served as a critical resource for providing water to new steam locomotives that were newly crisscrossing the American landscape (Righter, 1995). Travelling across the west by rail in the
early 1900’s, windmills would be commonplace and the abundance struck those travelling from city centers and the coasts (Torrey, 1976).

However, the plentiful winds of the Great Plains of the U.S. would prove a difficult adversary to traditional post-mill and tower-mill technology. As mentioned before, structural loading of vertical windmills was a continual challenge to millwrights, often leading to failures in the rotor as well as gearing and support structure. In addition, resources—wood and metal necessary for construction of traditional windmills—were scarce in the regions of the Great Plains. The development of windmill technology that could withstand the strong winds in the west and use substantially less material than traditional mills would be extremely valuable to western settlement. Nearly all the windmills used to support western expansion as described above are “American windmill” types as distinct from traditional tower or post mills. Whereas the tower mill was an evolution of the previous post-mill technology, the “American windmill” was a strict departure. Generally, the main feature that distinguishes American windmills from tower and post mills are their rotors that feature a multi-bladed or windrose configuration. While the sails or blades were historically constructed of wood and metal, the rest of the structure including gearing, governing mechanisms and pumping or other equipment was manufactured out of metal. The support structure involved typically a lattice tower that exposed the machinery to the elements. Finally, and most importantly, American windmills contained governing or control mechanisms that would automatically reduce loading of the structure during high winds that were typical of western American environments.

Several good treatments of the history of the “American windmill” have been written (Torrey, 1976; Baker, 1985; Righter, 1995; Hills, 1994) with the most detailed account part of Baker’s extensive work A Field Guide to American Windmills. The following discussion draws largely from these prior works. While American windmills featured the above traits of multi-bladed rotors, metal equipment, lattice support structure, and automatic governing mechanisms for high winds, there were various sub-classes of the American windmill including the sectional mills and solid-wheels that differed in their fundamental mechanisms for avoiding high loads in extreme winds. Daniel Halladay pioneered the first type, sectional mills, and these mills bare his namesake—“Halladay Standard” windmills. The history of the “Halladay Standard” windmill centers around two men—one with a question and the other with an answer. The first man, Daniel Halladay, comes from a somewhat obscure background (born in Marlboro, VT in 1826) but had an apparent ability and affinity for the mechanic arts. As a 19 year old, he began work as an apprentice machinist in Ludlow, Massachusetts just nearby and likely in cooperation with the Springfield armory (Baker, 1985). In the years prior to his arrival at Ludlow, the Springfield armory had been the center of development of the “American system of manufacture” enabled by machining technologies and the development of interchangeable parts (Smith, 1980). Halladay bore witness to the ideals that had been developed at Springfield under the leadership John Hall and was then subsequently employed for four years at Harper’s Ferry armory in Virginia where similar efforts were underway. Thus, Halladay had exposure to the most advanced manufacturing and machining technologies of the era prior to opening his own machine shops in Ellington, Connecticut in the early 1850s (Baker, 1985). It was there in Ellington that Halladay met the man with the right question: John Burnham. Burnham, born in Brattleboro, VT in 1816, apparently had extensive schooling and interests
in philosophy, but his father compelled him to take over the family business in foundry. Eventually, Burnham and a partner Henry McCray would establish their own pump factor (Baker, 1985). According to Torrey, Burnham was a roving “pump doctor” as part of the business and witnessed the considerable damage that strong winds could have on tower and post-mill structures (Torrey, 1976). The problem was that the manual methods for furling windmills and turning out of the wind during extreme wind conditions were inconvenient and the associated weather conditions were difficult to predict.

Burnham who was also living in Connecticut shared this problem with Halladay who apparently set about to find a solution. By 1854 the first version of the “Halladay standard” with four wooden blades was created with several key innovations: 1) the large tower or post structure necessary to house complicated machinery for grinding grains was replaced by a single slender wooden pole with supports, 2) the fantail necessary for moving the large bulky tower or post structures was replaced by a large slender weather vane tail that would passively orient the turbine “upwind”, 3) metal replaced several of the structural components including the hub to which the blades were attached, the driveshaft and gearing, and the linkages to the pump, 4) a centrifugal governor was used that would pitch the blades as the wind speeds increased in order to control their speeds and ultimately furl the blades in extreme winds to shut the windmill down, and finally 5) the configuration of the rotor shifted from a few sails (typically four to six) to a many sails (Baker, 1985). The inspiration for each of these innovations and predecessor technology does not receive as much attention but there do seem to be examples of each that pre-date Halladay’s invention. The use of a slender pole or lattice tower support structure was possible given the smaller size of the overall machine. The fantail control mechanism for orientation discussed earlier was not used as commonly in the United States as in Europe. The use of metal for various components corresponded with the general trends of the era with easier access to metal technology as well as advancements in machining of metal components (Smith, 1980). Use of centrifugal governors for windmill control in braking as well as controlling speed and the position of the millstones had all been demonstrated in the past (Hills, 1994).

Millwrights had previously developed the wind rose configuration though it was not common for windmill rotors of the time. In particular, the use of multiple sails had been an important aspect of fantails used to orient traditional post and tower mills towards the wind. In addition, the Mediterranean windmills featured multiple sails at least a few centuries earlier. However, neither of these configurations were exactly the “wind rose” configuration which consisted of an almost continuous collection of blades occupying the area of the rotor. A few patents and examples from the late 18th and early 19th centuries exhibited annular / wind rose rotor configurations both in England as well as in the United States (Hills, 1994). Moving from a few to many sails or blades on a windmill rotor significantly affects its overall functionality. In general, the more blades and higher blade surface area present, the more the windmill produced torque in low winds in order to overcome the start-up friction necessary for moving a piston pump or other machinery. In addition, the more blades, the higher the overall rotor solidity (area of the rotor occupied by the blades) and this in turn meant that the machine would operate at lower overall wind speeds which was well-suited to wind-pump applications. Fewer blades on small wind pump machines would result in a need for much higher wind speeds for start-up and higher overall operating rotational speeds that would provide unnecessary loading to the water.
pumping equipment. The principles of aerodynamics associated with different types of rotors and their performance was still unknown, but the general understanding of the relationship of blade number to rotor speed was empirically established and principles of rotor torque were known at the time.

Millwrights used annular sail mills within the United States in the 1850's from New York to Kansas along with the wind vane to orient them automatically upwind prior to incorporation of the configuration into Halladay's mills by the late 1850's (Hills, 1994). Still, Halladay's inventiveness brought together these different technologies together to create a new overall windmill configuration that would become literally a “Halladay Standard” for the technology. Many windmills would be home-built or manufactured over the next several decades that would ascribe to the main characteristics of the Halladay Standard windmill as described above. Variations would be incorporated into the design such as alternative governing mechanisms to furl the rotor as the winds grew higher and even a “vaneless” windmill were the windmill operated with the rotor downwind rather than using a large vain to orient it upwind.

The Halladay standard, however, was not the only common standard of a self-regulating windmill. In the 1860s, Reverend Leonard Wheeler and his son developed what would become an even more common method for avoiding high loads on windmills in extreme winds (Hills, 1994). The mechanism was quite different from the centrifugal governor of Halladay’s mill and arguably less mechanically complicated – though the concept of its operation was arguably more complex. The windmill used two vanes for orientation: 1) a large vane hinged and kept in place by a spring or weight mechanism perpendicular to and behind the rotor, and 2) a smaller vane positioned parallel to the wind that resisted movement and pushed the rotor out of plane with the wind flow. As the wind pushed the smaller vane out of plane, the wind would start to induce pressure on the larger vane that would reorient it towards the wind. When the wind was high enough, the pressure would overcome the spring and the large vane would swing parallel to the rotor thus orienting the entire rotor out of the

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Figure 1-XIV: Advertisement for a Halladay Standard Windmill from the U.S. Wind Engine and Pump Company (Baker, 1985)
wind (Hills, 1994). By 1869, the Wheelers had also adopted an annular rotor configuration though they kept the mechanism of yaw control the same (Hills, 1994). The Wheeler “Eclipse” turbine was again copied and improved upon by many manufacturers — the most significant improvements included the elimination of one of the two control vanes, use of all-metal rotors, and self-oiling mechanisms the tedious and dangerous processes associated with keeping bearings and gears well lubricated (Hills, 1994; Baker, 1985).

![Eclipse Windmill from the Fairbanks-Morse company](http://roaring-twenties.com/lfairbanks_morse.htm)

Inventors developed many more windmill configurations during the late 1800s as described in detail by Baker (Baker, 1985). While marketing advertisements touted significant advantages of one windmill over the competition, one variation by a former employee of the U.S. Wind Engine and Pump Company would prove to have performance levels of nearly four times that of its contemporaries. Engineer Thomas O. Perry performed various tests for the company between 1882 and 1883 that focused on rotor design for increased overall aerodynamic efficiency. The results of his work involved the development of specially formed multi-bladed rotor with concave metal blades that were an astounding 87 percent more efficient than the standard wooden rotors that the company currently manufactured (Baker, 1985). Amazingly, however, the company was not interested in pursuing the design for manufacture and Thomas Perry eventually left the company, met an inventor named LaVerne W. Noyes, and worked with Noyes and a few backers to establish the Aeromotor wind turbine company to manufacture the metal windmill. The new windmill would produce about 4 times the horsepower at typical wind conditions of 25 mph (Torrey, 1976).

The Wheelers, Halladay and Burnham as well as Perry and Noyes spent considerable effort on developing factories and promoting the sale of their technologies. The critical role of water needed for the expansion of the American railroad system would be an important customer for both types of mills. The Wheelers sold one of their “Eclipse” windmills for the use of railway water supply as early as 1870 (Hills, 1994). In 1855, Burnham sold a windmill to the Illinois Railroad Company of Chicago (Hills, 1994) and soon Halladay mills were sold to a help support the overall western expansion of railroads — 70 giant Halladay machines were sold to Union Pacific (Torrey, 1976). Both the Wheelers and Burnham would benefit from the growth of agricultural activity in the western United States during the late 1800s and in particular the development of Chicago as “Nature’s Metropolis” (Cronin, 1991). The Wheelers had a
friend, a fellow churchman by the name of Charles Morse, who had moved to Chicago and recognized the opportunities for western agricultural and railroad applications (Torrey, 1978). He bought stock in the Beloit windmill factor for eclipse windmills and sold windmills for various railroad tracks including the Burlington, Northwestern, the Illinois Central and others (Torrey, 1978). Burnham, on the other hand, established a windmill company specifically in the windy city. Understanding the opportunities that were possible for sails of windmills for water pumping to farmers of the western states, Burnham moved to Chicago in 1856 and organized the United States Wind Engine and Pump Company to distribute Halladay windmills (Hills, 1994). Eventually, the entire manufacturing operations of Halladay and Burnham's business would move west to Illinois. Burnham was a true “system builder” (Hughes 1983). He began with a problem, the need for a self-regulating windmill, but once he developed the technology, he set about to promote the technology – relocating the company to the agricultural center of Chicago and working to develop a network of distributors for the technology.

Beyond the standard windmills described above, there were many variations and the number of windmill companies in the United States by the late 1800s was nearly 400 as estimated from Baker's compilation of models and companies operating over approximate periods of time (Hills, 1994; Baker, 1985). By the time of the 1893 World's Columbian Exposition in Chicago, windmills for pumping had become so prominent in application across the country that the event featured a special 15-manufacturer exhibit with a myriad of fully constructed windmills. It was “probably the greatest exhibit of windmills ever assembled in one location” (Baker, 1995, p. 79) Baker's field guide to windmills features the various established windmill companies and associated windmill designs each with their own unique traits and short histories (Baker, 1995).
1.6 Discussion of diffusion and innovation of early windmill technology

This very brief history of windmill technology provides a background and context as we look towards the development of wind electricity generation machines in the following chapters. In addition, several themes around technology innovation and diffusion surface in the history of the windmill. Personal accounts of innovation of early windmill technology are sparse, and we must infer an understanding from analysis of the machines themselves, their chronology and their diffusion between various regions based on statistics and documentation of particular installations. Given the lack of first-hand accounts, the easiest framework to evaluate the technology’s development is that of technological determinism or trajectories.
The horizontal windmill likely originates from early horizontal waterwheel technology known to the region of Ancient Persia. While there are limitations to early horizontal windmill technology — the placement of millstones above the rotor, the use of drag over lift forces for propulsion — the technology developed along that path or trajectory because of the knowledge and experience with the earlier technology (a story of technology trajectory and determinism). This is evident in the shift in the configuration from the watermill convention of placing the millstones above the rotor to a configuration with the millstones underneath the rotor. From a deterministic viewpoint, the form of the vertical watermill technology directly influenced the form of the early vertical windmill technology and the underlying physics (loading of the millstones) drove millwrights to move the stones to the position under the windmill.

The earliest bifurcation in windmill technology was the development of the vertical windmill in Western Europe as distinct from the earlier development of the horizontal windmill in Ancient Persia and nearby regions. This study supported the explanation that the vertical windmill evolved from the Virtuvian waterwheel common in England and Western Europe during the 12th century than prior Persian horizontal windmills (Wailes, 1968; White, 1962; Sheperd, 1994). The adaptation of watermill technology for use with the plentiful and “free” resource of the wind resulted in a translation of currently known vertical windmill configurations. In this case, the drastic departure of the form of the technology owes to either economic/technical or social forces. Still, one could suggest the diffusion of the technology from trade partnerships such as in the case of the Vikings or Byzantium as well as military campaigns such as in the case of the Crusades as has been done by various scholars (Vowels, 1930; Lewis, 1993; Lucas, 2006). In the chapter, we focused on the technical and economic rationale for the preference of vertical to horizontal windmill technology in Western Europe and eventually the world. While horizontal windmills machines involve fewer mechanical moving parts and cheaper to construct, the overall superiority of performance (due to using lift versus drag force) and reliability (as documented) of vertical windmills drove the their adoption over the former. Similarly, the specific needs of water irrigation for the American Great Plains drove the design of the American windmill to diverge substantially from European Dutch or tower windmills. In all of these cases, it is the function, the machine performance, and cost that drive innovation (again reminiscent of Hughes’ reverse salient) rather than social context or factors.

Similar economic and technical reasoning is useful to analyze the diffusion of the technology as well. For instance, commonly cited are the advantages of windmill technology as compared to hand or beast mills in providing the labor necessary to grind grain and provide food for different communities. However, the economics of windmills had to agree to the particular locality similar to Griliche’s suggestions (Griliche, 1957). For instance, an economic explanation for the widespread adoption of windmills in eastern England during the late 12th century and after was the lack of water resources that would have made watermills feasible as well as the “free” nature of wind energy that meant that initially, the church did not tax windmills in the same way as other mill technologies. Resource scarcity often prompted the adoption of windmill technology over watermill technology. Windmills in general were adopted where water was scarce and winds were strong (such as in Ancient Persia) or where the target application was the removal of water (as in the Netherlands and other places which used windmills for drainage or the
use of windmills for salt factories in the revolutionary era for the United States). For the American “wild west” wind energy has been cited as an almost necessity in terms of an essential mechanism for providing water both for agricultural and transportation purposes. Windmill technology had to be adapted to the particular environmental conditions of the west – the high winds and scarcity of resources – and inventors created a new type of windmill to conform to the unique needs of the region.

Thus, this account of windmill technology development is more deterministic than constructionist. At the same time, there seems to be at least some social influence in the variation within key technology types. For instance, in Europe there are certainly regional varieties of the technology including horizontal windmills of Iran and nearby Arab states and even China, vertical windmills of the Mediterranean with their unique sail rotor configurations, dominance of the post mill across England, chandeliers in France, and smock mills in the Netherlands. While geographic diversity can explain some of the reasons for the differences across these technologies, social communication, traditions and processes are also a potential reason for the differences. However, without more detailed accounts of the development of the technology such a social interpretation of the technology innovation is not possible. For that, we must turn to the focus of this thesis – wind electricity generation technology.

1.7 References


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From Windmills to Windmill Dynamos: Electricity Development through the early 20th Century and Windmill Electricity Generation before WWI

Both vertical-axis and horizontal-axis windmills survived the evolution to wind turbine electric generators — or simply wind turbines. The prevalence of horizontal-axis wind rose windmills in the US influenced the design of the first wind turbines in the US while the traditional European style windmills of around 4 to 6 blades influenced the first wind turbines in Europe. The introduction of electricity-generation systems in the late 19th century along with increased use of electric appliances for the home and the workplace likely stimulated a number of independent attempts to convert windmills for use as wind turbines. In particular, most farms in the 19th and early 20th century lacked access to electricity distribution systems but at the same time were equipped with wind and/or watermills. To take advantage of new electric lighting and machines, windmill electric generators showed promise. This chapter will look at the history of early wind electricity generation systems.

The study will highlight how the earliest such systems tackled fundamental design issues of the technology that are still relevant today. These early identified challenges include: the ability to provide a constant speed input to the electrical machine, the ability to provide power continuously over long periods of time, a system with limited maintenance requirements that was also safe (requiring little direct access due to the self-regulation of the machine), and a low overall system cost. In tackling these challenges, the history shows that the basic physics of the technology affect the overall design. However, even in the earliest days, different wind energy pioneers defined their needs for the technology in unique ways that led to different realizations of the technology. Thus, we show early wind turbine technology as a product of social construction by its inventors (drawing from their experience, knowledge base, and even norms of practice) and a technologically determined product by its nature (the technology acts as mediator of its reality even in the earliest days when inventors first created it). More important, in this era we see the first evidence of true actor-networks for wind in Denmark where the technology successfully diffused through the country and even into nearby regions in Germany and elsewhere.

2.1 Historical Foundations: Magnetism and Electricity to the early 1800s

Before jumping to wind electricity generation technology, we will first look the general development of electric machines and grid systems that served as a precursor to its development. Electricity is a part of everyday life for most individuals in the world. Even though there is significant disparity in the development of electric grid systems across the globe, lighting is common at least for public buildings in even the least-developed countries and most individuals have a general understanding of the concept of electricity.

\footnote{In addition, two appendices will provide a history of electromagnetism as well as early developments of electricity generation systems.}
Magnetism as a concept or human experience is not quite as common though most people have the opportunity to experience it. Most everyone who owns a refrigerator uses magnets directly to hold up various notes. However, even today, the explicit relationship between electricity and magnetism is one that is not part of the common experience of many individuals. Though electromagnetism is the critical foundation for the whole of the electricity system, most individuals do not commonly interact directly with phenomena at the intersection and transition of electricity to magnetism and vice versa. While an understanding of each concept is typical, the link between the two is not as well-known nor as well understood. In fact, it was not until 1820 — just under 200 years ago — that the connection between them was demonstrated to the most learned scholars of the day. This critical knowledge underpins the development of the entire field of electrical power engineering and electricity systems while, at the same time, it is relatively new to human history.

Magnetism and electricity separately, on the other hand, were indeed known to ancient civilizations. Even the terms “Magnet” and “Electron” originate from ancient Greek. The word magnet stemmed from the name Magnesia — a territory in ancient Greece known as the most common source of magnetic ore (known as Magnetite). This iron oxide is the most magnetic of naturally occurring minerals and even without manipulation, the ore attracted small pieces of iron. Thales of Miletus discovered its ability to do so as early as 6th century B.C.E. who suggested that the soul of the stone provided the attractive force of the iron. Aristotle (384 B.C.E. to 322 B.C.E.) and later the Roman Pliny the Elder (23 AD to 79 AD) both attributed this insight to Thales and upheld the notion that the action induced by a magnet on another material was due to its internal soul or life force (Turner, 2010). There is also evidence that the Ancient Chinese were aware of magnetism as early if not earlier than the Greeks were and ascribed to it a life force or “qi” as well. There are accounts of the use of compasses by the Chinese for spiritual practices in the Han dynasty from 2nd century B.C.E. to the 3rd century C.E. People perceived the ability of magnets to cause movement in other materials as a mystical and animate presence.
These magical stones found application quite early on in the form of magnetic compasses that were in widespread use by the 13th century. We attribute the invention of the magnetic compass to the Chinese though the specific period is unclear. Compasses may have been common as early as the Qin dynasty in 3rd century B.C.E. and originating as early as the 9th century B.C.E. By 1190 C.E., the compass was apparently in common use by European sailors for navigation according to the writing of Alexander Neckham and a modern term for Magnetite, “lodestone” which combines the terms for “way” and “stone” from Middle English. The compass had even been used for furthering human understanding of the world, for instance by Petrus Peregrinus, who in 1269 performed experiments to use a compass to draw Meridian lines for the earth. Scientific properties of the compass informed better compass design. These included declination (error in measurement of true north due to its difference in position from magnetic north) and inclination (the influence in the earth’s field causing a pivoted magnetic needle to “dip” – an effect that varies according to latitude) observed well before the 17th century. Both Chinese and European sailors in particular had observed declination. Christopher Columbus noticed the phenomena during his voyages across the Atlantic Ocean and noted it in his journals as “the deviation of the compass needle which before had been north-east now turns to north-west” (Fahie, 1931, p. 1331).

Until the 19th century, the histories of magnetism and electricity remained intertwined yet distinct. Just as with magnetism, this distinct history of electricity began with ancient observations of electric phenomena – electrostatic phenomena in particular. Certain electrostatic phenomena are easily observable though only recently have we developed an understanding of the source of their behavior. Lightning is one prominent example that had an explicit role in the development of scientific understanding of electricity. A less common example is St. Elmo’s fire. Named after Catholic Saint Erasmus of Formiae who is the patron saint of sailors, St. Elmo’s fire is ionized gas, or plasma, created by coronal discharge atmospheric gases that surround pointed metal objects electrically energized by the electric field in the atmosphere - particularly when thunderstorms are near. Sailors would often observe these lighted gases at the top of tall masts when thunderstorms were eminent. The ancient Greek even
gave the name “helene”, or torch, to the phenomena and associated it with the element of fire. Still, an understanding of the electrical underpinnings of the phenomena would have to wait a few millennia.

Similarly, the northern and southern lights of Aurora Borealis and Aurora Australis, have been observed for many centuries but only recently have full understanding of the physics of phenomena been obtained. The physics of the northern lights are complex but involve generally the interaction and collision of ions from solar winds with ions of the earth’s ionosphere resulting in excitation and release of photons. Thus, the effect creates a visible light that is predominantly a diffuse dim glow but with high concentrations can also result in bright streaks of light of varying colors.

While these atmospheric demonstrations certainly highlight electricity as a grand and mystic wonder, the common artifact of terrestrial amber that provided the first theories on static electricity. Human civilization has valued amber, fossilized tree resin, for its beauty as early as Neolithic periods for the creation of jewelry and other artifacts. The Greeks recognized its ability via applied friction to attract
light bodies such as straw or wood. The first written account of the electrostatic properties of amber, or “elektron,” again comes from Thales in the 6th century B.C.E.

The history of electricity does not receive much attention until the latter part of the 17th century due in large part to Otto von Guericke’s invention of the first electrical machine in 1671: the friction generator. The machine consisted of a Sulfur ball rotated around an axis using a hand crank. Any number of materials, such as cloth, held against the ball’s surface as it rotated would create friction such that the Sulfur ball would charge and gave off sparks. Von Guericke himself was able to use his friction machine to support investigations by which he discovered the phenomena of “electric repulsion” whereby a feather was initially attracted by an excited electric but then repelled away until it was touched, or discharged, by a finger or other object.

The experimentation and improvement in friction machine design of the first half of the 17th century led to the development of the key experimental apparatus known as the “Leyden jar”. The development stemmed from an attempt to prevent the dissipation of the “electric virtue” of excited electric bodies. Corresponding to the effluvium theory, the air and vapors carried away the electric effluvia of the excited body (Fahie, 1931). Pieter van Musschenbroeck of Leyden University along with his colleagues attempted to electrify water contained in a glass bottle, and in 1746 while holding his bottle in his right hand, Musschenbroeck removed the wire after charging only to experience a severe shock. Soon, experiments found that external and internal coatings of silver and thinning of the jar walls increased the shock and charging multiple jars in series (connecting each jar to the next with a metal wire that linked the contained fluids) could increase the charge. These Leyden jars connected to long “conductors” to explore the transmission of electricity over great distances. Collections of Leyden jars brought together into a “battery” provided an even more powerful shock. Prior to his studies of

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2 von Guericke is most famous for his development of the “Air-Pump” machine which enabled experiments by Boyle and others which reinforced the shift towards experimental science as a way of understanding the world (Shapin, 1985).
lightning, Benjamin Franklin experimented with Leyden jars as well and proved via experiment that the charge was contained in the glass and not the water or coating.

Figure 2-VI: A historical graphic of a Leyden jar discharged through completion of the electric circuit by the external contact on the outer glass coating and the internal contact via the metal tube connected to the water contained inside the jar. The extension arm that ensures the lowest resistance path from one contact directly to the other avoids shock to the experimenter.

From a somewhat different path, further critical developments in scientific experimentation on electricity occurred at the end of the 18th century. Studies on anatomy and another of materials laid a foundation for the development of the third important electric apparatus after the friction machine and Leyden jar: the Voltaic pile, or primary battery. Electricity in animals inspired experiments in anatomy around electricity. It was known since ancient times that certain animals delivered a shock to their prey—the most famous being the electric eel. As knowledge of electricity spread, experimentation confirmed the electrical nature of these shocks. Luigi Galvani, an Italian anatomist, likely by accident observed that when near a charged electric machine, a dissected frog’s muscle would convulse when touched by a metal scalpel. Galvani continued to study the phenomena and concluded that the electricity was in fact “animal electricity” in the nerves—similar to the more concentrated form found in electric eels. Alessandro Volta, his contemporary, rejected this theory. Volta believed that the contact of two different metals caused the current flow. While this theory proved incorrect, it inspired Volta to repeat an experiment by J.G. Sulzer of Switzerland from 1762 where a piece of lead and silver placed together and on his tongue resulted in a bizarre sensation and taste. Volta repeated the experiment with different metals. In a subsequent experiment in 1796, he brought insulated copper and zinc together and on separation found that each was charged. Finally, he decided to try to multiply the effect by arranging a series of silver and zinc pairs into a pile. To avoid the cancellation of the current flowing from the upper and lower side of each contact, he interspersed disks of wet cloth (which should serve as good conductors) between each pair in the pile. Having constructed the pile, he received a strong shock by placing his hands on the pile connections one to either side.
Scientists made many improvements to Volta's "primary battery" or "Voltaic pile" technology. Humphry Davy provided an important innovation by shifting from the vertical to a horizontal configuration in a trough so that the stacking of pairs would be less limited. Though degradation of the primary battery was an issue, the Voltaic pile produced for the first time a consistent continuous current that opened the doors for many practical applications of electricity to human activities. In particular, scientists began to use primary batteries in a wide variety of electrochemistry experiments and significantly furthered the discipline. It was through experiments with the primary battery, that Humphry Davy first noticed in 1800 that well-burnt pieces of charcoal sparked when the ends of contacts from a battery nearly
connected. In 1809, he performed a grand experiment using a large batter of 2000 pairs and brought his charcoal carbon contacts close together. This resulted in an emission of an arc of light almost three inches in length. Early “arc lighting” thus employed the battery.

2.2 Early Electromagnetism, Magnetos and Dynamos: Inventions in Search of a Utility

While the history of the battery is rich and extends well beyond this brief account, the interest of this account is on electromagnetism and the development of early electric machines for power production. For this, we move quickly on from batteries and into the 19th century where the histories of electricity and magnetism finally merge and become one. Magnetism and magnets had had a practical role in society for many centuries before electricity was something that useful in practical applications. Some of the first practical applications in the early 1800s followed the invention of the Voltaic pile and focused on areas of electrochemistry — such as electroplating and electrolysis. Another important early application in the 1800s was telegraphy. Humphry Davy demonstrated the possibility of arc lighting in the early 1800s but the power source, the Voltaic pile, had limitations in terms of both reliability and cost for achieving practical arc lighting systems (Atherton, 1984). Advances on the materials used for carbon arc lighting as well as control methods to compensate for increasing distance between electrodes as the carbon burned away made arc lighting viable, but a reliable and low cost power source continued to be a problem. Faraday’s discovery electromagnetic induction was the key to future development of a new power source that would not only open up practical application of electricity to arc lighting and later incandescent lighting, but also to transportation, to industrial power applications and finally to an endless stream of appliances and devices for commercial and residential use.

The invention of a stable source of electricity in the form of the electric generator began with Faraday himself and his attempts to investigate the phenomena of Arago’s disk that demonstrated electromagnetic induction by a rotating metal disk affecting rotation of a nearby needle (see the appendix for further detail). In addition to the experiment on the original ring and the moving electromagnet, he created his own spinning disk set-up with a copper plate passing between a set of magnets at the edge. He covered the edges with mercury (as a lubricant) and then connected metal brush contacts at two different points on the disk with the leads connected to a galvanometer (Dunsheath, 1964). On rotation, the galvanometer deflected and he found the deflection increased with one of the leads on the disc edge and another on the disk axle.
Faraday’s machine was the first “magneto.” Early machines, termed magnetos, used permanent magnets to produce the magnetic field through which electromagnets (coils around an iron core) would pass. These were generally hand-cranked. By 1832, Hippolyte Pixii in France created an electric machine specifically designed for producing current by the rotation of a hand-crank with a single horseshoe magnet for the field and a single pole-pair electromagnet for the armature (the current-carrying portion of the device). It provided alternating current because of rotation of the hand crank. Ampere provided Pixii with a “commutator” for rectifying the alternating current to “battery-like current” which has been seen by some as a “backward step” in the overall evolution of electric machines and in the development of the electric grid. Indeed the struggle between electricity systems with “battery-like” direct current (DC) and others with alternating current (AC) would prove to be one of the most intense competitions in technology standards the world had ever seen. For a number of years, however, most development focused on magnetos and the development of more advanced machine designs and commutators for producing DC current.
While the commercial applications of the new machines remained limited primarily to electroplating, many inventors began to develop new magneto machines in a variety of configurations. Both Joseph Saxton and E.M. Clarke introduced magnetos where the lighter electromagnets were rotated by hand-cranks rather than rotating the heavier permanent magnets in the 1830s. While the development of Maxwell’s Equations were still some years out, the 1830s and 1840s saw a large degree of experimentation in configurations for magnetos. These included the relative positions and shapes of the field permanent magnets and the armature electromagnets, the number of magnets and coils used (i.e. the number of poles for the field and armature), and various other design aspects such as the commutator. In the late 1930s, William Sturgeon introduced a “shuttle type coil” that rotated between the poles of a magnet and developed the first metallic commutator without mercury (Dunsheath, 1969). Emil Stöhrer introduced the multi-polar idea in 1844.

Figure 2-X: The first multi-pole electric generator (Emil Stöhrer) from which used three horseshoe magnets and six electromagnetic coils for a six-pole machine (Dunsheath 1984 plate IX)

The “Great Exhibition of the Works of Industry of All Nations” took place in 1851 and highlighted the great variety of machines that existed at the time. The exhibition gave awards based on the greatest lifting power – one machine which itself weighed 100 lbs. and used 50 yards of coil was able to lift 1 ton (Dunsheath, 1969). However, up until the 1850s, a hand crank supplied the mechanical power for the machine rotation and the only actual industrial applications was electroplating. For instance, the Woolrich magneto that used more coils than magnets and carefully controlling the timing of contact of the commutator for when the coils directly aligned with the magnets. A continuous current was important for electroplating applications and Woolrich’s machine obtained substantial success due to its emphasis on continuous (or direct) current in the design.

Still, when one thinks of the myriad of applications for electricity today, it seems almost surprising that only one industrial application surfaced in the first twenty years of the development of the electric generator, or in the first fifty years since the introduction of the Voltaic pile. Early, scientists acknowledged the need of a reliable and low cost electricity supply for arc lights in the 1830s. The arc
lamp technology itself had advanced considerably since Davy’s discovery in the early 1800s – relatively pure carbon was a by-product of coal gas processing and a variety of regulation methods improved the ability to maintain the arc as the electrodes burned away (Atherton, 1984). From the perspective of Thomas Hughes, the power supply was the “reverse salient” in the development of a practical commercial lighting system. Primary batteries, or Voltaic piles, still did not prove a viable solution by the mid-19th century and magnetos likely were a potential solution – especially given the advances of Woolrich and others in the provision of continuous current.

Surprisingly, though, it was not arc lighting that inspired the first “power driven” magneto. Instead, Belgian Floris Nollet envisioned a power driven magneto-electric generator which would produce oxygen and hydrogen gases that would be combined in an oxyhydrogen flame to form a torch that would produce limelight from the burning of quicklime (calcium oxide) which would ultimately be used in lighthouses. Lighthouses were critical at the time to safe navigation of ships near shore and, at the same time, were incredibly labor intensive with lighthouse keepers as an occupation required of every lighthouse to maintain the fuel and lighting throughout the nights, fog and other inclement weather situations. Nollet was interested in mechanization of the process for lighting via limelight. He obtained a patent for the project in 1850 and borrowed from the work of William Millward in the England who had a patent for an improved Stoehrmer magneto that used steam power rather than a hand crank as a power source. The steam engine was in use since the 1780s in industrial applications involving rotary motion. Thus, the technology was available and was adapted by Millward and subsequently by Nollet to serve as the source of mechanical rotation for electrical generators in the 1850s. Unfortunately, Nollet passed away in 1853 before realizing his vision of electric generation for lighthouse limelight. F.H. Holmes, one of Nollet’s project engineers from England, decided to attempt the application of electric generation for arc lighting in lighthouses. The British lighthouse authority supported Holmes attempts to develop electric arc lighting as a trial with Faraday acting as a judge. In 1857 and 1858, Holmes successfully demonstrated steam driven electric arc lighting for lighthouses. In 1858 at South Foreland lighthouse, a steam-driven generator rated at 1000 candlepower (or candelas) powered an arc lighting system. Such a system operated for a low cost compared to the primary battery that used one-third a pound of zinc each hour lighting just a 100 candlepower light whereas 1000 candlepower consumed 3 lbs. of zinc per hour – a significant cost and maintenance disadvantage (Atherton, 1984). Holmes installed his machines for arc lighting of lighthouses at several locations though with the advent of the dynamo, the brief period of magneto applications for electricity generation would elapse.
Magnetos would never see widespread use for arc lighting. Just as Holmes' was installing his machines at various lighthouses, a new technology was being introduced that would replace the permanent magnets with electromagnets. The new "dynamo" used electromagnets for both the field and the armature. In 1866, Faraday read a paper by Dr. Henry Wilde to the Royal Society that introduced for the first time a dynamo. In this case, a magneto supplied the dynamo field magnet current. Shortly after, several inventors demonstrated "self-excited dynamos" where the current for the field magnet was provided from residual magnetism in the machine and amplified by using the whole current from the armature (series), a portion of the armature current diverted through the field-magnet coils (shunt), or some combination or second armature in the same field (Thompson, 1888).

Further advances in dynamo design involved a slow shift away from the classic "horseshoe" configuration of permanent magnets and it is parallel in electromagnets. The first major shift was to the "H armature" by Werner Siemens in 1856 for the magneto and then later in dynamos in the 1860s. It
had a small diameter for easier operation at high speeds (Atherton, 1984). However, the “ring armature” quickly usurped the popularity of the “H armature” configuration since it was able to produce truly continuous current in contrast to the pulsating direct current of the Siemens machine (Atherton, 1984). The “ring armature” was initially invented in 1860 by Italian Antonio Pacinotti but it was Z.T. Gramme of the French Alliance Company (the same company that Nollet worked with on his limelight system) which turned it into a practical machine for commercial applications in 1870 (Atherton, 1984).

The first commercial application of electric generators was indeed in arc lighting when a dynamo-lamp system provided better light for the same price than a gas light could do (Atherton, 1984). Early on, arc lighting became associated with a sense of grandeur as it was used in spectacular demonstrations such as in the Paris Opera for instance in 1849 when it was used to create the special effect of a sunrise (Nye, 1992). By 1855, the Paris opera employed an electrical expert to design a variety of lighted effects from spotlights to luminous fountains (Nye, 1992). In 1876, Russian army officer Paul Jablochkoff made a major innovation to the arc light known as the “Jablochkoff candle.” Whereas the carbon supply for most lamps were set-up opposing one another, Jablochkoff’s configuration had the carbon supplies on each side parallel to one another and supplied by an alternating current so that they would burn down evenly. However, the alternating current required special generator designs that were not typical of the dynamos developed for use over the last few decades. In 1875, an American Charles Brush invented a “clutch type” of regulator that became widely used in arc light systems where the top carbon was slowly released as the carbon burned away to keep a constant distance between the electrodes and a relatively constant luminescence. Brush also had developed his own dynamos and combined with the arc lamps, the Brush Electric Company formed in 1880 to sell his dynamo arc-lamp systems.

Figure 2-XIII: Brush Arc Lamp with solenoid based regulator (Left: Dunsheath, 1969, p. 126) and Brush Dynamo of 1878 (Right: Dunsheath, 1962, plate XII) make up the overall Brush system for arc lighting. The Brush Dynamo won an 1877 competition hosted by the Philadelphia Franklin Institute where it competed against the well-known Gramme dynamo. The next decades saw improvements to the Brush lighting system.

C.F. Brush and his company can be seen as one of the early “system builders” in the electricity grid system. Differentiated from inventors who created specific products, Brush brought together a host of technologies and the associated business structures necessary to develop and commercialize an arc-lighting system deployed in various U.S. cities such as Cleveland and San Francisco. His early successes mirrored those of companies in Europe such as the French Alliance Company and the German company Siemens & Halske that also deployed various arc lighting systems in the late 1800s. In the U.S.,
American Electric Company started by E.J. Houston and Elihu Thomson with their own dynamo and arc lamp configurations replicated the concept for his system. In 1880, there were some thousands of arc lamps installed in the U.S. while in the early 1900s (as incandescent lighting was taking off), there were nearly a million arc lamps deployed across the country. The arc light was central to the initial electric power system development that would soon affect almost every facet of social life.

2.3 The Development of the Electric Grid as a Socio-technical Process
Just as the development of the dynamo resulted in a swift decline in use of magnetos, the introduction of a practical incandescent lamp, most notably by Thomas Alva Edison, resulted in a decline in demand for arc lighting. At the same time, the possible uses for the incandescent light bulb would quickly grow from exterior lighting where arc lamps were used to lighting of interior spaces where gas companies at the time made ninety percent of their overall profits (Atherton, 1984). Just as Brush, Siemens and others, Edison understood that he was providing an electricity system solution and not just an electric light. This emphasis on the system is an important theme used by historians such as Thomas Hughes and others to explore the historical development of electric power technologies and electric grid systems. Furthermore, it is difficult to address the history of electric power without an appreciation for the social aspects and impacts of electric system development. An explosion of inventive activity led to applications of electricity not just to lighting but also to transportation, industrial processes and a myriad of commercial and residential appliances. How the system evolved intertwined closely with society and its uses for all these new electrical inventions. Generally, early development of electricity systems includes a series of épochs: first, commercial lighting systems in the 1880s followed by electric tractions in the late 1880s, factories in the mid-1890s and finally domestic applications in the 1910s. Rural electrification for farms and associated equipment followed later, much later in the United States in particular, and is its own subject in the next chapter as it relates closely to the history of wind-generated electricity in the first half of the 20th century.

Whereas arc lighting presented the first glimmer of the important role that electricity would have within society, incandescent lighting provided the definitive demonstration that would forever change society. Thus, moving from the arc light, we explore the social issues involved with electricity development along with the internal history of technology. Arc lighting in the 1870s and 1880s competed with rival exterior lighting technologies of the time including candles, oil lamps and in particular major cities in the U.S. and Europe by the mid-19th century used gaslights widely. Still, there were practical limitations for the use of arc lamps in individual office and home applications where candles, oil and gas lamps were still the only options. Firstly, fundamental understanding of electricity was still evolving and notion of “parallel” and “series” circuit connections where relatively new. In 1845, Gustav Kirchhoff published on a set of circuit laws that built on Ohm’s earlier work (see the appendix) and provide useful constructs for linear circuit analysis still in use today. Kirchhoff’s first law or Kirchhoff’s Current Law (KCL) stated that the sum of current into and out of a node or junction in an electric circuit should sum to zero while for Kirchhoff’s second law or Kirchhoff’s Voltage Law (KVL) states that the sum of voltages around a closed

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3 The company later became Thomson-Houston Electric Company and then later helped found the General Electric Company. In 1889, the Thomson-Houston Electric Company took over the Brush Electric Company.
loop should sum to zero. Using Kirchhoff’s laws and other related techniques, a growing appreciation for circuit analysis was present in the late 1870s, and in 1875, M.G. Farmer developed a parallel system for arc lighting with 42 lamps connected each in parallel (Dunsheath, 1969). This solved the first issue of arc lighting associated with home and office applications by allowing for individual connections turned off and on independent from one another.

However, the second issue, the general size of arc lights and their cost was still present. Instead of a solution involving the miniaturization and cost reduction for the arc lamp, Thomas Edison envisioned and eventually practically developed an alternative technological solution. The incandescent light bulb had great potential as a small and simple lighting unit. Attempts to develop practical incandescent light bulbs had been around for the whole of the 19th century. In 1802, Humphry Davy had demonstrated the property of incandescence by passing current through platinum, which has a high melting point, but the light emitted was not nearly as strong as that observed from the carbon electrode arcs that he also had demonstrated. Still, inventors made many attempts throughout the 1800s to create a practical incandescent light using a variety of materials including mainly precious metals and carbonized organic materials. A key advance was found in the 1840s by placing the circuit in an evacuated bulb (hence the light bulb) which would allow prolonged life of the filament by mitigating oxidation from reactions of the heating and electrically active filament with surrounding gases. Still, it would be several decades before Edison invented an incandescent light bulb that would operate for long enough periods for commercial use. In the late 1870s, both Joseph Swan in England and Thomas Edison in the U.S. focused on creating just such a light bulb.

Thomas Edison already had a reputation for his inventions related to the telegraph and other technologies and was able to obtain funding in 1878 to form the Edison Electric Light Company even before having a viable product. The world watched as the “Wizard of Menlo Park” experimented with different materials and bulb configurations and his early successes even had a short-term impact on the price of gas shares in the stock market (Atherton, 1984). By October of 1879, Edison had found that carbonized cotton sewing thread filament in an evacuated glass bulb could burn for two days. Carbonized paper filaments lasted even longer and Edison chose them for the first commercial lamps while carbonized bamboo became the most common filament in Edison’s early lamps. On top of this, Edison found that by “out-gassing” or heating and applying a vacuum on the bulbs during the manufacturing process, he could remove impurities that were absorbed in the filament material that further extended bulb life (Atherton, 1984). Edison took out several patents around light bulbs during this time period and a conflict soon sprang up between Edison and Joseph Sawn who had demonstrated a similar light bulb publically in 1888 and had disclosed inventions on incandescent light bulbs in configurations similar to Edison’s as early as 1860 (Dunsheath, 1969). Sawn soon improved on the natural fibers by developing artificial thread beginning with dissolved nitrocellulose squirted through a die – this produced threads that were more uniform and less susceptible to damage from localized heating (Atherton, 1984).
Both Swan and Edison are admired for their work on the invention of the incandescent light bulb. However, from a systems theory perspective, it was not the sole invention of the light bulb, but the invention of the electric lighting system that was of critical importance (Hughes, 1983), and this system was constructed within a particular social context that shaped its development. Edison recognized that ninety-percent of gas revenues came from lighting interior spaces. Edison also recognized that any solution that would compete with gas lighting of homes, businesses and factories would need to provide the entire set-up: from power generation to transmission to the end-use in lighting. Thus, his design of the system took a holistic approach as noted in Edison's own words: “It was not only necessary that the lamps should give light and the dynamos generate current, but the lamps must be adapted to the current of the dynamos and the dynamos must be constructed to give the character current required of the lamps, and likewise all parts of the system must be constructed with reference to all other parts, since, in one sense, all the parts form one machine, the connections between the parts being electrical instead of mechanical. Like any other machine, the failure of one part to cooperate properly with the other part disorganizes the whole and renders it inoperative for the purpose intended. The problem then that I undertook to solve was stated generally, the production of the multifarious apparatus, methods and devices, each adapted for use with every other, and all forming a comprehensive system” (Hughes, 1983, p. 22). From this perspective, Edison's light bulb was designed with a high-resistance in order to reduce current flow and limit losses in the transmission system (as was understood from Ohm's law the voltage was directly proportional to the current and resistance, but losses were governed by Joule's law and proportional to the resistance and the square of the current) (Hughes, 1983). From the generator side, Edison and his colleague Francis Upton developed a new dynamo with low internal resistance that had a high efficiency of 90% whereas earlier generators designed to supply arc lamps in series had high internal resistance and lower efficiencies (Hughes, 1983). Similar, Edison designed the transmission lines and other components specifically for the "Edison system" that resulted in a large number of associated patents.

This technological system, however, is just part of Edison's larger socio-technical system that involved not just the technical system but construction of a set of manufacturing and service business

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corresponding to a vision of an ever-expanding grid system that would touch all aspects of society. Edison established Edison Machine Works to manufacture generators, the Edison Electric Tub Company to manufacture cables, and the Edison lamp work to produce the incandescent light bulbs. Meanwhile the Edison Electric Light Company established the first central generating station in New York City, the famous Pearl Street Station, in 1882. Not only did the central station incorporate six of Edison’s “Jumbo” dynamos, each to power 1000 bulbs, it also contained a system of “load matching equipment” with signals supplied to the operator when the voltage was too high or low so he or she could add or remove resistance from the circuit (Hughes, 1983). After an initial break-in period, the plant was supplying a capacity of 11555 lamps in the surrounding New York City area. Edison actively sought to replicate his Pearl Street Station in other U.S. cities as well as quickly oversees. There were direct ties from Edison to companies developed to supply Edison lighting systems notably in England as well as Germany. By the early-1890s, shortly after the initial introduction of the Pearl Street Station, there were already over a million and approaching ten-million incandescent light bulbs sold each year for lighting systems in the U.S. alone – two-orders of magnitude more than the peak of arc-light installations.

In addition, how were these millions of light bulbs affecting society? The early small-scale Edison light installations, both in the U.S. and abroad, were located in highly visible city cultural centers from Chicago’s Academy of Music to Milan’s La Scala Opera House (Nye, 1992). Electric lighting had an element of prestige at the same time the economics were competitive with traditional gas lighting. New York’s Broadway, brightly lit with electric signs, was described in the media of the 1890s as “the Great White Way” (Nye, 1992). Certainly, many recognized the social impacts of reliable exterior and interior electric lighting early on, but quickly, as the number of incandescent light bulbs sold per year in the U.S. climbed from the millions towards the billions, electric lighting lost its grandeur. Public notice of electric lighting faded even as it began to “shape and organize” the night landscape as depicted in John Sloan’s The City from Greenwich Village shown below (Nye, 1992).

Figure 2-XV: John Sloan’s The City from Greenwich Village in 1922 that shows the lighted city in the background with lights along the nearby streets as well giving shape and structure to the city at night.
The “Great White Ways” provided the first large-scale use of electricity in commercial applications, but shortly after the installation of the first Edison electric lighting systems, demonstrations of electric traction were underway. Similar to arc lighting, a long history existed already with attempts to use batteries as a supply to electric transportation machines. Unlike arc lighting or incandescent-lighting, however, electricity for traction necessarily involved the conversion of the electric power back to mechanical power; in other words, the system needed an electric motor. While similar to that of the electric generator, the electric motor’s history evolved with some independence.

The first electric motor existed prior to Faraday’s discovery of electromagnetic induction. In 1830, Professor dal Nagro of Italy had demonstrated a motor using a primary battery, a pivoted magnet in a mechanical set-up. By 1839, Professor Jacobi from Russia had developed an electric motor to power a boat where a battery again provided the power source and a set of mechanical controls timed the activation of interaction between a set of electromagnet and permanent magnets to provide continuous movement in one direction (Dunsheath, 1969). In 1840, Robert Davidson of Scotland applied an electric motor with battery power to run a car on a British rail system – the first demonstration of an electric motor applied to ground transportation. Experimentation in motor development continued over the next few decades. One particularly important development was by Professor Pacinnoti of Italy who was seeking a motor “with greater regularity and steadiness of action” (Dunsheath, 1969, p. 180). In addition, Pacinnoti focused on a dynamo driven motor versus the battery motors developed in the past. In 1860, he introduced his motor that had the “ring armature” configuration mentioned before and adapted by Gramme for his commercial dynamo in 1870. Slowly, it was realized that dynamos could themselves be used as motors and exhibitions in the 1870s showed Gramme machines operated back to back – one serving as the dynamo driving the other serving as the motor (Dunsheath, 1969).

Figure 2-XVI: The Gramme Dynamo in 1876 with ring armature (Dunsheath, 1969, plate XI)

At the 1879 Berlin Trade Fair, Siemens & Halske demonstrated a miniature electric locomotive that carried 100,000 people over the course of the fair. Edison developed an experimental track and motor
system at Menlo Park in New Jersey in 1880. At the time when experiments in electric transportation were underway, there were a number of issues with current urban transportation systems using the horsecar. Horsecars left behind one million pounds of manure per day that lead to significant pollution (Nye, 1992). On top of this, the slow 5-mile per hour transportation meant that the eighteen thousand horsecars over the three thousand miles of city tracks caused constant traffic congestion – police officers often forcefully broke up traffic jams (Nye, 1992). Electric lighting indeed provided many social benefits, but many who lived in urban settings likely found electrified transportation to provide even more benefit to their lives. In the 1880s, two companies in the U.S. focused significant attention on the development of a practical DC electric motor transportation system. The Thomson-Houston Company had a team of engineers working on electric transportation and Frank J Sprague founded the Sprague Electric Railway and Motor Company in 1884 to tackle the transportation problem. Meanwhile, Siemens & Halske continued to work on traction following the Berlin demonstration.

The challenges of electric traction involved supply of power to a moving vehicle, the ability of a motor to operate over a wide range of speeds with many stops and starts, the harsh environmental conditions a motor on a tram would experience, and translation of motor power to motive power (Atherton, 1984, Dunsheath, 1969). Initially on-board batteries provided the power supply issue while later systems would obtain power from overhead and ground-based connections to a central power source. The biggest challenge of stops and starts was stress on the commutator brushes that produced “electric fireworks” with large currents and varying voltage (Atherton, 1984). Charles van Depoele of the Thomas-Houston Company as a solution introduced carbon brushes in the late 1880s. Major developments to address the other issues were made by Sprague whose 1888 system involved a series-parallel (combined) motor design so that at start-up a series connection was used then shifted to parallel as the speed is increased and resistance of the shunt is then further reduced to obtain maximum speed (Atherton, 1984). The running costs for Sprague’s system were 40% less than an equivalently sized horsecar system with faster operation and without the pollution (Atherton, 1984)4. A general consolidation of Edison companies into Edison Electric Company involved the buy-out of Sprague’s company. By 1890, there were two hundred cities cross the U.S. that had ordered electric tram systems and 90% of these involved patents from Sprague’s design (Nye, 1992). Horsecar tramways were increasingly converted to electric tramways and by 1897, 88% of tramways across the entire U.S. were converted over (Atherton, 1984).

Initially, citizens had mixed social reactions to the electric tramcars as some city dwellers welcomed the increased business traffic while others were concerned about noise or the danger of the wires (Nye, 1992). However, the flexibility that electric transportation provided enabled a shifting urban landscape in unintended ways. Outlying areas serviced by streetcars had population boons while the city centers began to lose population and became home to more business and shopping centers than residential communities. Cities with electric transportation developed districts for various facets of social life: commercial businesses, shopping and culture, industrial parks, and all surrounded by residential

4 Even with total costs included, electric tram system costs were considered to be about 70% of an equivalent horsecar tram system (Atherton, 1984).
suburban rings (Nye, 1992). Large downtown department stores with interior lighting replaced local specialty shops where suburbanites could buy a wide array of products for low cost (Nye, 1992). Trolley parks began to emerge at the end of tramlines of many major cities. One might say that electric lighting and tramways shaped a “new modern city” – the city of large skyscrapers and business cities peppered by bright lights and signs, luxurious shops and cafes, and all accessible by tramcar for those who wanted and could afford to live in tranquil suburban homes.

This reshaping of the city landscape intertwined with the growth of businesses that provided electricity equipment and services. Utilities formed that developed central power stations that supplied first lighting, then lighting and traction and the associated “trolley parks.” The addition of each element to the overall electricity demand profile allowed utilities to “smooth out” the demand profile and achieve additional “economies of scale” from developing larger and large central power stations. Samuel Insull of Chicago conducted studies to determine that the loads of lighting and traction peaked at different times that allowed him to supply overall demand more cheaply than one could if separate power stations supplied lighting and traction respectively (Nye, 1992). The trolley parks further smoothed out demand since they mainly operated in the evenings, on weekend and holidays when demand for electricity was otherwise low (Nye, 1992). Thus, the “peak demand” on a given urban electricity system was less than the combined overall rating of all the load elements with all the light bulbs, transportation and trolley park motors. The overall rating of the system only needed to meet that peak demand and a smoother load profile from diverse sources of demand meant a higher utilization rate of the equipment. This, combined with the economies of scale from building larger machines resulted in a trend in the development of central power stations to supply electricity for entire cities.

As electricity for lighting became common for city residences and businesses, lighting diffused into factories. It wasn’t until the early 1900s, however, that electricity began to be adopted for industrial power applications and eventually became the largest source of demand for electricity – overcoming demand for residential, commercial and traction electricity combined by the 1920s (Atherton, 1984). DC motors compatible with the dominant DC systems of the day had undergone significant innovation in the development of electric traction. The first DC motors in factors were quite similar to traction motors where variable speed operation and frequent stops and starts were required – for hoists and crane operation (Atherton, 1984). DC dominated the electric grid systems at that time, the late 1880s, and there were several advantages that could be touted for the DC system: back-up batteries could be used in the event of a grid outage and to support peak demand requirements, DC generators could be directly driven by engines whereas alternators at the time had to be belt-driven, dynamos could be operated in parallel while alternators had to supply separate lines, and dynamos could be transmitted at high voltage and stepped down to low voltages by batteries in series or by a DC transformer (back-to-back dynamos) while an efficient AC transformer had yet to be invented (Atherton, 1984).

While dynamos reigned supreme, there had been ongoing work for the development of alternators. The original machine of Pixii was an alternator at first and it was Ampere’s introduction of the commutator that turned it into a dynamo – dynamos are indeed alternators that use a commutator or some other means of rectifying and smoothing the output into a continuous current. Later in the 1870s, AC systems supplied power for arc lighting – in particular lighting of Jablochkoff candles – since the candles by
design required a symmetric AC current to enable an equal burning rate of the two carbon electrodes. AC systems, especially those already in operation, continued to supply power for incandescent lighting though DC systems did dominate. From the late 1880s through the 1990s, engineers addressed the challenges of AC system design listed above: back-up system compatibility, direct-drive engine compatibility, parallel operation, and high-voltage transmission.

The AC transformer solved the transmission issue. Though Faraday's ring of 1831 was indeed a transformer with two coils insulated from one another wrapped around a common core so that current flowing in one would produce a magnetic field in the core experienced by the other; application of alternating current to one coil would then (by electromagnetic induction) produce a current in the second coil. In an ideal transformer, the relative number of turns in each coil directly governed the voltage or current transformation. In 1882, Frenchman Lucian Gaulard and Englishman J.D. Gibbs took out a patent on a transformer for current regulation in arc lamps. This also demonstrated the practical application of a transformer for parallel operation in AC systems. These systems employed them in series with the power supply and the second coil on each would supply the loads separately. However, this was still a series system and later several groups, primarily the Hungarian group at Ganz & Company, who would adapt the Gaulard and Gibbs system to have each transformer in parallel with the generation source. The second coils would again supply the loads separately (thus obtaining the advantage of a parallel system in terms of maintaining voltage on the transmission line) (Dunshieath, 1969; Atherton, 1984). In the United States, George Westinghouse had purchased Gaulard and Gibbs transformers and his employee William Stanley patented an improved transformer in 1886 as part of the overall development of an AC system by Westinghouse.

Another problem emerged as DC motors came into use: the need for a practical AC motor. Similar to DC motors, one alternator could drive another alternator as a synchronous motor. Alternators of the day were synchronous machines – dynamos without commutators with the field current supplied by electromagnets. Thus, the first AC motors were of a synchronous configuration that posed difficulties since the machines would shut down when synchronization was lost and had no starting torque (Atherton, 1984). Another approach involved supplying a DC series motor with AC but this resulted in
sparking in the commutators and brushes (though later universal motors able to run off AC or DC were able to overcome this limitation (Atherton, 1984). The solution for an AC motor was the induction motor configuration in the late 1880s and 1890s.

Several individuals invented practical induction machines including most notably Galileo Ferraris in Italy and Nikola Tesla in the United States. Ferraris announced the development of an induction motor in 1888 that was two-phase and used a simple hollow cylinder as the rotor rather than windings; in 1887, Tesla developed two-phase induction motors with and without windings on the rotor. Induction motors work on the principle of induction demonstrated by Arago and explained by Faraday – via the application of current sequentially to coils in the stator, a rotating magnetic field is created that is experienced by the rotor cylinder or coils, and currents are induced that result in a magnetic field in the rotor that is then “dragged” behind the stator rotating field. Initially, Tesla, who went to work for Westinghouse, sought to use this for the main application of motors in the 1890s: electric traction. However, their attempts were not successful. Even more disappointing, induction motors performed poorly on the AC lighting systems of the day that tended to operate at 133 1/3 Hz (Atherton, 1984).

However, the desire for AC systems operating with both lights and motors led not to a change in the motor but to a change in the operating frequency of AC systems (from 133 1/3 Hz to 60 Hz). The reduced frequency of 60 Hz was still high enough such that incandescent lights would not experience flicker but low enough to accommodate operation in tandem with small induction motors. Furthermore, additional developments in technology including the important invention of the rotary converter in the late 1880s made the conversion between AC and DC practical. General Electric bought Tesla’s patents while Westinghouse developed their own rotary converter for AC to DC, frequency and phase transformations. At the Chicago World Fair in 1892, Westinghouse showed a complex system including a two-phase AC system where an induction motor drove a DC generator, rotary converters
converted AC to DC and electric motors drove additional alternators to provide a great variety of end-use systems both AC and DC (Atherton, 1984).

It appeared that AC was poised to overtake DC systems for power production for lighting and motors. Combined with the AC transformer, AC systems were even better equipped than DC systems to handle high-voltage transmission (DC transformers still relied on a crude back-to-back dynamo set-up). However, the “Battle of the Systems” – considered one of the first great technological standards wars – perhaps prevented large-spread use of AC power systems for the next several years. The battle, waged between the Edison Electric Company and the Westinghouse Company, began in the late 1880s just as Westinghouse developed the AC system technology. Edison employed Harold Brown to investigate the dangers of AC versus DC. In 1888, he began to perform a series of ghastly and ill-designed electrocution experiments on animals to demonstrate the danger of AC over DC. At the same time, the state of New York was investigating alternative “more humane” forms of execution than the traditional method of hanging. Edison invited several commission members to the labs to discuss the issue and a Westinghouse employee was able to sneak into the meeting (McNichol, 2006). He was discovered and this began a propaganda war. Brown had a letter published in *Electrical World* in 1888 that suggested “victims” of AC were unjustifiably high and labeled them “homicides” of the system (McNichol, 2006). Even Edison himself made public comment of the supposed dangers of AC systems. However, by 1892, the Edison Electric Company had merged with the Thomson-Houston Company to form the General Electric Company. Thomson-Houston had substantial investments in AC system, as did the Edison Electric Company through various patents. In the same year, the Westinghouse Company and General Electric competed for the bid to supply power to the Chicago World Fair and Westinghouse won the contract with an extremely low bid (only half of the General Electric bid) (McNichol, 2006). As mentioned, the fair demonstrated a large-scale AC power system that could supply end-use systems of both AC and DC. At the fair, Tesla also demonstrated the “safety” of AC by allowing extremely high-frequency current at 200,000 volts to pass over his body in a stream of light – traveling on the surface of his skin due to the high frequency (McNichol, 2006). In 1893, another boon to AC occurred when Westinghouse won the contract to set-up an AC power system of previously unseen proportions at Niagara Falls. By the mid-1890s, both Westinghouse and General Electric were supplying AC systems and in 1896 through a patent agreement, both companies settled on a 3-phase 60 Hz system with 25 Hz sub-systems for heavy power (the system that continues in use in the United States today) (Atherton, 1984).

Thus, AC systems were prevalent around the 1900s when factory use of electricity looked beyond lighting to power for machinery. Electrical power was by then well established and prices began to fall considerably. The use of electric power for factories first surfaced as a substitution of the drive for existing plants that had already built in a system of shafts and belts from earlier water mills or steam engines (Nye, 1992). However, these traditional systems involved a complex set-up in terms of organizing the plant in such a way as not to overcomplicate the shaft, belt and gearing system. Such systems also involved a lot of wasted energy since the shafts and gearing would turn even when not supplying power to a machine. Individual electric motors had the advantage that they fitted directly to a particular machine’s needs, did not operate when the machine was off, and allowed for the removal of
the large shaft and gearing system opening the way for factory layouts independent of power supply (Atherton, 1984). New plants were more likely to adopt electrical power and relatively new industries in product fabrication and assembly as well as chemical production electrified much more quickly than traditional industries such as textiles, mining and iron & steel production (Atherton, 1984). The development of factory electrification and individual motors was congruent with the trends already underway in the manufacturing including specialization, the development of interchangeable parts and the “American System”, and eventually mass production (Hounshell, 1985). Indeed, Henry Ford’s Highland Park automobile plant built in 1910 was design under the premise that “electrical power should be available everywhere” (Nye, 1992). Electric power meant that companies could organize machines according to sequence of work rather than by type (Nye, 1992). A traditional system of shafts, belts, chains, etc. would have made such organization very difficult – though not impossible. By 1920, nearly 100% of British and 75% of US “engineering” shops and factories employed electric power (Atherton, 1984). Thus, electricity was a significant part of the changes in manufacturing in the early 20th century.

Electricity would not just affect workers in the factories; however, residential applications of electric power in addition to electric lighting were growing and continued to grow for much of the 20th century. First irons and refrigerators were introduced for residential use and soon after numerous applications followed from clothes washers and vacuum cleaners to electric ranges and dishwashers (Atherton, 1984). Many authors have written on the social implications of appliances in the home. Ruth Schwartz Cowan in particular demonstrated how electrification in the home meant that many tasks shared by men and women were now exclusively performed by women (Cowan, 1983).

Figure 2-XIX: 2000 flatirons replaced by electric irons in the early 1900s (Nye 1992 from General Electric)

Beginning in the early 20th century, a great deal of social change linked with the growth of use of electricity in all aspects of society. All aspects, that is, save rural life. By 1920, two-thirds of farmers in the northern European states (such as Germany, France, the Netherlands and the Scandinavian countries) had electricity at reasonable prices. In the U.S., on the other hand, ninety-percent of farmers could not even get distribution lines to their farms and the “lucky” ten-percent often paid a significantly higher rate than urban users of electricity paid (Nye, 1992). By 1935, the situation had not much
improved and only one in nine U.S. farmers had electricity compared to rates of over 80% in countries like the Netherlands, Denmark, France, Germany and even New Zealand (Nye, 1992). The situation was exacerbated by the fact that most farmers who did have electricity were located in the northeast or on the west coast while the middle and south of the U.S. remained larger “electricity free.” If farmers did want electricity, they would have to supply it themselves either with small water or wind driven machines. Small-scale steam driven generators also became available, as did the number of electric power machines for farm use (Nye, 1992). However, largely, rural America in the early 1900s had limited access to electricity while the rest of society, from lighting and traction in cities, to power for factors, and to electric appliances in suburbia, was coming to know electricity as a fundamental part of their livelihoods. In a matter of decades, society had moved from experiencing the first installations of arc-lighting systems in the 1970s to large-scale electrification by the 1900s.

2.4 First Attempts to Generate Electricity from Wind Energy in the 19th Century

Economic historians Sam Schurr and Bruce Netschert estimated that in 1850, wind power accounted for 1.4 billion hp-hrs of the measurable work in the United States compared to 0.9 billion hp-hrs from water wheels and 0.4 billion hp-hrs from steam engines (Righter, 1996). While sailing ships had used wind power for centuries (not included in the above statistics), wind power had an important role for performing work in the U.S. and abroad. By the 1890s, the same study estimated that only ten-percent of work was performed by the combination of wood, water and wind (with steam power both in its raw form and via electricity taking the lion’s share) (Righter, 1996). As the use of steam-power grew, users of windmills, for applications other than traditional roles in pumping water and supporting farm activity, removed them or left them to rot. However, the idea of using wind and water as a “prime mover” for electricity generation in addition to or instead of steam-power was a concept that inventors investigated periodically during the latter half of the 19th century.

Francois Nollet (the visionary behind the dynamo-driven limelight lighthouse as discussed) supposedly was working on ideas of wind and water generated electricity as early as 1841 (Tanner, 1892). Nollet’s main contributions to the development of the magneto were through two British patents in 1850 and 1852 where he built on the work of Stohrer and Millward respectively (Dunsheath, 1864). This work was coincident with the development of his lighthouse limelight system and the formation of the Anglo-French company La Compagnie de l’Alliance that would become an important early electric power company in France. Both the above patents related to the development of multi-pole machines and enhancements to such configurations. Even earlier in 1841, Nollet acquired a patent in his home state of Belgium where he worked at the Military School of Brussels. Apparently, Nollet was the first to formally conceptualize in a published document (via the patent) the idea of a magneto-electric machine which might be operated not just by steam but also by “an air or water motor supplied by the forces of nature: a motor of this kind being of no great expense than the cost of applying it, furnishing a constant and continuous force, giving a uniform movement requiring small space, little repairs, and presenting no danger whatsoever” (Nollet, 1841; Tanner, 1892, p. 382; Righter, 1996).5

5 The above quote is a translation of the patent content “almost verbatim” according to the author A. M. Tanner who wrote of the patent in the Electrical Review in 1892.
In this statement, Nollet captured the opportunities and challenges for wind-generated electricity that were to come: the cost, the ability to provide a constant speed input to the electrical machine, the ability to provide power continuously over long periods of time, limited maintenance requirements and safety – all of these factors would affect wind energy development in the early years and are important aspects of current wind turbine system design.\(^6\) While such insights suggest that Nollet had experience with the development of such “air or water motors,” it is unlikely that he ever built such machines. Nollet passed away in 1853 and never realized his visions of electricity for lighting (limelight) as well as electricity supplied from natural forces (wind and water). His famous protégé F.H. Holmes would pick up his quest to develop a machine for limelight by electricity, but no one further developed his “natural force” generated electricity ideas.

It would be another several decades before inventors would pursue and realize the practical application of wind energy to electricity.\(^7\) In 1881, Lord Kelvin of England described the decline of the use of

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\(^6\) Nollet notes the need for “small space” pointing perhaps prophetically to the role of aesthetics in the design process for wind turbines. Today, aesthetic considerations of wind turbines and the “viewshed” are important factors in the overall success of a wind project.

\(^7\) Righter (1996) suggested that American Moses G. Farmer of Kansas, who developed parallel circuits for power systems as well as generator technology, invented a wind electricity generation machine and patented it in 1860 (source from a 1981 Kansas Wind Energy Handbook). He is known for his development around that same time of the Farmer, a self-exciting dynamo introduced about the same time as others such as Siemens and Gramme (Atherton, 1984). However, of the many patents that Farmer had approved during the period, none contains any reference to such a wind driven machine. I know of no concrete evidence that Farmer did indeed conceptualize, let alone build, such a machine.
“natural forces” for performing work and in particular the “lamentable decadence of wind-power” (Thompson, 1881; Righter, 1996). There is almost something nostalgic about the way Thompson juxtaposes steam technology and wind technology; he quotes the letters of a young woman staring over a winter plain feeling that it would be a desolate landscape were it not for windmills which lent “revolving animation to the scene” (Thompson, 1881). Still, Thompson had hoped that the situation was temporary as “subterranean coal-stores of the world ore [were] becoming exhausted surely” (Thompson, 1881). Even though the production of coal was growing in the United Kingdom and elsewhere, scholars had already begun to question the sustainability of reliance on this “subterranean” fuel source. In 1865, economist William Stanley Jevons published the book: *The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines*. While not the first to explore issues of sustainability and “limits to growth,” Jevons was the arguably the first to engage with such questions from the perspective of society’s growing dependence the non-renewable source of coal. In his book, he builds upon the work of Thomas Robert Malthus who suggested that population growth would overtake the ability of the earth “to produce subsistence for man” (Malthus, 1798, p. 61). Looking at the growth of use of coal energy during the 19th century, Jevons finds:

“For the present our cheap supplies of coal, and our skill in its employment, and the freedom of our commerce with other wide lands, render us independent of the limited agricultural area of these islands, and take us out of the scope of Malthus’ doctrine. We are growing rich and numerous upon a source of wealth of which the fertility does not yet apparently decrease with our demands upon it. Hence, the uniform and extraordinary rate of growth that this country presents. We are like settlers spreading in a rich new country of which the boundaries are yet unknown and unfelt.

Then I must point out the painful fact that such a rate of growth will before long render our consumption of coal comparable with the total supply. In the increasing depth and difficulty of coal mining, we shall meet that vague, but inevitable boundary that will stop our progress. We shall begin as it were to see the further shore of our Black Indies. The wave of population will break upon that shore, and roll back upon itself...

There is too this most series difference to be noted. A farm, however far pushed, will under proper cultivation continue to yield forever a constant crop. But in a mine there is no reproduction, and the produce once pushed to the utmost will soon begin to fail and sink towards zero.

*So far then as our wealth and progress depend upon the superior command of coal we must not only stop – we must go back*” (Jevons, 1865, p. 177-178, original italics).

Jevons ideas on the “coal question” drew widespread public attention. Though unmentioned in Thompson’s 1881 lecture “On the Sources of Energy in Nature Available to Man for the Production of Mechanical Effect,” Jevons perspectives on depletion of coal and its relationship to economic growth probably influenced Thompson. However, ever the engineer and scientist, Thompson saw a solution in
the natural sources of energy: “When the coal is all burned; or, long before it is all burned, when there is so little of it left and the coal-mines from which that little is to be excavated are so distant and deep and hot that its price to the consumer is greatly higher than at present, it is most probable that windmills or wind-motors in some form will again be in the ascendant, and that wind will do man’s mechanical work on land at least in proportion comparable to its present doing of work at sea” (Thompson, 1881). He even recommends an early design of a wind turbine which involved a wind mill driving a dynamo feeding new “accumulator” or storage batteries from Camille Alphonse Faure in France so that power could be provided during “calms [which] do not last often longer than three or four days at a time” (Thompson, 1881; Righter, 1996). Yet again, Thompson early-on suggests a prime challenge of wind energy system design in the lulls or calms that would result in days without wind-generated electricity. However, he sees a solution in the use of new storage battery technology. Early batteries, such as that developed by Volta, involved an irreversible chemical reaction. Eventually, batteries existed that could have the chemical reaction could be reversed and these became known as secondary batteries or cells to be distinguished from primary batteries or cells. These secondary batteries (also known as storage batteries or accumulators) were first invented in 1859 by Gaston Plante and then innovated upon by Faure with a design that leant itself towards easy manufacturing and large scale production. Thus, Thompson’s suggestion of electricity generation by wind follows directly on the heels of the announcement and demonstration of the first practical electricity storage system for large-scale production. However, he also suggests that the costs of such systems would likely be unacceptably high “without inventions not yet made” in particular around the costly windmill as the “probable cost of dynamo and accumulator does not seem fatal to the plan” (Thompson, 1881).

Thomson’s ideas were shared across the Atlantic via engineering journals as well as popular newspapers such as the Chicago Tribune and then further transmitted by local papers, for instance in Texas where the Tribune was quoted as saying “In the opinion of most of the scientists of Great Britain electricity is to take the place of steam in driving machinery and moving cars, and is to be generated by the action of tides, winds and falling water” (“The Future Motor-Power”, 1881). While an exaggeration of the scale of the claims – being one scientist, William Thompson, who provided many caveats to his ideas – the papers did spread across the United States the idea that wind could “generate electricity for moving machinery, lighting streets, and warming dwellings” (“The Future Motor-Power”, 1881). It is perhaps not surprising, then, that the first patent for a practical wind electricity generation system in the United States was applied for and granted just a year after Thompson published his remarks published. In March of 1892, inventor Charles E. Buell applied for and received, just a month later, a patent on a “Device for Charging and Discharging Secondary Batteries” which provided a detailed description of several configurations of a wind electricity generation system.

One might describe Charles E. Buell as a renaissance man. Born in 1841 in Connecticut, to farmer Joseph Case Buell who owned roughly 65 acres of land, he attended Wilbraham Wesleyan Academy near where his family lived (U.S. Census Bureau, 1860; Who’s Who). He worked as a telegraph engineer during the latter part of the 1860s including the American Telegraph Company and Western Union Telegraph Company among others. He was a contemporary of Thomas Alva Edison’s in the telegraph industry and they were apparently quite friendly as they exchanged a series of letters in the 1870s
regarding topics of telegraphy, materials acquisition, carbonizing materials, and even the “Edison Effect.” (Buell, 1873, 1874, 1875, 1880; Edison, 1874, 1875). He and Edison exchanged letters in the 1870s while Buell worked for the New York, New Haven & Harford Railroad Company initially as a “time keeper” – someone who used telegraphic systems to ensure that “railroad standard time” was kept across different stations in different cities to support scheduling as well as ensure safety (Buell, 1873). While serving as a timekeeper, Buell was involved in a variety of experiments in particular on the development of a system of telegraphy for recording signals photographically. Edison offered Buell the opportunity to come and test his system at Edison’s own laboratories but it appears he was unable to due to the demanding nature of his timekeeper role (Buell, 1873). Edison seems to have later elicited Buell’s help in tracking down materials suppliers for a few things and in particular, “paper for carbonizing” in 1880 while refining his carbonized incandescent lamp filament. Buell was happy to help and provided him with a few ideas and sources of silk fiber. Buell was obviously a strong supporter of Edison and told him, “I want you to make your light permanent if not already so – if your light ain’t new these college snides can’t duplicate it... eh? I can see invention in it and you have simplified, nay perfected it so as to place it in the hands of the public, a result which involved invention of the most marked character” (Buell, 1880).

Perhaps inspired by Edison’s triumphs, Buell applied for 13 patents in a variety of areas including lighting for electric streetcars, telegraphy, telephony, electric power and battery charging, and fire alarms and safety. He may have applied for earlier patents on his photographic telegraphic system, but none were granted. While quite broad in application, the underlying theme of his work and his patents was switching and control technology that Buell developed during the past 15-plus years in which he worked with telegraphy systems. Though not discussed in this work, the history of communications technology intertwines with that of electrical power engineering and the disciplines share many common points in history and sub-disciplines including switching and control among other topics. Many of Buell’s patents related to telephony in particular and he assigned them to the U.S. Telephone Company in New Haven, CT, a small company he likely founded himself, of which he served as president (U.S. House of Representatives, 1883). Over his lifetime, he would receive approval for nearly 100 patents in areas of telegraphy, electrical power and fire safety and controls. However, none of the patents seem to have resulted in significant commercial success and the U.S. Telephone Company likely failed a few years after its founding - by 1900 he was living in North Plainfield, NJ where he now listed himself as a “patent attorney” (U.S. Census Bureau, 1900). Also during that time, he joined Professor H. K. Carroll, Special Commissioner to Puerto Rico, on his mission to Puerto Rico in 1898 just after the Spanish-American War and supported Carroll in writing his report for President William McKinley on “The Island of Porto Rico” (Carroll, 1899). He joined the American Academy of Political and Social Science which was formed in 1899 and published his own report on the newly acquired territories titled “Industrial Liberty; Our Duty to Rescue the People of Cuba, Port Rico and the Philippine Islands from that Greatest of All Evils – Poverty” (Buell, 1900). Carroll notes him as a man who had studied the topic of labor extensively – apparently in addition to his studies of “electrical science” which he began in his early twenties or possibly even in teens according his an expert witness in the case of American Bell Company v. the Overland Telephony Company of New Jersey.
Thus, Charles E. Buell appears to have been tried his hand at a little everything from an electrician and telegraph engineer to an inventor, patent attorney and business owner to a “minor diplomat” and political scientist. The number of patents he acquired is certainly evidence of his aptitude in “electrical science” as he had claimed though none of them appeared to succeed on a large commercial scale – perhaps with exception of his fire alarm and related safety equipment. One of his lost patents was in fact US patent 256450 for his wind electricity generation system (Buell, 1882). Later patents never cited the patent, and Buell may never have constructed a working machine. Still, in it, Buell addresses quite smartly some of the challenges in wind electricity generation system design important to practical implementation. It is likely that Buell, who appears to have been well-connected and well-read, was familiar with Thompson’s comments on using wind energy for electricity production from the year before – it is likely not a coincidence that his patent was filed just a year later. In this patent he presents several configurations for using wind to generate electricity via direct connection to a dynamo (figure 29), through an air compression system, or using a pumping system to isolate the windmill from the dynamo (figure 30).

Figure 2-XXI: The Buell Wind Electricity Generation System with Windmill Directly Coupled (though Gearing) to a Dynamo (Buell, 1882).
In January of 1882, Buell had already submitted a patent for a control switch, again likely pulling from his expertise in telegraphy and telephony, that activated by the movement of a lever from a ball governor that would selectively close “the developing circuit” and then the “charging circuit” as the dynamo’s speed increased above certain thresholds. As the wind speed increased, the centrifugal forces push the masses up and out which moves the lever first to a position to connect the developing circuit and then the charging circuit. The designer would have calibrated the governor based on the dynamo design. The “developing circuit” charged the electromagnetic circuits in the field magnets of the dynamo until enough speed was developed, the magnets were charged and the machine could then be connected to the secondary batteries. Avoiding the back flow from the batteries to the generator that would result from connecting the dynamo to the batteries before the magnets were fully charged. Then in March of 1882, he filed for his wind electricity generation patent in which the speed of the dynamo governed the ball governor switching mechanism. A windmill either directly or indirectly drove this dynamo through an air compression or pumped hydro system. In addition, he added an automatic switching mechanism based on a patent filed in November of 1881 for controlled time switching for engaging secondary batteries (Buell, 1889). In this way, the batteries were sequentially (in groups of three as shown above) connected to either the dynamo for charging or to the working / discharging circuit. Buell was quite optimistic about his device and suggested that “Although there is a percentage of loss of power in converting the current of the machinery, it is small percentage of loss, while in many instances it is available as the utilized power of the wind, tides and moving trains, and if it required one horse-power of the initial power to afford the equivalent of one-half a horse-power in the secondary effects it would in those instances cited have cost only the outlay for apparatus” (Buell, 1882, p. 3).
Thus, Buell demonstrated a machine with significant technical promise about which he was quite confident in its ability to address some of Nollet’s challenges for a wind machine: the cost, the ability to provide a constant speed input to the electrical machine, the ability to provide power continuously over long periods of time, and limited maintenance requirements. Yet, it does not seem that Buell’s patent went any further than a concept. He developed his patent at a time where integrated power systems including practical lighting solutions from inventors and entrepreneurs such as Brush and Edison were just beginning to gain ground. In addition, he filed his wind electricity generation patents in the same year as his many telegraphy related patents. With the development of the US Telephone Company, it is likely that there was no leftover time to devote towards his ideas in wind energy and though his ideas showed technical promise, they were never pursued as far as is known.

Still, wind electricity generation was beginning to capture the popular imagination. In late 1883, Scientific American ran a series that solicited ideas for the storage of wind power for “gathering it at the time we do not need it and preserving it till we do” (Righter, 1996). In contrast to Buell, the articles were apparently dismissive about the use of storage batteries because of their high cost, short lives, low reliability and safety issues. Suggestions including air compression, spring compression, weighted-pulley systems, pumped hydro and others were suggested (Righter, 1996). By the end of the series, the editors had made no specific recommendations on which system they felt could be developed practically, if any, but the dialogue served as a beginning and not end to the development of practical wind electricity generation systems. By the end of the 1880s, inventors made at least three concrete attempts to develop and demonstrate practical wind electricity generation systems.

There were a few attempts in the 1880s to build wind turbines in Europe. The popular press reports that “at a station near the mouth of the Seine [at Cap de La Heve] a windmill is made to drive a dynamo, the electricity produced being stored in suitable batteries, and afterwards employed for lighting beacons to guide the seamen” (“Wind and Electricity”, 1888). The installation was apparently constructed in 1887 on behalf of the French Duque de Feltre in particular to see whether or not a system could be designed with wind coupled to accumulators so that electricity would always be available to light the La Heve Lighthouse (“The Advance of Electricity”, 1887). There was also some press surrounding the experiments of Professor J. Blyth of Glasgow who also in 1887 developed a vertical-axis windmill using the “revolving cups of the Robinson anemometer” via semi-cylindrical boxes on 26 ft. long arms (“Electricity from Wind”, 1894). It appears that Blyth, like Buell, also used a governor system to make the electrical contacts when the dynamo was running at speed (through a mercury pool switch) but rather than a sophisticated time-switch for controlling the charging of the secondary batteries, he again used a governor based control mechanism to split the current between the cells (“Electricity from Wind”, 1894). In a “strong gale”, the machine supposedly produced about 2 hp or 1.5 kW of power.

However, no early wind turbine – even into the 1890s and beyond – was as large in scale both in size and generation output, as Charles Brush’s “Wind Dynamo” built in 1887-1888 in Cleveland, Ohio. It is

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8 Righter gives a nice description of some of the more fantastic ideas as well as the editors’ critiques of such proposals.
highly likely that Brush, the self-described “omnivorous reader of scientific literature,” saw the reports of Thompson in 1881 and Scientific American articles in 1883 and was perhaps by such means inspired to experiment with wind generated electricity (Righter, 1996). We mentioned Brush earlier for his work in developing a full practical lighting system based on the arc light and his own Brush dynamo design. Charles Brush was born in 1849, and he grew up on a farm near Cleveland, Ohio where he experimented at an early age with electrical machinery in the farm's workshop. At his graduation, he gave a speech entitled the “Conservation of Force” traced the conversion of energy from sun to vegetation to coal to steam to electricity to light (Righter, 1996). He went to University of Michigan and continued experimenting with electric machines. He patented his own variation of the Gramme dynamo (Brush, 1877) in 1876-1877 that, as previously mentioned, beat out the Gramme dynamo in the Franklin Institute competition of 1878. From there he went on to develop the Brush Electric Company until he sold it in 1889 - just around the time he developed his wind dynamo system. Before selling the company, in 1884 Brush built his mansion and private basement laboratory where he would live for the rest of his life and which was the first home in Cleveland to have electricity.

It was for this home and his laboratory that he developed the massive wind-dynamo in 1887. The machine included a 60 ft. (18 m) tower and a wind rose rotor configuration of 56 ft. (17 m) in diameter with 144 wooden blades (Righter, 1996). The DC electric generator designed specifically for the wind turbines was capable of producing 12 kW of power (8 times that of the Blyth machine) at a full load of 500 rpm and provided power to 350 incandescent light, two arc lights and various electric motors via a battery bank consisting of a total of 408 cells (Righter, 1996). The figure on the next page shows the exterior and interior structure of the machine. There is a fusing of design elements in the image from American-style wind-rose windmills and more classic Dutch-style post-mills of Europe. Rather than rotating just the top power as was done in tower mills, the entire structure rotated on an 80,000 lb. iron-frame tower connected to a circular track. A huge weather vane helped to yaw the wind turbine passively into and out of the wind. However, the rotor connected to this post-mill more closely resembled the American windmills with its multi-bladed wind-rose configuration. To these conventional elements, Brush adds a system of geared shafts and pulleys that translates the horizontal rotation of the wind mill rotor shaft down to the rotor shaft of a generator at the base of the tower. We know little about the Brush design since much of the original information about the machine and the machine itself is lost. One does wonder why Brush chose to use a full post-mill configuration rather than the more recent configuration of tower-mills with gears used to translate the mechanical motion into different orientations feeding machinery on the ground. Likely, the size of the rotor and the load it transmitted would have been too much for a tower-mill type configuration; metal braces supported the iron-frame tower structure and connected to the fixed track in order to avoid excessive loads on the tower base (Righter, 1996). Brush admitted that the machine cost him more than, if he were to use electricity supplied by the city, but “he preferred] to be independent, and the machinery [was] a pet invention of his own” (Carpenter, 1895).
Figure 2-XXIII: *Scientific American* cover article on the Brush Dynamo in 1890
The dynamo operated throughout the 1890s to supply Brush's entire 5-acre residence and after 1900, when Brush had his home connected to the grid, the machine still charged batteries for use in his laboratory until 1908 when he took down the sails (Righter, 1996). Brush never patented his wind turbine technology nor did he attempt to commercialize it. After his company was sold, Brush, a private individual who did not use assistants and wondered "would an artist hire an assistant to paint his pictures," appeared to retreat even further away from the public eye (Righter, 1996). In an 1895 interview, he talks about interests in painting lanterns (again he preferred to color them himself) and how sought to get further away from business to "devote more of his time to scientific investigation and experiments" (Carpenter, 1895). While holding nearly 200 patents, Brush was suspicious of the patent process and suggested that the patent office "subordinates sometimes allow important information to leak out" such that he was somewhat distrustful of the system. Since there were no patents on his windmill dynamo, no commercialization of it, and since the machine itself rotted away after a failed attempt by the Ford Museum to move it from Cleveland to their Greenfield Village (Righter, 1996), there remain no specifics on the construction of the machine save a few sparse source.

The lack of information about the design was a loss in particular since the machine appeared to have a number of advanced design features — in particular electrical system. To contemporaries, however, the Brush "Wind Dynamo" would serve as an awe-inspiring example of the potential for wind-generated electricity. In just a few years, evidence of growing interest in and development of smaller-scale wind dynamos would appear in both the United States and Europe in the form of public demonstration projects, company formation and a series of patents for wind dynamo systems.

2.5 Experimenters and Inventors: Windmill Dynamo Pioneers in the United States at the End of the 19th Century to the Start of World War I

While Charles Brush came from the electrical power engineering tradition, others came from the windmill tradition with the similar intent of creating a wind electricity generation system. Andrew J. Corcoran was one such famous millwright and windmill company owner. Corcoran, pictured below, was born in 1841 in Ireland to a Blacksmith who moved his family to New York just five years later.

ANDREW J. CORCORAN was born in Dublin in 1841. His father, who was a Blacksmith, removed to New York in 1846, and carried on his trade at the corner of Warren and Washington Streets for six years, removing his business to South Brooklyn in 1850. His father wanted him to learn the Blacksmith trade, but his bent being for machinery, he left his home in 1857 and went to Syracuse, N.Y. to serve as apprentice, and at the age of twenty-one became a journeyman. Subsequently he went to Canastota, a town twelve miles from Syracuse, to build some machinery for a saw-mill owner. While working on this saw, a man named Mills appeared with a windmill pump, and he made such a strong impression upon Mr. Corcoran that he decided his course in life. He performed the mechanical devices contained in Mr. Mills' trade machinery, and it was so successful that Mr. Mills bought the entire plant in which Mr. Corcoran was employed, and removed into a windmill manufactory. Mr. Corcoran became superintendent, and, after much labor, produced the first windmill that was self-regulating. It took the prize at the Rochester Fair in 1852. At this period he met with an accident which injured his hand and made him permanently blind. He was using babbitt metal and it exploded in his face. While he was suffering he was drafted for the army, but was exempt on account of his blindness. He slowly recovered his sight. Mr. Corcoran represented the Empire Windmill Company for a time, and after that went into business on his own account. He was at one time president of the Board of Trade.

Figure 2-XXIV: Bio of Andrew J. Corcoran from Jersey City of To-Day written in 1910. A synopsis of his life and windmill company is in T. Baker's Field Guide to American Windmills (1985).

He worked as a salesperson for the well-known Empire Windmill Company based out of Syracuse from the mid-1860s to the mid-1870s when he established his own company the "A. J. Corcoran Windmill Company" in 1875 that became quite successful and even had sales agents in Europe (Baker, 1985). Critics praised the design, the Corcoran, for its good engineering and sturdiness but not for its expensive
Corcoran, for his part, directly criticized the low quality he saw in the designs of many of his competitors (Baker, 1985). His customers were mainly wealthy estate owners (Baker, 1985) and he had a number of patents approved for his windmill modifications including overall design as well as controls and system modifications (for example in U.S. patents 384427, 387212, 404605, 411581, 450736). Most interestingly, though, was Corcoran’s apparent inclination towards creating extremely tall and impressive windmill structures. Baker suggests that of all the claims of having built the “tallest” windmill tower, A. J. Corcoran is the most likely to have held the title (Baker, 1985). He built several windmills on towers in excess of 100 ft. and built one structure 150 ft. high on a Long Island Estate in 1893 (Baker, 1895). The height was in some ways a necessity several bluffs surrounded the location and obstructed the wind flow at lower heights. Still, there is also the fact that Corcoran was attracted to advanced and impressive technology as evidenced both by his tall tower construction as well as by his general emphasis on high quality design.

Figure 2-XXV: Corcoran’s 150 ft. windmill and tower on Long Island (Baker, 1995, p. 83)

It was perhaps his affection for fantastic technology that led him to construct a windmill for electric lighting around 1894. Indeed, in an article on his windmill dynamo in the same year, the author considers Corcoran’s idea and notes that “engineers now study applications which were hardly considered proper for a sane man to consider a decade ago” (“Electricity Made by Wind”, 1894). His
machine, assumedly using the basic Corcoran windmill, had an 18 ft. diameter and connected to a
dynamo using a belt-pulley system. The machine was designed for a max operation of 35 A at 35 V for a
1.225 kW rating though another source suggested that the peak output would climb to 3 hp (2.24 kW) at
wind speeds of 20 mph ("Electricity Made by Wind", 1894; Bismark 1894). Though experimental,
Corcoran considered the effort a success and felt that windmills could thus be designed using the
thousands of windmills across the country to provide lighting for homes, which was still a novelty in
particular in rural areas where windmills were prevalent ("Electricity Made by Wind", 1894). Again,
however, Corcoran’s machine seems to have been a one-of-a-kind and there is no evidence that his
company produced windmill dynamos commercially. Nor again was his technology for windmill
dynamos patented, despite the number of windmill patents he held generally.

Other windmill companies did however provide windmill dynamo solutions. A company directory in
1895 lists two companies with windmill dynamo lighting systems: the Lewis Electric Company of 80
Broadway St. in New York City and a company of O. J. Arnold for “Electric Lighting Outfits for Windmill
Power” out of Fennimore, Wisconsin (Johnston, 1895). The Lewis Electric Company of New York sold
dynamos compatible with existing windmills to provide lighting – though it is unlike the company sold
many of those systems (Righter, 1996). However, one installation used a 3kW Lewis Dynamo attached
to an Eclipse American-style windmill that charged 46 Bradbury-Stone storage batteries to provide
lighting and even run electric motors ("A New Wind Motor", 1894; Righter, 1996). Bostonian George E.
McQuesten installed the machine on his estate when he decided his steam generator, installed a few
years earlier, took too much hands-on involvement from his gardener in terms of “firing up the engine”
("A New Wind Motor", 1894). The windmill dynamo from the Lewis Electric Company provided the
solution with a “graceful and artistic tower that ornaments the lawn” (Righter, 1996). Also in the 1890s,
Fairbanks Morse and Company that manufactured the Eclipse windmill itself provided a small dynamo
and batteries for connection to an existing windmill set-up (Baker, 1985). Aeromotor Windmill
Company, which at the time sold the most popular water-pumping windmill, also began investigating
wind dynamos and the company’s co-founder La Verne Noyes had one experimental wind dynamo
installed on the roof of its New York office – though it would not actually sell such machines until the
1920s. All of these machines had a few things in common: they used existing American-style windmill
technology fitted to a dynamo by a pulley or gearing system. The dynamo fed a battery bank that
provided direct-current supply for lighting and motors. The overall configuration stemmed from existing
technology (the American wind-rose windmill) and fitted to electric technology – rather than a
configuration designed specifically for electricity production and storage.

A similar story exists in the patents approved during the period. Nearly every year from 1889 to the end
of 1913 (just before the start of WWI), at least one patent was filed in the US on wind electricity
generation. With few exception, the patents assumed the use of a relatively traditional American-style
wind-rose wind mill that was then hooked up to a dynamo via a number of different mechanisms:
direct-drive, gear system (typically using bevel gears), belt-pulleys, rotor edge driven either with gear-
teeth or a belt, and even decoupled systems using an air compressor or pumped hydro system. The few
non-wind-rose configurations used a vertical-axis configuration (typically termed a wind motor versus a
windmill).
No direct evidence was found which links the windmill companies selling dynamos referred to above, and the inventors who submitted patents on windmill dynamos in the late 19th and early 20th centuries. Inventors likely attempted to commercialize the concepts but we know little about those attempts – except for one case that we will later discuss. Five of the patents9 merely mentioned electricity generation as one application of their machines and that implies the inventors likely never developed actual wind electricity generation systems. There were also a few outlandish concepts including a wind sail track and a ship propulsion system.10

This leaves 21 patents that focused on windmill or wind motor technology developed explicitly for electricity generation including 2 in 1882 from Charles E. Buell as discussed earlier and one other11 which uses a pumped hydro system so that the electricity generation and windmill are decoupled. Of

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9 U.S. patents (Stretch, 1901; Steude, 1900; Phronimos, 1904; Williams, 1904; Terzian, 1906; Neren, 1911).

10 U.S. patents (Stretch, 1901; Corning, 1893).

11 US patent (Clements, 1911).
the remaining 18, ten incorporate the dynamo more or less as an appendage to the system.\textsuperscript{12} They focus mainly on the windmill side of the system include three vertical-axis designs and two rotor-edge driven (where the pulley or gear teeth are affixed to the circumference frame of the wind wheel). The rest involve conventional American-style wind-rose windmills and include gear-, pulley- and direct-driven dynamos but without much discussion on the interface to the dynamo or the rest of the electrical architecture. The last eight\textsuperscript{13} emphasize the dynamo aspects of the system and the controls needed to regulate power from the windmill to the dynamo and from the dynamo to the storage system. However, they also tend to deemphasize the windmill itself and even show it in drawings sometimes as a caricature of a windmill.\textsuperscript{14} Similar to Buell’s patents, this last set of patents focus on how to control connection of windmill to the dynamo when rotation reaches a particular speed, how to then regulate and control the interface of the dynamo to the storage battery system. Circuits that use electromagnets and springs to make and break electrical circuit contacts (old-fashioned relays) make up several of the filings while a few others use a ball-governor control system similar to that which Buell used in his designs. In this way we can see how it is likely that those coming from a mechanical tradition developed a switch control mechanism that was mechanically-based while those more familiar with the electrical arts where able to employ relay technology in which electromagnets. The latter produced a precisely controlled level of mechanical force (pull or push on a contact lever) based on the input electromotive force. A few of the patents also described switching mechanisms related to the battery charging side of the system which again followed Buell’s approach of a “clock-like” mechanism where gears turn in precise intervals to select between charging sinks.

\textsuperscript{12} U.S. Patents (Bramwell, 1895; Negbaur & Feely, 1896; Gale, 1896; Gibboney, 1896; Heidel, 1900; Church, 1904; Johnson, 1908; Cox, 1908; Carlson, 1910; Southwick, 1913).

\textsuperscript{13} U.S. Patents (Mitchell, 1891a; Mitchell, 1891b; Willard, 1894; Gale, 1896; Ringer, 1907; Haskins, 1911; Heyroth, 1914; Waters, 1915).

\textsuperscript{14} U.S. Patent 565138 on the “Distribution and Regulation of Power” in particular focuses on combining power sources from a variety of sources (including wind mills) and thus represents the actual windmill in a very simplistic light (Gale, 1896).
The lack of documented success of the various efforts to develop wind electricity generation systems – either by conventional windmill companies promoting electricity generation adaptations of their systems or from the various inventors who proposed wind electricity generation system – is likely due to a number of factors. There is one striking aspect evident in the patent survey in particular, however, and that is the lack of a multi-disciplinary system understanding and integrated design approach. Windmill dynamos married the relatively new discipline of electrical engineering with the craft-tradition and mechanical engineering discipline associated with windmill technology. In the surveyed patent set,
which is comprehensive for the United States from that period, the vast majority of the patent
drawings and descriptions show that either the inventor had a solid understanding of electrical
engineering or of mechanical engineering but almost never of both. In addition, one could of course
consider the intra-disciplinary issues of the early stage of development in electrical power engineering
technologies as well as the lack of study in the nascent field of aerodynamics which would of course play
a critical role in the future development of the technology. Integrated wind electricity generation in the
late 19th century was a technology ahead of its time.

Still, inventors made several practical attempts to develop the technology like those of Charles Brush
and Andrew Corcoran. To add to this list, we can include “lawyer-mechanic-inventor” Joseph Feely and
his partner Walter Negbaur of Massachusetts (Negbaur & Feely, 1896) who developed a windmill
dynamo at Feely’s home which received a fair amount of press in 1896 and 1897 with captions claiming
“Electra may be Harnessed to Old Boreas” (“Your own Electric Light”, 1897). The patent itself was issued
in 1895 and involved a few years of experiment with the main obstacle of the project being the
variability of the wind “from the electrical point of view” which resulted in “erratic fluctuations of
electrical pressure, which rendered their utilization impossible and also subjected the ordinary
mechanical connections to excessive strains” (“Utility of a Windmill”, 1896). Designers used a self-
regulating dynamo and “speed-equalizer” as a means of mitigating this challenge though the patent
does not give detail of either. Feely was quite optimistic about the machine being able to “run for 12 to
15 years with practically no expense other than lubricants” and would run “absolutely no attention
required in two weeks except when it is cleaned and oiled” (“Utility of a Windmill”, 1896; “Old Boreas
Harnesssed”, 1897). But, yet again, even with a patent in hand, a practical demonstration, and a fair bit
of press, it does not seem that the Feely machine was installed in many, if any, other places or for other
customers.

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15 A comprehensive search was done for patents from 1800 to 1973 which included terms windmill, wind motor,
winds turbine and electricity, dynamo or generator. On top of this, a snowball search method was applied where
the patents which cited all of the above patents were inspected for other citations in the period of 1800 to 1973
that would be relevant to wind generated electricity. The number of “new” patents found decreased as the
number of citing patents inspected increased until there were no additional patents found having reviewed every
citing patent for ever cited patent in the 1800 to 1973 time period.
Feely’s windmill dynamo was yet another stop-and-start to the wind industry in the United States. Nevertheless, more and more attempts continued to surface as the century ended. Everard B. Wilton had yet another windmill dynamo installed at his estate in Long Island. The headline read “The windmill supersedes the servant girl: acts as cook and housemaid for long island inventor” (“Windmill Supersedes the Servant Girl”, 1902). Somewhat fantastical, the article stated that the “cooking is done by electricity and the cradle is rocked by the same power... Mr. Wilton has lighted his entire house, and a crescent of incandescent lights shows the front gates of the grounds. There are electric bells in every room, a complete system of burglar alarms and the pressing of a button can light each lamp. Every door in the house can be made to swing noiselessly open and shut by the press of a button” (“Windmill Supersedes the Servant Girl”, 1902). Whether true or not, the description invokes a “Gatsby-esque” type of scenario where the very rich enjoy an exclusive set of luxuries – the caveat here being that these luxuries are provided by the power of wind. Another of the New York Elite, an ex-judge Thomas H. Williams of Brooklyn, installed windmills to generate electricity at his home as well (“Farm Women attend Auxiliary Meeting”, 1910).

All the examples up to this point, Brush, Corcoran, Noyes, Feely, Wilton and Williams, featured rich estates – not surprising given the relative newness of electric lighting and electricity for homes in general. The press, on the other hand, began to imagine how to utilize windmill dynamos for the vast majority of rural America that still lived without electricity up to and following WWI. As earlier mentioned, by 1920, only 10% of homes in rural America had access to electricity so that around the turn of the situation the percentage would have been even less. Discussions on windmill dynamos involved hope of a solution to provide electricity to the thousands of farms across the country where the
electric lines did not and would not run. One reporter wrote, “like the trolley lines which run far out into rural districts and bring many small hamlets into close communication with great cities; like the rural delivery of mail ... the windmill promises much more than it has already given the agricultural districts of the United States ... [there is a] promise to ultimately make the application of wind-generated electric power to the wants of American rural life one of the most important additions to the pleasure and comforts of the farm” (“Windmill Electric Power”, 1905). Another reporter wrote: “Procuring of electric power for farms can be solved by long distance transmission, electrical utilization of windmills or currents of tides or rivers. ... There are 1,000,000 windmills in the United States. Every one can be adapted to generation of electric power” (“Electric Farming”, 1896). Another inventor from a more rural part of the country, R. W. Wilson of Indiana, developed a pumped-hydro windmill dynamo system that was highlighted in local papers across the country as a solution for “every farmer who has a windmill on his grounds” to “enjoy electric lights and the many other services” (“Electric Lights from Windmill”, 1906; “Making Electricity”, 1906; “Wind-made Electricity”, 1906). In fact, wind electricity seemed well suited to farms in particular since it was felt that electricity for farms was mainly useful in the winter months. “The days of least wind occur in the summer months when the days are longest and the least artificial light is required,” and this justified yet again a good-match between rural America and the windmill dynamo (“Farmers Getting Electricity through Windmills”, 1913). Another reporter went so far as to call windmill dynamos a “godsend in the far northern countries where coal and wood are practically unknown” and spoke of one windmill in a prairie state that provided both irrigation and the production of electricity (“Great Fortunes of the Future”, 1907). By the 1910s, the Fairbanks Morse and Company, mentioned earlier, and other companies did start to provide integrated solutions for wind generated electricity including the windmill, dynamos, storage batteries and the all-important control system with relay switches etc. (“Electricity from Wind”, 1910; “Fairbanks Morse and Company”, 1912). And with a great sense of national pride, another reporter claimed that the first windmill dynamo was installed in Illinois: “the Yankee with his barlow knife has whittled out more labor-saving inventions than all the other nations put together, and it is not to be wondered at that an enterprising Illinois farmer was the first to provide his farm with an abundance of electricity direct from wind power” (“Put the Wind to Work”, 1910).

Interest in windmill dynamos strengthened as thoughts began to return to worldly concerns including energy supplies (coal in particular) and the environment. 1913 turned out to be the peak year of coal production in the United Kingdom and globally scientists returned to the discussion of the finite life of coal, and now oil, and how the production of “electricity is manifestly the sole dependence of the future” (“Is Windmill Hope of the World?”, 1911). Those who were worried about the demise of coal, such as scholars like Professor P. C. Day and Dr. Harvey W. Wiley (“Is Windmill Hope of the World?”, 1911; “When Coal Gives Out – Wind”, 1913), looked to windmill dynamos – but how that history develops takes us into World War I and beyond. By World War I, wind generated electricity was still struggling for a footing while centralized, fossil-fuel driven electricity systems continued to spread across the cities of the United States.
The Government Prepares to Harness the Air Currents After 20 Years’ Study, and Will Use Windmills for the Storage of Electricity—Drop a Nickel in the Slot, and Re-charge Your Auto!

Figure 2-XXXI: Citizen article on wind generated electricity as a solution to the inevitable decline in coal and oil reserves ("When Coal Gives Out – Wind", 1911).
By World War I, interest in windmill dynamos was well established, but the United States, despite the above claim of “yankee” precedence, was not the only country where windmill dynamo pioneers were experimenting with and developing commercial systems. The attempts made in Europe were even more successful and in particular in Denmark beginning with the work of Poul La Cour at the end of the 19th and into the 20th century.

2.6 Experimenters and Inventors: Windmill Dynamo Pioneers in Europe at the End of the 19th Century to the Start of World War I

Professor Blyth developed his vertical-axis windmill dynamo built in 1887. In the 1890s, British company Rollason Wind Motor Company began selling wind dynamos rated for five hp (3.7 kW) to customers in the English countryside – their system featured a 5-blade wind wheel (Heymann, 1995). Then in the early 1900s, a few wind electricity generation systems where installed in England that charged a battery storage system for: 1) an industrial plant with 100 Osram metallic filament lamps and a 50 V motor that could drive a few different power machines, 2) an eatery where the windmill dynamo was used to power an electric stove, 3) another industrial facility for crushing machinery as well as lighting, and 4) heating and cooking, at a church for lighting, or even a London shop for its various needs (“Scientific Miscellany”, 1909; “Cooked by the Wind”, 1909; “Powerful Windmill”, 1910; “Electrical Notes”, 1911; “Electric Power from the Wind”, 1910).

Another interesting early application of windmill dynamos in Europe was aboard various Arctic and Antarctic expeditions. At least four ships were equipped with windmill dynamos to provide lighting and even heat during the long voyages – displacing the need to bring along large quantities of coal. The famous Norwegian polar explorer Fridtjof Nansen who had a windmill installed on the ship Fram for his polar expedition from 1893-1896 (Nansen, 1897; “Great Fortunes of the Future”, 1907). There was an onboard dynamo to provide lighting (via arc lights) and heating which ran by steam when the ship was operating and by either windmill or horse mill (operated by the men onboard) when it was not (Nansen 1897). The sailors did not use the horse mill due to the multitude of other activities needing attention on the ship, but the windmill proved to be extremely useful. The crew tried it in the first winter and the machine worked “splendidly” providing “beautiful” electric light even though the wind was not very strong (around 5-8 m/s or 16-26 mph) and Nansen noted what a “strong influence light has on one’s
spirits! There was a noticeable brightening-up at the dinner table to-day; the light acted on our spirits like a draught of good wine. ... Wonderful moonshine this evening, light as day; and along with it aurora borealis, yellow and strange in the white moonlight; a large ring around the moon – all this over the great stretch of white, shining ice, here and there in our neighborhood piled up high by the pressure. And in the midst of this silent silvery ice-world the windmill sweeps round its dark wings against the deep blue sky and the aurora. A strange contrast: civilization making a sudden incursion into this frozen ghostly world” (Nansen, 1897). Nansen also noted another occasion where a polar bear approached the ship, and he attributed to the bear’s curiosity over the spinning windmill – he came so close that they were able to shoot him and have “roast bear” for dinner (Nansen, 1897). Still, the windmill operation was not perfect – it apparently required manual yawing to turn the machine into the wind, reefing of the sails when either the winds were too strong or the accumulators were full that was “not a pleasant occupation” in the cold winters in the Arctic (Nansen, 1897).

Several other explorers attempted to use windmill dynamos as a supplemental power source on their ships. The Antarctic Expedition of explorer Brit Robert Falcon Scott on the ship Discovery also employed a windmill for supplemental lighting and heat (“Novel Electrical Generator”, 1901). The crew used the windmill to power two dynamos that supplied accumulators to power the ships 50 incandescent light bulbs (“Novel Electrical Generator”, 1901). The British National Antarctic Expedition took place from 1901 to 1904 and Nansen was consulted on both planning for the journey as well as ship construction – he recommended that the Discovery be a duplicate of the Fram and was likely also influential in the choice to carry a windmill on board. Captain Joseph-Elzéar Bernier of Canada also supposedly had a windmill dynamo on his ship the CGS Arctic for his Arctic explorations from 1904-1911 (“Power from the Wind”, 1902). Finally, a windmill was used by Professor Eric von Drygalski on his voyage on the Gauss in the German South Polar Expedition run from 1901-1903 (Bruce, 1901; von Drygalski, 1904). Unfortunately, the windmill never ran as expected and it appeared that the overall system had no efficient power regulation methodology. Drygalski found that “the light [the windmill] generated was too unsteady to be of use” and “the unsteadiness of the wind produced considerable variations of voltage in the [dynamo] (shown by the way the lamps burned), and the charge in the accumulator flowed straight back into the dynamo each time the voltage dropped away” (Drygalski, 1904, p. 218). In the end, the crew abandoned the entire windmill system for oil lamps, and they used the remaining parts of the windmill to make a spinning machine to produce clothes (Drygalski, 1904). The difference in experience between Nansen and Drygalski reflect the importance of a proper overall control system to ensure the power regulation in particular.
Nansen's machine appears surprisingly advanced for the time. Indeed, German activity with windmill dynamo was limited before the turn of the century. Perhaps this is more surprising given the level of expertise Germans had separately with windmill and electricity technologies. The German role in the modern windmill industry was also strong in the later part of the 19th century. Though already present in Europe by the 1870s, the Philadelphia World's Fair in 1876 led to a boom in growth of American-style windmills in Europe – with windmill companies licensing American technology being established in Germany in particular (Heymann, 1995). The self-regulating aspects of the machines like the Halladay and Eclipse windmills made them very attractive in comparison to the large bulky tower and post mills (Heymann, 1995). The technology impressed many Germans, like millwright Adolph Pieper, who licensed and built the Halladay windmills for sale in Europe and found the “automatic regulation [to be] extremely easy, reliable and perfect” (Heymann, 1995, quoting Pieper). With the prominence of industrialization, German entrepreneurs like Pieper attempted to provide windmills as wind motors or wind engines to perform factory work with little success. The market for such machines remained small – likely, manufacturers produced around 100 such wind motors per year in all of Germany (Heymann, 1995).

In addition to the development of wind motors and engines to perform mechanical work, there were also attempts to adapt the American-style windmills to electricity generation in the 1900s. A Halladay windmill in England fit to a dynamo and drove two millstones and an Eclipse windmill connected to a 500 W dynamo in France to supply electricity to a villa in French Saint-Lunaire (Heymann, 1995). In 1900, a German publication, die Mühle – the Mill, recommended that “non-performing Millers” (those
without business) use their mills for the production of electricity for the local community and charging for the service (Heymann, 1995). Shortly thereafter, Herr Gustav Conz, founder of the Gustavus Electric Company, set up a relatively large-sized windmill dynamo based on an American-style windmill sold by the CF Neumann Windmill company that was 40 ft. (or 12 m) in diameter (Heymann, 1995; “Electricity from Wind”, 1908). He spent a considerable amount of time working out the challenges associated with the electrical system including constant speed operation of the dynamo and switching controls for the various circuits for charging and discharging the batteries. His system, installed near the Neumann facility at Kappeln, included a shunt-wound dynamo that would output up to 30 hp (22 kW) with output current sent via a switchboard to charge a at a constant “tension of 110 V” a “battery of accumulators having a capacity of 66000 Watt-hours” (“Electricity from the Wind”, 1908). The accumulators then powered small motors on lighting circuits or larger motors on separate circuits (“Electricity from the Wind”, 1908). His demonstration was successful but the costs were high in particular for the storage batteries (Heymann, 1995). There were also technical problems. The battery charging which required a minimum voltage to be maintained to preserve the battery-life but a maximum rate for charging which led to a complicated switching system that still had limitations (Heymann, 1995). Another practical limitation was in the dynamo-windmill coupling. Shunt dynamo configurations were used for self-excitation but with the sharp changes in wind speeds led to sharp changes in power output (since the power from the windmill rotor is a function of the wind velocity cubed) and this led to overloading of the dynamos (Heymann, 1995). At the time, there was no solution for developing a constant speed windmill rotor even with the self-regulation of speed provided from the American-style windmill. In particular, the short jumps or gusts in wind speed were difficult to buffer against, and this would have been a significant source of overloads and fatigue loads on the generator components. This could most-likely cause sparking at the commutator that was a perennial problem for DC motors operated with variable loads similar – an effect that similarly experienced by a dynamo fed a variable input from its prime mover.

One of the most famous figures in the early history of wind electricity generation, Professor Poul la Cour of Denmark, addressed both issues of constant-speed input to the dynamo and the controlled charging of batteries. Professor Poul la Cour’s solutions to the aforementioned problems resulted in a system that diffused in Denmark and elsewhere beginning in the late 1890s to World War I and the next decade. The social context in which it developed can help us to understand his work better. In the late 1800s, Poul la Cour, a folk high school teacher of mathematics and science, began to consider that the rural population would benefit from electric power generation and his ideas would eventually form the foundation of the 20th century wind energy movement.

Born in 1846, Poul la Cour was a son of a farmer who would eventually become an inventor in telegraphy before turning his eye to electric power (similar to his contemporaries Charles E. Buell and Thomas A. Edison). His father was apparently a very modern farmer who consistently introduced new technology to his work that would have given la Cour exposure to how technology can improve farm life and work. He had talents in the sciences and went on to study and work in Meteorology at the suggestion of his brother Joergen. He played a critical role in setting up the Danish Meteorology Institute and served as its Deputy Director when founded in 1872. It was at this time that he began to
experiment in telegraphy when he noted that slow telegraph communications were delaying weather forecasts (Nissen, 2009). He created a concept using tuning forks to transmit different frequencies to allow for simultaneous transmissions and received a patent for the idea in Denmark and England but could not afford to patent it globally. Elisha Gray, well known for having a competing claim to the invention of a practical telephone system with Alexander Graham Bell (Nissen, 2009; Atheron, 1984), contested La Cour’s patent in America in particular. An even more promising invention, “Phonic Wheel” was created by la Cour in 1875 and allowed signal division into small discrete bits of time so that at fast enough rates, many messages could be sent “simultaneously” (Nissen, 2009). His patent was sold to an American company, modified by the same and then used (in its modified form) as the basis for systems in both England and the United States – and la Cour felt twice-cheated by the United States patent system (Nissen, 2009). Already having resigned from the Danish Meteorology Institute, his patents in telegraphy did not produce the economic fortunes he had hoped, and with the birth of his third child, it was necessary to find new employment (Nissen, 2009). It was at this time he became a teacher at a rural high school tied to the movement of Nikolaj F.S. Grundtvig.

Wind electricity generation history in 20th century Denmark tied to a social movement associated with larger political developments that stem from the mid-19th century. Following the Napoleonic wars and the two wars of Schleswig, Denmark had to cede control of large areas of land including Norway, Schleswig and Holstein (Christensen, 1983).

Figure 2-XXXIV: The Jutland peninsula of Denmark showing the Dutchies of Schleswig (North – bright red, South – orange) and Holstein (yellow) which Denmark lost control of after defeat by the German Confederation in 1864.

Norway was lost to Sweden at the signing of the Treaty of Kiel in 1814 at the end of the Napoleonic Wars in which Denmark had aligned with France and subsequently had suffered many hardships including mass starvation. Two later wars with the German Confederation: the First Schleswig War from 1848 to 1851 and the Second Schleswig War in 1864 resulted in victory and defeat respectively and
ultimately the loss of the Duchies of Schleswig and Holstein. The impact of the wars resulted not just in a loss of fertile lands within its control, but also resulted in a larger national crisis in terms of political stability, economic growth and the sense of national identity.

The loss of territory and general national crisis instilled a new sense of need for national identity and the ideas of Danish philosopher Nikolaj F. S. Grundtvig’s ideas fit well with such notions. Danish philosopher Nikolaj F.S. Grundtvig, considered by many to be the father of the Danish National identity, in particular conceptualized the idea of “folkehoejskole” - folk high schools or “Schools for Life” meant to serve in contrast to more conservative or classical ideals of education (Christensen, 1983). There was a division in Grundtvig’s philosophy on schooling to include two paths: a “School for Life” (the folk high schools) and a “School for Passion” (the universities) where the former, emphasized practical knowledge and enlightenment through national identity especially for rural citizen while the latter would focus on universal and world concerns (Christensen, 1983; Nissen, 2009). Followers of Grundtvig established the first folk high school established in 1844 and many more followed up to and through the wars. Shortly after the second war ended, the movement to establish folk high schools took off and 21 such schools were established and operating by 1867 – almost all of which were entirely run by disciples of Grundtvig.

During his studies in meteorology in Copenhagen, la Cour learned of Grundtvig’s ideas by his uncle who was a follower. La Cour even had the opportunity to regularly attend services where Grundtvig spoke. His commitment to those ideals furthered when he married his uncle’s adopted daughter Hulda Barford who was a devout follower. Poul la Cour and his wife attended a meeting in Tivoli in 1878 to discuss transforming one of the existing Folk High School’s into one that would specifically carry out Grundtvig’s vision of the “School for Life”. The Askov Folk High School set up a parallel track to follow Grundtvig’s format and la Cour and his family moved to Askov to serve as a teacher of mathematics and science in the new school (Nissen, 2009). After many years of teaching, the idea of bringing electricity to rural Denmark inspired la Cour but by means of wind energy rather than fossil fuel based systems. It is unclear how la Cour came to regard wind-generated solution as having great potential. It is hard to say if la Cour was familiar with the ideas of William Thompson on wind electricity generation from 1881.
Professor Blyth's vertical-axis machine of 1887, or the large-scale windmill dynamo of Charles Brush also built in 1887. Most likely, inspiration would have come from Denmark where plenty of wind and windmills covered the countryside. La Cour was quoted in a biography as having said that large amounts of energy exist free of charge in Askov and move across the country, but the country is dependent on imports of coal for which it has to pay dearly (Heymann, 1995). The idea of combining such mills with dynamos may have easily arisen out of this understanding. Whatever the source of inspiration, la Cour decided to approach his brother Johann Christian, who worked in the Ministry of Agriculture, to propose the idea of windmills to generate electricity (Heymann, 1995). His brother successfully secured funding support and la Cour received 4000 DKK to set up a test windmill.

The first experimental windmill from N.J. Poulsen, a prominent windmill producer, was of a traditional Danish-style configuration that typically featured four blades, sometimes slatted, and typically in a "smock-mill" configuration (Christensen, 2013). Poulsen, at his Esbjerg factory, produced "American-style" wind-rose windmills based on patents he obtained in Denmark in 1881 and 1883, and the 4-bladed windmill he delivered to la Cour combined elements of older Danish-style windmills (in particular the rotor design) with elements of the newer American-style windmills (in particular automated control mechanisms) (Christensen, 2013). The slatted-rotor (see above) had self-regulating sails – the hinged shutters would open if the winds exceeded a certain speed. The new windmill was set up on the roof of la Cour's lab in Askov and ran a belt pulley system attached to a dynamo in the lab building. However, in order to make his machine a practical reality for electricity generation, he needed to overcome several challenges.

Like Brush and other before him, la Cour soon became familiar with the key challenges of a windmill-operated dynamo: speed control and power regulation. The novelty and uniqueness of his technical solutions to these issues are further evidence of the independence of his invention from contemporary
systems in Europe and the United States. His solutions demonstrate a mastery both of mechanical as well as electrical disciplines. Firstly, there was the challenge of speed fluctuations discussed before which would have led to overloading and fatigue loading of the dynamo. In 1891, La Cour developed a mechanical solution to the problem called the “Kratostat,” better known as a differential regulator or “rocker belt,” that could achieve an effective constant speed to the dynamo by damping the windmill speed fluctuations (Heymann, 1995; Powell, 1910; Quistgaard, 2009). The Kratostat system involved the use of weights in conjunction with the belt-pulley system that connected to the dynamo. The weights were used to hold the pulley belts in tension; as gusts would disturb the rotor speed the belt would tighten or loosen to keep the speed at the dynamo input shaft constant (within 1% of the rated speed) (Heymann, 1995).

![Figure 2-XXXVII: La Cour’s “Kratostat” developed in 1891. On the right is a realistic portrayal of the machine installed at Askov and elsewhere (Quistgaard, 2009) and on the right is a simplified description from La Cour’s publication on his windmill system in 1904 and adapted in a US Publication on windmill design in 1910 (Powell, 1910).](image)

The Kratostat had applications not just for wind energy but also for steam engines. However, because he developed the Kratostat had with Danish government funds, he could not patent it and instead, a person could buy the entire design for one single Danish crown (Quistgaard, 2009; Heymann, 1995). In December of 1891, La Cour formed a company “I/S La Cour’s Kratostat” with his assistant Jacob Appel and the owners of the machine factor Konstantin Hansen & Schroeder (Heymann, 1995; Nissen, 2013b). The limitation on the ability to patent the technology in Denmark did not limit the possibility in other countries, and he sought a patent on the “Steam Kratostat” in the United States (Nissen, 2013b). Appel attended the Chicago World’s Fair along with colleague Harald Gabe in 1893 in order to exhibit the
Kratostat (an implementation of the machine was shipped in its entirety to Chicago for display) but they were met with rejection—a patent by English steam engineer Benjamin Hicks was approved in 1841. Benjamin Hick along with his sons owned the British engineering company B. Hick and Sons which was successful in producing many commercialized inventions related to steam power technology both for locomotive as well as industrial applications. His patent, English Patent 8613 “Certain Improvements in Regulators or Governors for Regulating or Adjusting the Speed or Rotary Motions of Steam Engines, Water Wheels, and other Machinery” involved a machine “for the purpose of governing or regulating the speed of such rotary motion under any variety of circumstances which may tend to destroy the requisite and uniform speed of steam engines or other machinery” (Hick, 1840). The patent image (shown below) of the governing mechanism is nearly identical to the Kratostat.

Figure 2-XXXVIII: Hick’s governor contained the various elements central to La Cour’s Kratostat (Hick, 1840).

Gabe wrote to Appel in a hotel letter after arriving to Hoboken, NJ to head to the fair: “You are like us, expecting big surprises in this country, and I am in a way very sorry to be the first to give you a bucket of cold water in your face, but we should just jump into it. Our patent on the chain Kratostat cannot be given in A[merica]. It was rejected with the comment, that the Patent existed owned by Mr. Hick,
English patent no 8613 of 27 Aug. (Gabe, 1893). There were no subsequent efforts to patent the technology and the company returned its focus to the Northern European markets. By 1894, the Kratostat was installed on 9 windmills, 2 water mills and 1 horse-pulled milling system; eventually over 50 were sold to farmers and mill owners and many dairies across Denmark and elsewhere used the technology (Nissen, 2013b). Given the simplicity of windmill dynamo patents awarded in the United States during the 1890s, it is possible that the windmill dynamo “system” might have been successfully patented, but of course there is no way to know at present and the patent system once more failed la Cour in his attempts to create economic fortunes from his inventions. Still, it does appear that la Cour and his colleagues tried to market the device in the United States and had meetings set up with a company in particular in Boston about what appeared to be discussions on a project of some sort. Gabe also suggested they not discuss the news of the patent rejection with contacts in the United States (Gabe, 1893).

Having overcome the issues of speed control, power regulation and energy storage were still present. While batteries were certainly prevalent, the work of Italian Professor Garuti on electrolysis for hydrogen production and storage published in an 1893 magazine impressed la Cour (Heymann, 1995). La Cour used his government funding to visit Garuti and quickly moved forward with plans to purchase an electrolysis unit for production of hydrogen and oxygen for lighting purposes (Heymann, 1995; Christensen, 2013). The folk high school at Askov would pay for the new hydrogen tanks as well as piping for a distribution system that led to the final locations of the hydrogen gaslights (Heymann, 1995). It took a few more years to work out the technical challenges of the system but eventually la Cour’s home and laboratory as well as the school auditorium – a feat that drew significant attention and many visitors (Heymann, 1995). La Cour also attempted to develop a Hydrogen based engine for use with his system but use of hydrogen proved too dangerous and unstable for the purpose and he eventually gave up (Heymann, 1995). He also worked on electrolysis for chemical production as a way to support rural industry – an activity that would continue throughout his life with an initial focus on production of calcium carbide and later on sodium carbonate and fertilizers (Heymann 1995). His experiments and technology continually focused on rural life and ways of either improving existing conditions or creating new opportunities for rural economic pursuits.

In 1897, la Cour received additional funding from the Danish government and he installed a second, larger experimental mill at his laboratory. The larger mill featured a tower-mill type construction and the new rotor came this time from Christian Soerensen with six blades in a conical formation. In particular, Soerensen worked in the 1870s to produce windmills with fewer blades and a unique patented “conical wind rotor” (Keglevindfanget) with convex and concave vanes meant to “catch the wind” (Christensen, 2013). His design derived from a series of experiments with different numbers of blades, blade sizes and angles of the blade elements throughout (Heymann, 1995). Soerensen had approached la Cour to use and test his novel windmill rotor design in hopes that it would prove to be more efficient than the traditional windmills (Christensen, 2013). Soerensen’s need to prove his

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16 The author thanks Povl-Otto Nissen of the la Cour Museum in Askov, Denmark for his translation of the letter written by Harald Gabe in 1893.
technology led la Cour to perform a series of aerodynamic experiments in the late 1890s. He built one of his windmills in Askov in 1896 at his own expense but the wind was too unstable for reliable results. Shortly thereafter he went to Copenhagen to use the wind tunnel of Broch and Henriksen Engineering to perform tests in artificial flow but the results were still unconvincing (Heymann, 1995). La Cour in particular felt that the artificial environment was too far from reality to produce good results, but at some point, likely after the 1897 installation of the Soerensen conical wind rotor at Askov, he became convinced.

Figure 2-XXXIX: Experimental windmills at La Cour's Askov laboratory in 1897 featuring the new Soerensen windmill (left) with the original traditional windmill on the right (Quistgaard, 2009).

In the late 1890s, La Cour performed a series of in a small wind tunnel created in his laboratory using a fan driven by directly from the windmill-driven Kratostat. The Kratostat, as mentioned before, provided uniform speed output that meant that the fan connected to the device would produce a uniform wind speed. Using small models of Sorensen's rotors, La Cour quickly determined that the four bladed configurations had superior efficiency compared to the 6, 8, 12 or even 16 bladed machines, and he thus discovered that the windmill power did not grow in direct proportion to the number of blades or wings used. Instead, la Cour showed that the power was greater for a smaller number of blades (Heymann, 1995). This directly contradicted the thinking at that time from millwrights and scientists alike that a windmill should have as many blades as possible to produce the most power. The equation:

\[ P = 0.0338 \cdot F \cdot v^3 \]

Was the generally accepted equation for wind power production at the time where \( P \) is the amount of power produce, \( F \) was the sum of the blade sail area and \( v \) was the velocity of the wind (Nissen, 2013a). Today we know that the power output from a wind turbine depends not on the sail or blade area but on the total swept area of the rotor and the aerodynamic efficiency of the rotor that favors a smaller number of blades (1-4) over a larger number (6+). La Cour instead attributed the production of power to not just the wind hitting the rotor blades but the wind that flowed between them – perhaps the first
insight by anyone into the important role of aerodynamic lift versus drag in windmill performance (Nissen 2013 a). This also was the first step towards eventually establishing the supremacy of a few-bladed versus wind-rose multi-bladed rotor configuration for applications in windmill electricity generation.

La Cour continued his aerodynamic experiments using two very simple wind tunnels of 2.2 m in length with diameters of 1 m and 0.5 m for experiments on full rotors and single plates respectively (Nissen, 2013a). Fans at the front end drove wind through the tunnels and there was no convergent section. However, as seen in the photo below, there were vanes inside of the tunnels to help better direct the airflow to help produce more steady airflow. However, the tunnels were short and the areas were quite small compared to the size of the test specimens that were located outside of the tunnel themselves – further compromising the results. Both Nissen and Heymann provide detailed accounts of la Cour’s aerodynamic experiments which involved comparison between flat, bent and curved plates, comparison of sizes of plates, comparison of performance with different inflow angles at different wind speeds, and the aforementioned comparison of various numbers of blades in the rotor design (Nissen, 2013; Heymann, 1995).

![Figure 2-XL: The Kratostat driven wind tunnels at the Askov laboratory with test models of a single plate and a scale model (la Cour 1900).](Image)

The work ultimately led to the designation of an “ideal windmill” with a list of design criteria including: 1) blade area should diminish moving towards the tip of the blade, 2) the ratio of the sail width to chord should be one-fourth to one-fifth, 3) surface of the sail should start from the axis at a distance of one-
fourth the sail length, 4) sail cross-section should be bent about one-fourth to one-sixth from the sail fore-edge, 5) the bending angle is calculated from the chord profile with decreasing angle moving towards the tip, 6) the tip speed ratio should be about 2.4 (for the ratio of tip speed to incident wind speed), and 7) work and horsepower of the mill can then be calculated using the fact that a 60 g/m² sail surface for a wind velocity of 1 m/s (Nissen, 2013a). La Cour set up a contest in 1901 in the journal “Moellen” the Mill in order to have millwrights submit their designs for idea windmills from which he would select a winner. Some traditional millwrights embraced la Cour’s ideas while others were offended by the idea of an “ideal” windmill. Soerensen in particular, whose conical rotor had proved in experiments to be unstable at large sizes, was particularly angry and published a pamphlet that criticized la Cour’s competition as favoring old designs over new innovative designs (Heymann, 1995). This in turn helped to fuel growing dissatisfaction in government over the continued funding of la Cour’s work.

In 1900, la Cour published an account of the experimental windmills “the Research Mills I and II” which received significant criticism in particular from the Danish Electrical Engineering Journal Elektroteknisk Tidskrift (Heymann, 1995). The Kratostat was criticized as unstable, the accumulators as overly expensive, the overall system inefficient due to losses from the dynamo to the batteries to the motors, and the general ideas of industrial chemical production as impractical (Heymann, 1995). The government reduced his annual assistance by a factor of three and instated a review process for each year. Still, the idea of electricity for the “3000 farms” across the country was still recognized as having positive potential and in 1902, he convinced the town of Askov to set-up a windmill power plant to generate electricity for the whole city (Heymann, 1995). Gone were the ideas of hydrogen storage and instead a more conventional system using battery accumulators would be introduced. This meant that la Cour now had to face the second electrical system design challenge of regulating power to the battery system. For this purpose, he used an automatic rocker switch termed “La Cour-scher nøgle” or La Courscher key (Heymann, 1995). Similar to American technologies previously discussed, the La Courscher Key acted as a relay between the dynamo and battery. Powell’s 1910 translation of la Cour’s 1904 machine description provides a thorough overview of the operation both of the la Cour Kratostat and of the La Courscher key (Powell, 1910; la Cour, 1904). With the dynamo off, a small residual current flowed from the battery through the key that kept it energized in the off position. As the dynamo became active, the current in the key would eventually change direction and charge the electromagnets to pull the switch to the on position. A secondary circuit created by closing the switch would further strength the polarity of the switch ensuring that the on position would be maintained.
The system had the disadvantage of the residual flow required when the dynamo was not operating, but it functioned well in terms of overall control of power to the battery system. In 1902 and 1903, La Cour's windmill dynamo system with two shunt dynamos rated at 6 kW supplying accumulators with enough capacity to supply 2 days of power for 450 incandescent arc lamps as well as two electric motors (Heymann, 1995). The estimated rate of return on the project was 12% based on an initial cost of 16000 Danish Crowns, operating costs of 600 DKK per year but revenues of 2500 DKK (Heymann, 1995).

The La Cour windmill dynamo power plant inspired installations in Denmark, northern Europe and beyond. In 1903, la Cour published the second set of reports on his windmill dynamo work “the Research Mills III, IV” which described the windmills and associated facilities in technical detail which was translated subsequently into German in 1904 (Heymann, 1995). It was praised in England and received significant press as well in the United States where the system design (especially the superiority of the 4-bladed configuration) and costs were documented ($4700 USD for the installed costs, $165 USD annual operating costs) (“The Electrical Value of Wind Power”, 1905; “Scientific Miscellany”, 1906; “Wind-Made Electricity”, 1906; “Windmills and Electricity”, 1907; “Power from the Wind”, 1908; “Electricity from the Wind”, 1910). La Cour’s system further spread in the United States and other English speaking countries due to the publication of F.E. Powell’s book *Windmills and Wind Motors: How to Build and Run them* which included a full description of the technical aspects of La Cour’s Kratostat and La Courscher Key in his final chapter on windmills for electricity generation (Powell, 1910). The book was published at least through 1918 indicating a solid publication rate - it has been reprinted in the last several decades as a still useful practical guide on do-it-yourself windmill construction.

Evidence of direct la Cour-inspired installations in the United States would be very difficult to pinpoint. It is hard to say how the situation may have been different if la Cour received a patent on his Kratostat based system, but certainly, there is no evidence of la Cour and his colleagues attempting to sell or license their windmill system in the United States after the patent rejection in 1893. There is, however,
significant documentation of la Cour installations throughout Denmark and northern Germany following la Cour’s report publications in 1901 and 1903. There was enough interest in wind generated electricity, that la Cour, along with leaders of the Danish agricultural community, started an association in 1903, the Dansk Vind Elektricitets Selskab (DVES) or the Danish Wind Electricity Association. The DVES’ mission was “to offer guidance at the planning of power plants essentially based on wind power, and through lectures, papers and courses to work for the knowledge of all leading aspects” (Thorndahl, 2009). The engineer employed by DVES, Jacob Bjerre, visited 100 potential sites and by 1905, 25 power plants supported by DVES (22 of which were based on wind power) were producing electricity (Thorndahl, 2009). In return for their engineering work, the organization would charge about 1% of the overall estimated project costs (Heymann, 1995). The organization continued to support the development of power plants until 1915 and planned overall 132 small power plants – initially mostly wind based but eventually mostly diesel based (Thorndahl, 2009). La Cour’s trainees eventually installed hundreds of windmills across rural Denmark that served either as the main source or as a supplement of electricity at farms and even at industrial locations (Thorndahl, 2009).

In addition to the direct consulting on projects, la Cour led classes for “rural electricians” that included coursework on wind-generated electricity and a practicum involving installation work of a small power plant – usually at a DVES affiliated site (Thorndahl, 2009). The state provided funding to la Cour to run the courses which he did until his death in 1908; by that time 230 students had already been educated as “rural electricians,” and the courses were continued even after his la Cour’s death until 1919 when the state determined that the interest was too low to continue supporting them (Heymann, 1995). Many referred to the students who graduated from the program as “The boys of Askov,” and they went on to install many wind electricity generated plants with and outside of DVES (Thorndahl, 2009). Centralized electricity systems continued to grow in Denmark, but la Cour continued to fight them because it was not profitable for large-centralized systems to serve rural areas that had a small potential number of customers (Heymann, 1995). The role of wind electricity in Denmark would continue to shine under la Cour, DVES and the Askov students until the beginning of World War I even as the threat of extinction due to fossil fuel based electricity generation systems became increasingly imminent.

Beyond the borders of Denmark, German companies also imitated and innovated upon La Cour’s designs and installed various wind-electric systems in the country before World War I. The rocker belt and later the Courscher key were featured aspects of the new windmills along with the European-style rotor designs of few blades. However, slipping in the belts did lead to electrical losses (Heymann, 1995). New generator designs for wind turbines included the “Gegenkompounddynamo” or Compound series-shunt dynamo that redirected current flow to control and stabilize field magnetization at high speeds; a second solution from Siemens involved a double dynamo system where one was the exciter that provided current to the main dynamo (Heymann, 1995). Swiss Company Oerlikon provided even more complex systems of regulation that targeted not just constant speed but also optimal battery charging (Heymann, 1995). The inventive activity surrounding wind dynamo design in the 1900s in Germany is a strong signal of the importance placed on the technology as a potential electricity power source.

Various installations of wind electricity generation systems were found in Germany just as they were in Denmark (Powell, 1910). Most of these installations, however, appear to have used the American-style
wind rose windmills that were prominent in Germany at the time – including a Herculean steel windmill at a castle near Hamburg or an Eagle-Wind Turbine at the estate of a rich widow in Schleswig (Heymann, 1995). There were also examples of rural applications such as at the home of a blacksmith who sought to reduce the operating costs of using the old steam engine on his site by supplementing it with wind energy (Heymann, 1995).

Indeed, the 1900s up to World War I were a “bright spot” for wind electricity generation in Europe and for Denmark and Germany in particular. In one respect, the trend would continue – bolstered in particular by scientific advancement and interest in aviation. On the other hand, the growing networks of centrally controlled large-scale electric grid systems that began to reach into rural areas in the near future overshadowed the attempts of la Cour and others to develop wind power plants.

2.7 Discussion: Context and ANT Moving Frames of Reference

From windmill technology through the 1800s, we turn to an era of “hard energy” and the growth of large-scale complex electric grid systems. Many things are changing quickly and the history of windmill and wind turbine technologies must ride on the turbulent waters of these changes. Actor-networks are not without context. On the one hand, everything is part of a great actor-network that is moving through time. One might say that in the 1800s, a stabilization of sorts existed for windmill technology actor-networks with their prominence for water pumping, traditional services in milling and new applications for industrial motors. However, actor-networks can go through periods of destabilization as well. The revolution that followed the discovery of electricity-generated magnetism (Ampere) and magneto-electricity (Faraday) resulted in fast-paced époque of discovery and invention culminating with the development of the first large-scale centrally-controlled electric grid systems by the end of the 19th century. We could say much about the actor-networks involved with the development of electric machines and the electric grid itself and many authors have looked in detail at these socio-technical systems (Hughes, 1983; Nye, 1992). However, here we seek to understand the history of the electric grid not for its own sake but for its role in the actor-network history of wind turbine technology. Several important aspects of the history of the electric grid are part of the frame of reference or context of wind turbine history.

Indeed, the electric grid (in its entirety as a contained actor-network) is as a mediator within the windmill actor network. From the wind turbine network perspective, firstly, there is the development of electric generators for lighting and power production. These magnetos, dynamos and alternators are adaptable to windmill technology to create for the first time our protagonist the wind dynamo (or wind turbine in more contemporary language). From a crude perspective, a dynamo or any electric machine simply needs mechanical power from some input shaft to produce electricity. While hand-cranks at first and eventually steam power provided the necessary torque, windmills also provided the shaft rotation needed by these new machines. Then, there is the antagonism within the electric grid network between dynamos and alternators, DC and AC systems. While today, a wind turbine can work for either DC or AC output (though most are grid-connected and thus supply AC output), wind “dynamos” were originally just that: dynamos. Even into the 1900s where the current chapter in the history ends, the basic configuration of a wind power system including: 1) a windmill, 2) a dynamo, 3) a set of batteries/accumulators, and 4) end-use appliances such as lighting and motors. A wind energy based AC
electricity generation system has yet to make an appearance. Thus, as a presentiment, the outcome of the Battle of the Systems at the end of the 19th century that largely favored AC systems was likely to have an unfavorable impact on the future development of wind dynamos. Though Westinghouse demonstrated the compatibility of any system using AC or DC operating at any voltage level or frequency, the percentage of the grid on DC systems slowly waned with the exception of High-Voltage Direct Current transmission. With an all AC grid, the role of a DC wind dynamo would be isolated to areas where the grid was not yet present.

Not only this, we have the larger social, economic and political context of the grid. Just as we reached the end of the discussion on grid systems in this chapter, there was an acknowledgement of growing consolidation in the sector. Generally, the systems involved large central power stations carefully controlled to supply an every-changing load. Wind power plants as part of a centralized power system, with the exception of La Cour's rural windmill dynamo power plants, were a distant notion and most wind dynamo systems had value only for isolated factory or farm locations. As large-scale systems grew and spread even into some rural areas, windmill dynamos would have to contend with a competitor whose competitive cost was significantly lower due to economies of scale of centralized power as well as the lack of need for supplementary storage. As noted, the accumulators (or battery technology) of early wind power systems were quite costly and though La Cour's constant speed rocker belt provided some solution, there was still a lot of difficulty in the storage costs for wind produced electric power. Still, the lack of attention by the large utilities in the early 20th century, particular in the US, to rural communities would create opportunities for windmill dynamo power plants for many years to come. Shortages in fossil-fuel resources, coal in particular, would also serve as a boon to windmill dynamo development in the next several decades not just for rural communities but also for urban and industrial applications. Indeed, fuel shortages generally would play a critical role in the resurgence of the technology in the latter half of the 20th century.

From the wind turbine actor-network perspective, we can see the beginning foundations starting to develop. The technology aspects of the network are still rather premature and one might consider the windmill dynamo of the late 19th century to be completely distinct from the modern wind turbine actor-network. Still, it provides an important context for current technology development. For instance, we see the preference for the few-bladed wind dynamo in the work and development of Poul la Cour. American-style windmills were the state-of-the-art for the day and most early systems in the United States as well as many in England, Germany and elsewhere used these systems with their self-regulating capabilities. However, la Cour was able to demonstrate that the multi-bladed configuration, while suitable for applications that wanted to have significant torque at low speeds — such as in water pumping, these same machines hindered performance for electricity generation. His findings and subsequent work would result in systems that shifted away from the American-style windmills of the 19th century towards few-bladed configurations.

The first 40 years after Charles Buell filed patents on his wind electricity generation system involved experimentation and recognition of the difficulties inherent to harnessing wind energy for electricity production. Wind turbine specific challenges for electricity generation include the multi-disciplinary design of the system and the need for sophisticated system controls specific to the combination of a
windmill, dynamo and battery storage system. The multi-disciplinary design of the machine becomes an important challenge that will play a role throughout the history of the wind electricity generation technology development. There was evidence from early accounts of windmill dynamos that many early inventors either had a strong foundation on the electrical side or came from the millwright tradition with a stronger understanding of the mechanical aspects of the system. Without a thorough understanding of each, a windmill dynamo system design was unlikely to succeed. The understanding of how to design a structurally sound and efficient windmill was joined with the challenge of designing an overall electrical system with generation, storage and distribution. Where these two halves of the system met was in the overall controls. The controls included the windmill-dynamo-interaction controls including the development circuit for the dynamo and the constant speed operation of the dynamo. On the dynamo-battery side, the power regulation controls were important to buffer against the variable nature of supply from the windmill prime mover.

Inventors developed and implemented a number of creative approaches to dealing with these challenges, and it is perhaps not surprising that early inventors like Buell and la Cour come from a tradition of telegraphy where they are exposed to a wide array of intricate controls technologies. In the case of la Cour, we also see someone trained in the new field of meteorology and thus who had a more sophisticated understanding of the wind physics than many inventors of early windmill dynamos did. La Cour’s unique combination of experience in telegraphy and meteorology combined with his many years of teaching electrical sciences meant that he was arguably the best suited of any of the other early inventors to develop a practical windmill dynamo system. Indeed, of all the early efforts, his technology had the most impact in terms of widespread imitation and development. In this way, he was able to address the various challenges posed originally by Nollet for development of practical wind electricity generation systems: the ability to provide a constant speed input to the electrical machine, the ability to provide power continuously over long periods of time, a system with limited maintenance requirements that was also safe (requiring little direct access due to the self-regulation of the machine). All this was also done in a way that the overall system costs were relatively low and provided a decent rate of return (estimated at 12%) that would make the technology attractive to various communities.
However, it was not just the technical aspects of la Cour’s system that gave it success. Many social factors came to bear. For instance, Charles Brush’s system ran for 15+ years and powered batteries at his laboratory in Cleveland throughout that time. Brush, though, was an extremely introverted individual who had no desire to patent or share his invention with others— with the exception of a few news reports. He did not like working with assistants; he did not patent or publish his work; and he did not make any efforts, as far as we know, to commercialize his system. His example stands in stark contrast to the example of la Cour who worked as a teacher and used his windmill dynamos as a part of his overall teaching program—educating the “Boys of Askov” to go out and do practicums to implement his systems throughout Denmark. He published and advocated for his inventions through reports and the formation of companies both for the individual Kratostat as well as for the overall windmill dynamo power plant. He created a community of advocates for and practitioners of windmill electricity generation and even after his death, this community continued to develop and install windmill dynamo power plants. His students and company worked directly with rural communities to design and build systems to ensure that the systems met the design and cost criteria of la Cour’s original system as well as ensuring community involvement with the plant development. In this way, the network extended not just to the students and business agents but also to the large numbers of individuals in communities that had the la Cour systems all over Denmark and northern Germany. His use of publications ensured that his ideas diffused not only where plants were installed but also across the ocean as well. There, Powell’s classic design guidebook promoted his system design as “the” method for developing a windmill dynamo power plant. A central agent in the network, la Cour mobilized other actors through his teachings, publications and business dealings while also working with the technology to create a system solution that was viable for commercial deployment.

All of these aspects will continue to be part of the narrative as our modern wind turbine actor-networks begin to develop. Before that happens, however, we will address additional key époques in the pre-history of wind turbines. In the first half of the 20th century, significant changes continue to develop
both for the electric grid as well as in the development of modern science and technology — in particular for aerodynamics and aerospace science. Poised on the edge of World War I, windmill dynamo actor-networks in the United States and Europe would both continue to develop — with very different initial contexts but eventually meeting the same fates. A high tide formed for windmill dynamo development on both continents and ultimately receded into the calm — waiting for another great force to move them shoreward.

2.8 Appendix: Scientific Developments in Magnetism and Electricity and the Birth of Electromagnetism

2.8.1 Scientific Origins of Magnetism
The earliest “scientific” explanation of magnetism is accorded to the 1st century writings of the Lucretius in his “De Rerum Natura” (On the Nature of Things) who found that “there must needs be that there stream off this stone very many seeds or an ‘effluence’, which, with its blows, parts asunder all the air which has its place between the stone and the iron... atoms of the iron start forward and fall into the void... the ring itself follows... with its whole body” (Fowler 1997 p.1). Lucretius (98 B.C.E. to 55 B.C.E.) was a follower of Epicurus (342 B.C.E. to 270 B.C.E.) who believed that all things were made up of atoms, a theory which in turn was based on the views of Democritus (c. 460 B.C to 370 B.C.E.) who coined the term ἄτομος for an indivisible or smallest particle of matter. This view of a world constituted by atoms was related to the “effluvium” concept supposedly espoused by scholars Empedocles17 (490 B.C.E. to 430 B.C.E.) and later by scholars such as Plato and Plutarch. This “effluvium” (a Latin word for a flow of small particles from an object — such as vapors etc.) and the associated atomic view is part of Lucretius’ account of magnetism above. The effluence or tiny atoms of the magnet create the void into which iron rings are attracted. The general theory of atomism and associated ideas of atoms and effluvia remained a dominate philosophy into the 13th century when the similar theory of corpuscularianism by an unknown alchemist,18 with corpuscles as small particles which could sometimes be divided, became dominant. Returning specifically to magnetism, there is no evidence that more advanced ideas on the subject existed from antiquity until the 17th century.

Scholars did not undertake systematic study of magnetism via the compass and other devices until the beginning of the 17th century. It was in 1600 exactly that William Gilbert of England published his “De Magnete” book used as a foundational text of knowledge on both magnetism and electricity for the next few centuries. Gilbert’s text provided an account of the many experiments he undertook to study magnetism, to understand it, and to refute common misconceptions about the properties and uses of magnets in everyday life. His six-book opus demonstrated some novel insights such as the enhanced

17 Empedocles is also given credit for the related concepts of the four basic elements which constitute all things in the world — fire, air water and earth — and attributed them as tied with different Greek dieties. Plato (428 B.C.E. to 348 B.C.E.) extended this idea to the terminology of “elements” thus arriving at the classical elements of fire, air, water, earth and eventually a ‘quintessence’.

18 Notable philosopher / scientists such as Isaac Newton and Robert Boyle used the corpuscularianism as a principle philosophy and tool in their own studies of light and mechanical phenomena respectively.
power of a magnet via the application of magnetic caps to both ends and the first definitive account of terrestrial magnetism (Fahie, 1931). While compasses were in widespread use by the time, there was no understanding that it was the earth's own magnetism provided the source of magnetism for the physics that enabled the device's operation (Fahie, 1931; Atherton, 1984). Perhaps because of his connection of the earth's magnetism to those of loadstone, he came to the conclusion, similar to Thales and others that, being part of its animate mother earth, "'magnetick virtue is animate'" (Atherton, 1984, p. 15). While ideas of effluvia of electrical phenomena are present in his work, as we will see later, he gives magnetism a more spiritual identity. Shortly after the publishing of *De Magnete*, Galileo read it and subsequently engaged in a series of experiments that contributed a significant amount to the engineering of magnets via various cuts to enhance their magnetic field strength. However, similar to Gilbert, neither did Galileo evolve the underlying theory of magnetism. In 1644, René Descartes published his "Principia Philosophiae" which returned to the ideas of effluvium, or particles of matter ejected from the magnetic material. He even incorporated the ideas of effluvium into diagrams depicting magnetism in action, such as in the example shown below, which yielded results similar to present-day depictions of magnetic lines of flux or force.

![Diagram of magnetic field lines](image)

Figure 2-XLIII: René Descartes not only provided an advanced theory of effluvium for electric and magnetic phenomena, he was also the first to depict magnetic field lines. In this case, the lines represent actual effluvium, or small particles of matter, directed through the earth magnet's South Pole (A) to its north pole (B) affecting various lodestones positioned at different latitudes. The magnet earth, by his theory, was then filled with parallel threaded pores through which this minute effluvium would flow.

Theories of effluvium persisted into the 18th century but scholars abandoned them in favor of fluid theories for both magnetism and electricity.

### 2.8.2 Scientific Origins of Electricity

As with the magnetism of the lodestone, Aristotle and Pliny the Elder again followed Thales works and observed the attractive force of amber and recorded the associated sparks that friction sometimes
induced (Fahie, 1931). William Gilbert pursued the systematic study of the electrostatic properties of Amber in tandem with his studies of magnetism. In his De Magnete, he coined the term “electricity” and ascribed to it a physical explanation based on effluvia thrown out by the “electric” and which “take hold of bodies, embrace them as with extended arms, and draw them to the source” (Fahie, 1931, p. 1335). While magnetic attraction was the result of the animate nature of magnetism, effluvia seemed a better explanation of the electric attraction. Eventually, Descartes would use effluvia to explain both magnetic and electrical phenomena. Support for the ancient effluvium theory continued for instance by Robert Boyle who suggested that excited electrical bodies “threw out” the attractive effluvium (Atherton, 1984). Thus, by the end of the 18th century, the effluvium theory stemming from 1st century B.C.E. or earlier still reigned. However, a revolution was at hand. The “Scientific Revolution” of the 16th and 17th centuries in which Gilbert, Descartes and Boyle were part was leading directly into the cultural movements in the philosophic and scientific communities as part of the “Age of Enlightenment.” The seminal works of Francis Bacon in 1620 with his “Novum Organum” and of René Descartes in 1630 with his “Discourse on Method” along with the writings and growing number of accounts and apparatuses for scientific experiment led to increased applications of the “scientific method” towards the study of natural phenomena.

After von Guerick invented the friction ball in 1671, scholars used it to support scientific investigation into the phenomena of electricity. The Sulphur ball supposedly emitted the still popular effluvium by the applied friction (Fahie, 1931). Sir Isaac Newton himself, whose work provided the foundation of classical or Newtonian mechanics, found the effluvium theory attractive and consistent with his own perspectives on how matter was constructed and bodies exerted influence each other. Yet, some aspects puzzled him: “Let him also tell me how an electric body can by friction emit an exhalation [effluvia] so rare and subtle and yet so potent as by its emission to cause no sensible dimunition of its weight, and to be expanded through a sphere whose diameter is above 2 feet, and yet to be able to agitate and carry up leaf copper or leaf gold at a distance of above 1 foot from the electric-body” (Fahie, 1931, p. 1336). Thus, scientific inquiry began to hint at the shortcomings of the theory.

From this time, we begin to see more and more an intertwining between experimental science and the development of electric machines so that the idea of effluvium begins to lose ground. Heading into the 18th century, a series of developments used both von Guericke’s friction machines to perform scientific studies of electrical phenomena. The scientific developments of this period were significant, and we only provide a few highlights here. Experiments by Francis Hauksbee, a former lab assistant to Isaac Newton, combined air pumps and friction generators via the replacement of the Sulphur ball with evacuated or air-filled hollow glass balls. He was able as a result to witness light appearing from the application of friction on the interior and then the exterior of the glass. In 1708, another philosopher D. William Wall presented a paper before the Royal Society on his experiences with friction and amber in which he suggested that the resulting “light and crackling seem in some degree to resemble thunder and lightning” (Fahie, 1931, p. 1337). Thus, the work brought written speculation of the tie between electricity and lightning. Later, Benjamin Franklin would demonstrate conclusively that lightning was indeed a form of electricity.
Other investigations in the early 1700 have provided further insights into electricity and the electrical properties of materials. Since Gilbert’s experiments in magnetism and electricity, the world of materials divided between “electrics” (today known as insulators) and “non-electrics” (today known as conductors). In 1729, Stephen Gray by accident discovered a new way to classify materials based on their electrical properties. Initially he tried to excite metal “non-electrics” in similar ways as was done for “electrics” such as resin, glass, etc. He did not experience success, but in experiments with an ivory ball suspended from a glass tube by brass, iron wire or Deal pinewood connected to a cork top at the tube, Gray found that the ivory ball would acquire the same electric state as the glass tube when excited. This led to further experiments in which packthread, used for tying parcels, connected the ball and the tube at an increasing horizontal distance from one another and buffered by different types of material. It was in this context that he discovered silk was an appropriate buffer while materials such as brass were not – silk opposed the dissipation of the electricity while brass carried it away so that the packthread either would respectively successfully or unsuccessfully carry the electricity to the ivory ball (Fahie, 1931). John Theophilus Desaguliers made the distinction between conductors (such as metals) and insulators (such as glass) in subsequent studies and he was the first to use this terminology to classify materials – terminology used today.

In the 1930s, Charles Du Fay of France found that all materials except for metals and materials in a liquid state classified as “electrics” when he heated them to appropriate temperatures and rubbed with cloth. He also found confirmed von Guericke’s findings on electric repulsion and found that some excited electric bodies would repel gold leaf while other excited bodies attracted the same gold leaf. In particular, glass and resins seem to behave in opposite manners and thus two types of electricity (“vitreous” for glass and “resinous” for resin) were distinguished (Fahie, 1931). This led to the very important idea that for electric behavior, like repels like and attracts what is different.

Research into electricity continued following the invention of the Leyden jar – with leading experiments conducted in particular by Benjamin Franklin in the United States. Benjamin Franklin’s experiments and research into electricity led eventually to confirmation of the electrical nature of lightning and resulted in the popular notion of his “discovering electricity.” In his famous “kite experiment” of 1952, a key was suspended during a thunderstorm from a kite and from this Franklin was able to experience a shock.
when the string was wet and sparks were drawn to the key from the clouds. He performed similar experiments with iron rods fitted to his rough and connected by metal wire to a metal ball. He suspended a second metal ball from the ceiling and insulated and whenever lightning struck the exterior rod, the ball was repelled and struck a nearby bell. Throughout this period, Franklin was developing the “electric fluid” theory of electricity which came to supplant the effluvium theory until field theory appeared in the late 19th century. In this fluid theory, electricity consisted of a single type of charged particle that repelled other charged particles but not the rest of matter. Franklin suggested, “the electric fluid is attracted by points” as was demonstrated by his iron rod experiments (Fahie, 1931, p. 1342). Others such as William Watson in England who was involved in various experiments on Leyden Jars also developed the one-fluid theory of electricity. However, a rival two-fluid theory also surfaced, championed by scientists such as Charles-Augustin de Coulomb. In particular, Coulomb advanced the application of two-fluid theory to magnetism and suggested the idea of molecular polarization to account for the fact that a magnet cut in half still maintains similar magnetic field structure (Atherton, 1984). Fluid theory, however, removed the physical interaction component of electricity and magnetism that was present in effluvium theory and its minute particles. To compensate, Coulomb brought the old notions of the “animate” nature of magnetic and electric materials back into consideration though now embodied as forces of attraction via “action at a distance”. Something physical allowed these special materials to exert influence on objects without physical contact – though that something was still unexplained. Gradually, fluid theory with the addition of the “action at a distance” concept supplanted the old theory of effluvium was supplanted.

2.8.3 Scientific Origins of Electromagnetism

At the close of the 18th century, the idea of an explicit link between electricity and magnetism was gaining more support. Speculation of the link between electricity and magnetism existed long before its confirmation. In 1774, the Electoral Academy of Bavaria sponsored an essay competition asking for explanations on “a real and physical analogy” between electricity and magnetism (Atherton, 1984, p. 31). However, none of the explorative thinking and speculation leded to anything concrete, and the grand experiment that linked these two phenomena occurred under the most humble circumstances during a lecture by Hans Christian Oersted to his advanced students in early 1820. In a lecture on electricity and associated topics, he found that completion of an electrical circuit contact caused a week effect on a nearby magnetic compass needle. As long as the circuit was closed, there was notable deflection of the magnetic needle. Various philosopher scientists had searched for such an interaction and had noted the ability of an electric discharge to magnetize materials. However, not until Oersted’s famous experiment was the direct interaction of magnetic and electric forces demonstrated. Oersted repeated the experiment with more powerful batteries for a more powerful effect and noticed that the influence on the needle’s direction was “the same as when above it, except that the needle moves in the opposite direction” (Fahie, 1931, p. 1351).

This work published July of 1820 spurred a flurry of activity on the experimental and philosophic nature of this new “electromagnetism.” September 11th of 1820, D.F.J. Arago introduced Oersted’s work to French Academy of Sciences. On the 18th of September (just a week later!), French physicist André-Marie Ampère presented experimental results to the French Academy which showed that parallel wires
with current flow in the same direction repelled one another while if the current flowed in the opposite direction, they would attract. Here we can see electric fluid theory at work: scholars speculated that magnetism and electricity were one-in-the-same and that one was the fundamental source of the other (Atherton, 1984). Coulomb had earlier reasoned that the electricity and magnetism had different causes, and this view became dominant — Ampere noted that Coulomb's view was "believed as though it were fact" (Atherton, 1984, p. 31). Oersted's experiments showed that there indeed was a link and thus Ampere reasoned that they should indeed be of part of a more fundamental cause and he believed the "electric fluids" were more fundamental than "magnetic fluids." He further reasoned that if electric fluids were fundamental then Oersted's experiment was a demonstration of electricity acting on electricity. He went on to demonstrate this effect through his famous experiment noted above and demonstrated in the below figure.

![Diagram of Ampere's experiment](image)

**Figure 2-XLV: Diagram of Ampere's experiment that shows the magnetic fields around a wire (field direction established via the "Right-Hand Rule")**

He also established a law for determining the position of the magnetic needle relative to the direction of current flow in a wire. This law, relating the magnetic field to its current source, evolved into "Ampere's Circuital Law" and James Clerk Maxwell eventually extended it as "Maxwell-Ampere" equation in the set of four famous "Maxwell's equations."

\[
\oint_C \mathbf{H} \cdot d\mathbf{l} = \iint_S \mathbf{J} \cdot d\mathbf{S} + \iint_S \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \cdot d\mathbf{S}
\]

Essentially, the above equation states that the integral of the magnetic field \( \mathbf{H} \) around a counter \( C \) is directly proportional to the total current flowing through the surface \( S \) enclosed by the contour which
includes the free current $J$ and the polarization current $D = \varepsilon_0 \frac{\partial E}{\partial t}$.\textsuperscript{19} Ampere’s original law is also known as the “magnetostatic” law since it did not include the effect of a time-varying electric field (i.e. it excluded the second term in the right-hand side of the equation above). Additional work in the 1820s led to significant experimental advances towards practical applications of electromagnetism. Firstly, electromagnetism provided the basis for the development of the “galvanometer” or ammeter. In 1820, J.S.C. Schweigger reasoned that he might double the deflection of a magnetic field if he doubled back the wire over and under the needle and then applied current flow. The more magnetic turns, the larger the effect that thus led to more and more sensitive equipment for measuring current flow. This established more generally an understanding of the intensifying effect of using multiple coils for the production of a magnetic field via electric current flow. This understanding was used then in 1825 by William Sturgeon to produce the first electromagnetic – a soft iron core wrapped by a coil of wire through which current was fed. The American Professor Joseph Henry made huge advances in the design of electromagnets. In particular, he used several tightly-wound coils in series around the horseshoe magnet such that 1) the magnetic fields induced within each coil would be in a nearly uniform direction and thus more powerful and that 2) more coils could be wound around increasing the overall magnetic field strength (Atherton, 1984). The magnet lifted 650 lbs. via a small horseshoe bar of soft iron 20 inches long and 2 sq. in. in length were wrapped with a length of 120 ft. of coil in nine separate coils evenly spaced around the horseshoe. For a power supply, he used only a small voltaic pile: two copper cylinder with zinc in the middle with active surfaces of 370 cm^2.

\textsuperscript{19} The current density $J$ includes the “free current due to electron flow” as well as the “magnetization current” due to the change in orbit of electrons in a magnetic field and the “polarization current” due to a time-varying electric field’s effect on bound charges in the material. The latter term is also due to the time-varying effect of an applied electric field – it is independent of material effects and results in a magnetic field.
Experiments with electromagnets also led Henry to insights about the relationship between voltage and current. He coined terms for quantity magnets with short-coils paired with a quantity battery of a single pair of plates and intensity magnets with long-coils paired with an intensity battery of many plate pairs. Even before this, in 1827, Georg Simon Ohm published on the relationship between current, voltage and resistance and established the now well-known “Ohm’s Law” which can be stated as:

\[ V = IR \]

Where \( V \) is voltage, \( I \) is current, and \( R \) is the resistance of the medium through which the current flows. His work, however, was not initially given much credence since the generally accepted view of the period was that voltage and current were “unconnected phenomena” (Atherton, 1984, p. 43).

All of the experimentation of the period was slowly leading toward the establishment of the converse relationship, “magneto-electricity,” but no success was found during the 1820s. A few experiments hinted at the idea. Most famously, “Arago’s disk” demonstrated electromagnetic induction though scholars did not obtain the understanding of the cause until some years after. Electrical Engineering Historian Percy Dunsheath viewed Arago’s disk, Ampere’s insightful analyses, and Oersted’s critical discovery, as the core body of work that led to the discovery of electromagnetic induction (Dunsheath, 1969). In 1824, Francois Arago performed an experiment he suspended a needle in a circular copper cage at the bottom of which was a metal disk. The needle would swing and depending on the metal, its oscillations would dampen more or less quickly. He furthered the experiment by having a metal disk rotate near to a magnetic needle. He found that the needle would deflect further and further as the disk speed increased until it began to rotate the disk (Fahie, 1931). The most interesting thing, perhaps, is that whether the disk was iron (which had magnetic properties) or copper (which did not), the effect
on the needle was similar. Iron would interact with a magnetic needle at rest while copper would not – but in the disk experiment, both could influence the needle’s rotation.

Figure 2-XLVI: Arago’s Disk (Dunsheath 1969 p. 86)

Various attempts were made to explore the inverse relationship of using magnetism to induce electricity but these had generally involved stationary magnets (which as we know today would not have worked) or a lack of understanding, such as in Arago’s case, of the underlying cause for their experimental observations. As mentioned, Faraday unlocked the secret by “obtain[ing] a key... to open out a full explanation of Arago’s magnetic phenomena” (Dunsheath, 1969, p. 94). In 1831, Faraday created what was in essence the first “transformer” by wrapping one long coil around half an iron ring (side A) and connecting it to a battery and then wrapping a second long coil around the other half of the ring (side B) and insulating it from the first and connecting it to an galvanometer (or ammeter). His diary read “connected the ends of one of the pieces on A side with battery; immediately a sensible effect on the needle. It oscillated and settled at last... on breaking connection of A side with battery again a disturbance on the needle” (Dunsheath, 1969, p. 95). The key in this case, as we know today, is that electromagnetic induction operates by a change in the electric field. Thus, past attempts that did not involve moving magnets or a changing magnetic field did not yield the same results.

Figure 2-XLVIII: Left: Faraday’s famous “transformer” ring used to establish experimentally electromagnetic induction. Right: Faraday’s experimental set-up.

Joseph Henry independently discovered electromagnetic induction – possibly before Faraday. His experiments included a similar set-up essentially using a transformer as Faraday did in his experiments. His results were published after Faraday’s and thus Faraday is generally credited with the discovery.
Faraday also linked the behavior to Arago’s experiment noting “may not these transient effects [meaning making/breaking the electrical connections] be connected with causes of differences between powers of metals in rest and in motion in Arago’s experiment” (Dunsheath, 1969, p. 97). Faraday went on to characterize the nature of induction and moved definitively away from the idea of “action at a distance” that was intertwined with the fluid theories of electricity and magnetism, and instead, he moved to the idea of “lines of force” which still today are a useful construct for the study of electromagnetism. Scholars have written a lot on the origin of Faraday’s “lines of force” theories. In general, these lines of force were an analogue of mechanical strain, but rather than existing only within physical mediums, these lines existed also in a propagating medium. In that way could, one object would exert influence via propagated forces through a medium on objects at a distance. For magnets, he found that the forces would originate at one pole and transmitted through the medium to another pole and thus formed loops, while for electrical bodies, the forces permeated either out of or into the electrical body.

Through subsequent experiments, Faraday was able to use his lines of force to develop his theory of induction which suggested that induction produced an “electromotive force” that was a result of relative motion of a conductor through a medium with active lines of force. Thus, a stationary magnet
does not induce current in a nearby coil while a moving magnet does. Maxwell developed this insight into formal mathematics, generally referred to as Faraday’s Law (of induction), with the integral form:

$$\oint_c \mathbf{E} \cdot d\mathbf{l} = - \oint_S \frac{\partial \mathbf{B}}{\partial t} \cdot dS$$

Where a magnetic flux density $\mathbf{B}$ with its “lines of force” passing through a surface $S$ change with time and induce an electric field $\mathbf{E}$ which can be integrated around the counter $C$ enclosing that surface and current flow results. To Faraday, “lines of force” were the critical foundation of everything and even served as a philosophical basis for reality (as evidenced by the fact that they existed even in a vacuum). Later in the 19th century, James Clerk Maxwell and others evolved Faraday’s lines of force theory and grounded them as existing in ether—a medium interlinking physical objects in which electromagnetic forces, light and other non-physical entities propagate (Atherton, 1984).²¹

Two other equations make up the set of “Maxwell’s equations” which still today are widely used for analyzing and understanding electrodynamic systems. Carl Frederic Gauss conceived them in 1835 though did not publish them until 1867 and appear in Maxwell’s definitive work in 1873: Treatise on Electricity and Magnetism. Gauss’ flux theorem says that the total electrical flux normal to a surface is proportional to the charge enclosed by the surface:

$$\iint_S \mathbf{E} \cdot dA = \Phi_E = \frac{Q}{\varepsilon_0}$$

Where $\mathbf{E}$ is the electric field at a given surface point, $\Phi_E$ is the total flux (the electric field integrated over the surface area), $Q$ is the charge enclosed and $\varepsilon_0$ is the electrical constant. Similarly, Gauss’ law for magnetism states that the integral of magnetic flux over a closed surface will be zero:

$$\iint_S \mathbf{B} \cdot dA = 0$$

²¹This philosophical perspective was a useful construct to Maxwell in his construction of “Maxwell’s equations.” He studied mechanics and in particular states of tension and motion in media to find analogous behavior to that observed in electrical and magnetic experiments. In so doing, he was able to conceptualize electrodynamic systems as a mechanical phenomenon and to apply the rigorous mathematical analysis resulting in the four equations. He created an explanation of electromagnetism where magnetic force lines where surrounded by rotating vortices and each vortex was separated from its neighbors by “idle wheels” or bearings. The kinetic energy of vortex motion results in magnetic energy while the drift of the interspersed particles resulted in electric current flow (Atherton 1984). Impressively, these equations were conceived in an era where the concept of an electron did not yet exist. Maxwell’s mechanical representation, though inconsistent with today’s understanding of electron spin, orbital moments and electron current flow in a coil, still is the focus of courses on fundamentals of electromagnetism.
Where B is the magnetic flux density. Gauss’ flux theorem and law for magnetism follow from the differences Faraday’s notion of “lines of force” for electricity and magnetism respectively and today correspond well with our current understandings that electric fields result from accumulation of charges (unequal amounts of electrons and protons) while magnetic fields result from dipoles and current loops where there is no source or sink but a “loop” of magnetic flux. Figure 14 illustrates the ideas encapsulated by Gauss’ laws that make up the remaining two of Maxwell’s Equations.

And God said

\[
\begin{align*}
\{ \mathbf{E} \cdot \mathbf{a} \} = \{ \mathbf{B} \cdot \mathbf{a} \} & \quad \quad \quad \quad \nabla \times \mathbf{E} = -\varepsilon \frac{\partial \mathbf{H}}{\partial t} \\
\{ \mathbf{H} \cdot \mathbf{a} \} = \{ \mathbf{D} \cdot \mathbf{a} \} & \quad \quad \quad \nabla \times \mathbf{B} = \mu \frac{\partial \mathbf{E}}{\partial t} \\
\{ \mathbf{D} \cdot \mathbf{a} \} = \{ \mathbf{J} \cdot \mathbf{a} \} & \quad \quad \quad \nabla \cdot \mathbf{D} = \rho \\
\{ \mathbf{B} \cdot \mathbf{a} \} = \{ \mathbf{J} \cdot \mathbf{a} \} & \quad \quad \quad \nabla \cdot \mathbf{B} = 0
\end{align*}
\]

and there was light

Figure 2-LI: A popular t-shirt shows Maxwell’s four equations in its integral and differential forms and humorously suggests their relationship to biblical ideas of God’s will to create “light.”

Thus, the four equations explain various electromagnetic phenomena. However, there were inconsistencies in the world of classical mechanics that inspired much of Maxwell’s work and electromagnetic theory. J.J. Thomson confirmed the notion of a fixed minimum electrical charge, the “electron,” by experiment by in 1897. Electrical effects were now associated with movement of particles with a definite charge (and mass) through the ether. Classical mechanics suggested that Maxwell’s equations would be valid only from the absolute reference frame of the ether. Hendrik Lorentz’s “Theory of Electrons” or “Lorentz Ether Theory” was published in 1892 and 1895 and suggested that bodies moving through the ether contracted – a result that showed Maxwell’s electromagnetic theory was valid for the references frames of both the ether and the electrons (Atherton 1984).22 The result of his work was the addition to Maxwell’s equation of the Lorentz Force Equation:

\[
\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})
\]

Where q is the test charge, \( \mathbf{F} \) is the force acting on that test charge, \( \mathbf{E} \) is the total electric field seen by the charge, \( \mathbf{v} \) is its velocity vector and \( \mathbf{B} \) is the magnetic flux density seen by the test charge. The world of electromagnetism could now relate to the world of forces and combine with gravity, nuclear forces,

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22 Albert Einstein was generally inspired by Maxwell’s Electromagnetic Theory and Lorentz’s Ether Theory in his development of the special theory of relativity. The publication of the theory in 1905 was indeed “On the electrodynamics of moving bodies.”
etc. to affect the behavior of particles. Maxwell’s equations along with the Lorentz Force Equation complete the set of classical electrodynamics equations for analysis of electromagnetic phenomena. These equations, and engineering simplifications of them, served a critical purpose in the support of developing practical electrical machines and subsequent wind electricity generation technology.

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2.9.1 Patent Citations


3 The Wind Charger Era

The massive upheavals caused by World War I and World War II are the types of exogenous shocks that can serve as catalysts for network stabilization or destabilization. The wars influence wind energy through resource shortages and through knowledge transfer from the newly developed aviation sector. Still, the fast pace of electrification even in rural areas in Europe destabilized the networks that had developed in the early 1900s and much of the market disappeared in the second quarter of the 20th century. At the same time, the lack of rural electrification in the United States through the 1930s helped create a market demand for the new “wind charger” technology and the first large-scale actor-network for wind-generated electricity in the United States. Remnants of both networks would survive to the 1970s and the birth of the modern wind energy era.

3.1 Wind Energy and the Great War

Two critical aspects of World War I affected wind energy development – the first was the wartime support of aviation technology, which would begin to influence wind energy system design in the 1920s and after, and the second was the coal shortage or “crisis”, which served as a boon to sustained interest in wind energy development in Denmark in particular. In addition, immediately following the war, perhaps due to the return of troops from the electrified cities of Europe and the East Coast of the US, interest in rural electrification began to grow in the United States that spurred the adoption of wind power for farms without access to centralized grid networks.

There are many books on the development of aviation technology in the early part of the 20th century. Indeed, the airplane has had a significant role in shaping society in the 20th century. World War I served as an important catalyst for the support of aerodynamics research as well as the development and commercialization of aviation technology. From the German airships with their menacing forms dropping bombs over London to the airplane flying “aces” going head to head or providing reconnaissance and support to ground troops, aviation technology played an important role in determining the war’s outcome (Fritzsche, 1992). Just 10 years after the Wright brothers flight of 1903, the importance of airplane technology in particular was recognized first by the Allied forces (France and Great Britain) and then by the Central Powers (Germany) shortly thereafter. There are strong synergies between wind turbine and airplane (propeller based airplanes in particular) technologies. As will shortly be discussed, the adoption of airplane technology to wind turbines is a theme that begins in the 1920s and continues to present day. Perhaps more importantly, the underlying science of aerodynamics which also flourished during the war with substantial funding in Germany in particular of Ludwig Prandtl and his research laboratories at the University of Goettingen (Anderson, 1997). Towards the end of the war, Prandtl’s research led to the use of thick airfoils (the outer shape of a cross-sectional slice of airplane wind) which enabled aircraft with faster rates of climb and better maneuverability in famous German airplanes such as the Fokker Dr-1 and D-VII (Anderson, 1997). Soon after the war, as will be discussed later, Prandtl’s student Albert Betz would publish what would form the foundation of aerodynamic science for wind energy. Indeed, the growing interest in aviation catalyzed by the Great War and continuing after would influence many aspects of wind energy technology going forward and, as will be shown, many of the actors would become important in modern wind energy actor-networks.
Returning to World War I, energy shortages highlighted for the first time critical issues associated with fossil-fuel production including the non-renewable nature of the resource and the geographic heterogeneity of their supply. Combined, these two factors would influence the ability of the Allied and Central Powers to meet wartime industrial production demands and limit the access to energy resources by neutral countries. In 1913, Germany, Great Britain and the United States were the top three producers of coal worldwide and entering into the war in 1914 strained Germany and Great Britain and eventually the United States as it entered the war in 1917. The crisis was due in large part to the need within each country to balance manpower requirements between operating the mines – producing the coal needed to fuel industrial development and production of wartime related technology – and serving in the military – about 10 million in both Germany and the British Empire alone. In Great Britain, these led to nationalization of the mining industry (Stamp, 1948) and in Germany, this led to a reduction exports to even neutral countries such as Denmark that entered the war only near the very end (Heymann, 1995).

These energy shortages helped to spur continued interest in wind energy development in both Germany and Denmark. In Denmark, the “Boys of Askov” continued to carry their learnings about wind energy technology to farms and industrial operations in rural Denmark. While some of the wind motors produced through the war period in Denmark were American-style in construction, wind motors in the design tradition of the Soerensen and la Cour wind motors were more typical with their 4-6 blades having many adjustable sails per blade that could be opened or closed (shuttered) depending on desired operation (Christensen, 2009). Some 15-20 companies that had foundries or contracted with local foundries capable of fabricating the various metal parts fabricated these motors. Many marketed the wind motors as kits for customer assembly on site.

Figure 3-1: A wind motor kit from the “Holstebro Iron Foundry” showing all the drivetrain components and full assembly. The foundry was located in Jutland where many firms produced wind motor kits. (Christensen 2009 p. 29)

From 1907 to 1923, the number of farms in Denmark using wind energy (either directly as motors or electric generators) grew from 4,600 to 16,600 with estimates of around 750-1,000 installations per year (Christensen, 2009). During the war years of 1915-1918 inclusive, approximately 4000 new wind motors were installed which highlighted the importance of wind energy to supplement or replace fuel-based energy systems (coal as well as diesel fuel). At the same time, the metals – iron and steel – used in most
new wind motors for rotors, drivetrains and towers were also in short supply during the war which may have limited new wind motor production as the war continued into 1916 and beyond. Indeed, statistics and anecdotes from the period indicate that iron and steel were scarce to come by and prices were unstable which caused at least one company in Denmark, the Fjerritslev Iron Foundry, to refuse future orders while other companies show wind motor production peaking in 1915 and decreasing thereafter (Christensen, 2009).

In addition to the shortage in production and despite the shortage in fossil-fuel based energy, the general growth in use of diesel engines on farms for power production threatened the future of wind motors and dynamos. By the end of 1917, the Danish Wind Electricity Association (DVES) shut down its operations due in particular to “the strong development of the internal combustion engine” (Thorndahl, 2009). The electrician courses conducted at Askov with DVES support continued through the end of the war when in 1919 formal exam standards were set up for electricians (Thorndahl, 2009). The bright spot for commercial reality of wind energy in the early 20th century was slowly dimming. The network for wind energy motors and generators created by Poul la Cour and the Askov school community found it increasingly difficult to maintain stability as the network with diesel generation systems at the core grew and flourished. Still, the legacy of this network would continue in several ways: the culture of Askov and the larger folk high school culture of which it was a part, the students who were educated at Askov (in particular Johannes Juul who will be discussed later), and the physical artifacts of the wind motors and generators themselves which would continue operation for decades to come. The fragmented pieces of the network would form the inspiration and nucleation for the Danish wind energy actor-network that formed in the aftermath of the 1970s oil crisis.

On the other hand, wind energy for electricity generation was still very much in an experimental phase in the United States – a trend that continued through the war. There were identifications of the needs and potential for wind-generated electricity, various patent filed on wind dynamos, and small number of demonstrations of the technology, but no concentrated network existed comparable to that in Denmark. Though not as acute a shortage as experienced in the battleground nations of Great Britain and Germany, the United States experienced constraints on its resources. The government took measures to moderate coal consumption through so-called “Fuel-less Mondays” and the adoption, similar to European nations, of Daylight Savings Time to reduce energy usage for electric lighting in the winter months (Small, Westwell & Westwood, 2002). Though the US did not enter the war until April of 2017, the lead up to the war involved a propaganda campaign emphasizing conservation in anticipation of wartime resource needs. This, perhaps coupled with awareness about European shortages, prompted some scholars to reflect on fossil-fuel dependencies. American Chemist “Old Doc” Harvey W. Wiley, who had served as the first commissioner of the recently formed Food and Drug Administration, reflected on wind energy “that breeze... represents a vast amount of power that is going to waste. When all the coal mines and oil wells are used up we shall employ the energy of the wind to warm our houses and illuminate our cities” (“Man Plans to Harness Winds”, 1916). These remarks in 1916 followed similar remarks he made in 1913. During that time, Dr. Wiley was the head of the laboratories of Good Housekeeping magazine and thus had a keen sense of the growing role of electricity particular in the home. Aware of current status of electricity use on farms though that role, he suggested that
there were already many farms across the nation that utilized wind energy over diesel engines for electricity production with “the switchboard controlling the entire operation of the outfit... in the kitchen... it will operate the bread mixer, the potato peeler, and the meat chopper... the vacuum cleaner, to freeze ice cream, to manufacture ice... to pasteurize the milk... but from [the housewife’s] point of view, it is likely to be of greatest value in the laundry” (“Man Plans to Harness Winds”, 1916). Experimental research stations in Kansas and North Dakota made actual demonstrations of wind electricity generation plants for farms. In the former, costs were prohibitive particularly due to “the size of the battery necessary to store up current for use when the mill does not run” (“Can Get Power from Wind”, 1917). The latter however, provided a more optimistic view with an 18 ft. windmill that provided electricity for farm business as well as housekeeping activities. More importantly though, the wind turbine could “make blizzards produce heat” for North Dakota farms in winter (“Science Is Harnessing the Blizzards to Get Heat and Light for Rural Homes”, 1918). The experimental station in Fargo, ND operated very well in the winter and provided heat to the station with a new electric heater along with providing light for a farm of 1200 acres. This theme of electricity for the farm through wind energy would be an important part of the general narrative of rural electrification beginning in 1918 just after the end of the war. Indeed, the push for rural electrification would provide the cohesion for the creation of the first stable wind energy actor-network in the United States.

During the war, however, actual use of wind energy continued along the experimental vein that had characterized United States wind electricity generation up to that point with the exception of the use of wind electricity generation devices to power electrical equipment onboard new airplane technology. Aviation technology – from German airships to Allied and Central Power airplanes - was a critical technology in the war and airplane research and development received a huge boost on both sides as the war continued (Anderson, 1997; Fritzsche, 1992). The on-board windmill dynamo power supplies provide the first glimpses of applying new aviation technology to wind energy technology. The technology first emerged on French aircraft during the period, but would soon become a feature of aircraft developed in the United States and elsewhere (Gray, 1919). Ideally, the airplane engine would directly produce electricity on aircraft, but this was not common practice at the time due to organizational constraints since the companies designing and delivering engines were completely separate from those delivering onboard electronic equipment (Gray, 1919). In the rush to develop a solution during the war, the onboard windmill dynamo was therefore as the next best solution.

In 1916, Elmer A. Sperry, the famous inventor of the gyroscopic compass and related control systems, filed a patent for a “Wind Driven Generator for Aircraft” (Sperry, 1920). These small onboard wind turbines for aircraft emergency electricity generation are today Ram Air Turbines (RATs). Sperry had a

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23 The term “Ram air turbine” doesn’t start to appear in either technical or popular literature until the late 1940’s and Honeywell Corporation, who inherited Sperry Flight Systems in the 1980s, claim the first ram air turbine for emergency aircraft power in 1951 (http://honeywell.com/SITES/AERO-TECHNOLOGY/KEY-TECHNOLOGIES/Pages/industry-firsts.aspx ). However, this is likely for the more literal interpretation of a “ram” (forced air intake) air turbine rather than the propeller based version in Sperry’s patent filing. Today ram air turbine describes both propeller and turbine versions of the technology. A propeller type ram air turbine was featured on the German Rohrbach all metal airplane, the RO VIII “Roland” in 1926 (“Rohrbach All Metal”, 1926).
few years earlier had demonstrated the viability of an aircraft autopilot system used gyroscopic heading and altitude indicators to hydraulically control the airplane elevators and rudders. His patent application dealt with the need for a “new and improved means for generating electric currents on aeroplanes and other swiftly moving vehicles” since “electricity has been found to be an indispensable asset for aeroplanes” which is “used for lighting signals and other lights, operating wireless transmission sets, operating the aeroplane controls through servo-motors, actuating various kinds of instruments for signaling... operating gyroscopes or other stabilizing apparatus, and for charging engine starting batteries (Sperry, 1920). Sperry’s “Wind Driven Generator for Aircraft” behaved very much like RATs do today – providing backup power particularly in the event of a system failure. Sperry’s machine embodied many features of modern wind turbines and borrowed noticeably from his knowledge of aviation technology but also demonstrated an appreciation for the particular needs of using that technology for electricity generation rather than propulsion.

Figure 3-II: Sperry’s 1916 patent drawing of a “Wind Driven Generator for Aircraft” (Sperry, 1920)

Designers used a propeller type ram air turbine on a British commercial airplane the Westland IV monoplane as part of a gasoline pump system to assist in pumping gasoline to the engines particularly during steep climbs when the gravity-based main pumping system could fail (“The Westland IV”, 1929).
The above graphic illustrates Sperry’s machine. The aerodynamic design of the machine is noticeable in the shape of the hub and nacelle of the machine – by that time recognition of the impact of drag on machine performance was recognized. Sperry commented that the “hub is designed especially to reduce the head wind resistance of the generator” and “the rear portion of the generator is also of stream line shape to reduce air resistance to minimum” (Sperry, 1920). Sperry did not specify the number of blades (Sperry used the wording “plurality of blades”) but the number was far fewer than the American-style wind rose windmills common to that period. The blades were opposite each other’s centers of gyration with some inclusion of a braking mechanism by which the blades pulled inward and the angle of attack increased to promote stall of the turbine itself and decrease the effective rotor plane area that would serve as a source of drag for the airplane.

Perhaps most interesting is Sperry’s discussion of the blade design which suggests that the blade be “preferably of somewhat different design from standard blades used on airplane propellers and on electric fans... in order to secure the maximum efficiency, that is, in order to secure the maximum power with the minimum head resistance, that the blade should taper toward its tip so that the quantity of air which is brought to rest by each unit of length of the fan approximates the same value. In other words, since the tip of the fan is revolving with much greater speed than the portion near the hub, it will intercept more air in the course of each revolution than the said hub portion of the same breadth, and hence will therefore do a greater portion of the work...” We recognize this design principle in today’s modern wind turbines, but it was not representative of windmills that existed in that period.24 In addition, Sperry also found that “the blades become inefficient as they approach the center unless they are broadened and even when broadened a point is reached when I find it preferable to discontinue the blade and merge it with a large hub, shaped to reduce head resistance” which again reflects Sperry’s advanced understanding of how each section of the rotating blades performed meaningful work. Sperry’s design also featured two generators: one a direct-current generator and the other an alternating current inductor-alternator that would reflect the use of both types of equipment onboard or the option of one or the other. A manual yaw system to control the machine speed or turn it out of the wind if defective was also included shown in figure 2 and connected to a handle shown in figure 1, label 20. The popular press highlighted a prototype of the technology as shown in the figure below.

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24 The first design principle of la Cour’s ideal windmill suggested, “the blade area should diminish moving towards the tip of the blade” though actual la Cour machines and their derivatives did not appear to use this principle.
Ultimately, however, the Sperry design was not a success as it was found to be "mechanically weak" but his general concept of a pitch-regulated wind turbine (called "pivoted blade air fans") was adopted as general practice with successful designs having been developed by Thomas Slate of the American Mechanical Improvement Company (the FA-4-A Variable-Pitch Air Fan), the American Propeller and Manufacturing Company (for production) and then after by John Pinaud of the Des Lauriers Aircraft Corporation (Gray, 1919). Without the pitching mechanisms, the rotational speed of the machine (and the input speed to the generator) would continue to increase to very high levels (up to 8000 rpm at 90 mph wind speeds for example) that would lead to a variety of problems including increased drag from the device contributing to overall airplane drag, potential for damaging vibration and excessive stress on the generator, various issues with the bearings as well as dynamo commutator, and general issues with the electronics due to varying voltage of the device (Gray, 1919). Reducing the speed through pitch control alleviated many of these issues and thus found popularity once proven.

“Proving” these designs was a task taken on by the military. While Sperry, known for his technology merging man and machine (MacKenzie, 1993), envisioned an auto-piloted plane, the main use of early
onboard electronic equipment was in radio communications (radiotelegraphy and telephony) (Gray, 1919). An important role of aircraft in World War I was in reconnaissance (Fritzsche, 1992) and radio communications from aircraft to ground would expedite the ability of providing intelligence from aircraft back to command stations. In the US, 1917 was a year overshadowed by the impending entry of the country into war and the abandonment of President Woodrow Wilson’s earlier non-interventionist policies. During the neutrality period of the first years of the war, overall funding for aviation and related research had been minimal. Thus, the government increased the levels substantially to prepare for the war and to try to catch-up with European advancements in military technology generally and aviation technology specifically (overall, US defense spending rose from 1.5% to over 20% during the period). The United States Army Signal Corps Aviation Section was responsible for aviation related activities of the US during World War I. Within the Aviation Section, an Airplane Engineering Division oversaw aeronautical research and development including the development of an experimental laboratory at McCook airfield in 1917 near Dayton, Ohio. Dr. Elisha N. Fales, a professor at the University of Illinois with his PhD in aeronautics from MIT, joined the Airplane Engineering Division and would spend several years working at McCook airfield and subsequently Wright airfield. Fales worked with Frank Caldwell to design and build the first high-speed wind tunnel in the United States and to apply it to research on the effect of high-speed operation on airfoil lift and drag (Anderson, 1997).  

In addition to his pioneering wind tunnel design and experimentation, Fales oversaw the work of H. R. Stuart, Captain G. Francis Gray and others to study the performance of “little windmills” to power aircraft electronics (Fales, 1927; Gray, 1919). At the wind tunnel of the Bureau of Standards, the Radio Development Section compared a variety of designs for onboard aircraft windmill dynamos including fixed-blade (fixed-pitch) non-regulating air fans, fixed-blade “special blade shape” fans that were meant to warp at high speeds to control speed, fixed-blade fans with “wind brakes”, fixed-blade fans that used either a centrifugally regulated friction clutch or brake to control speed, or the pivoted-blade (pitch-regulated) air fans where the pitch mechanism was centrifugally controlled (Gray, 1919). The fixed-blade non-regulating air fans represented “pre-war” technology and were insufficient for onboard aircraft operation due to the aforementioned issues resulting from the continuous increases in speed.

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25 Experiments performed by Caldwell and Fales using the wind tunnel provided important insights into the idea of a “critical speed” where the lift-drag ratio for an aircraft is drastically reduced as a result of compressibility effects in flow. Anderson (1997) suggests that the term “critical Mach number” stems from this work, and the subsequent interest of NACA in compressibility research and the “high-speed frontier” in the 1920s was due in part to their findings.
The "warping" designs did not show improvements when operating under load, and designs with braking mechanisms resulted in low efficiency and high drag (or "head resistance" as it was known at the time). Thus, as was mentioned, the pitched-blade designs faired the best in tests at operating speeds (typical radio telegraphy sets used dynamos of 200 W which operated at 4500 rpm while radio telephony sets used dynamos of 80 W operating at 4000 rpm) and in over speed tests (8000 up to 14000 rpm) (Gray, 1919). John Pinaud was the designer of one of the successful pitched-blade designs that was unique in that it had only one blade with a counter-balance that reduced the strain on the shaft bearings and was unique in its design for manufacturability (Gray, 1919). Pinaud patented the design in 1923 for general applications related to "wind motors of the type adapted to rotate at comparatively high speed and particularly adapted to drive electric generators for charging storage batteries" (Pinaud, 1927).
The direct work of Fales on wind turbine design in collaboration with Stuart also extended beyond wind driven generators for aircraft to wind driven generators for general electricity production. The findings from their work mimicked that reflected in the Sperry patent: the number of blades reduced from many to a few (1 to 4) with “streamline cross-section, like that of an airplane propeller” (Righter, 1996). These turbines turned at speeds 6 to 10 times those of the American-style windmills for equivalent wind conditions and sizes and were much more efficient and lighter (critical design features for aircraft mounted RATs). After the war, Fales continued to develop these propeller-style wind-electric plants including a demonstration at Ohio farm that suggested such aviation-inspired wind electric plants could even compete with gasoline plants (Righter, 1996). Fales interest in aviation technology applied to wind energy to provide an affordable solution for rural electrification was timely. After the war ended in 1918, attention turned to domestic issues and rural electrification in particular. The next decade would see the first development of wind electricity generation actor-networks in the United States.

3.2 After the Great War: Rural Electrification and Wind Energy in the US

3.2.1 “Without Power the People are Poor”

Rural electrification via wind energy technology was in commercial application in Denmark and nearby countries due in significant part to the efforts of Ørnen and the actor-network connected to the Askov folk high school. As previously mentioned, despite some demonstrations in different parts of the US, no stable network existed for promoting wind energy electricity generation through the end of World War I. This changed, however, in the 1920s and beyond. By the mid-1920’s, nearly 60% of urban homes in the United States had some form of access to electricity (almost totally supplied by centralized utility systems) (“American homes wired for electricity 1920 – 1956”, 2014). In contrast, just 5% of rural homes in America had electricity by that time – growing from just 2% at the end of the war (“American homes wired for electricity 1920 – 1956”, 2014). This low percentage seemed even less acceptable when compared to European rural electrification rates of 51% in German Bavaria, 31% to 50% in Denmark, 40% in Sweden, and 60% in France.\(^{26}\) In the 1910’s, electricity was seen as a luxury and rural electrification as the notion of “visionary dreamers” and “impractical idealists” (Evans, 1925). However, perhaps due to knowledge of rural electrification efforts in Europe, the need for rural electrification was a necessary component of progress. Lighting, running water, better storage of food were needed to avoid perennial problems in rural communities related to malnutrition, disease and poor health that included parasite infestations, such as by hookworms, and pellagra – a disease caused by vitamin deficiency which had become an epidemic in the southern part of the United States in the early 20th century (Brown, 1980). Electricity had the potential to alleviate many of these problems and make farm life more appealing overall. The percent of the US population living in rural communities versus urban communities was dropping (down to 48.8% in 1920 from 54.4% in 1910) (U.S. Census Bureau, 1993). Not only this, the share of agriculture as a percentage of GDP had slipped form 20.5% in 1900 to 9.3% in 1921 due in large part to pricing pressures from a global market for agricultural goods (Tripp, 1926). The decline would continue throughout the century for many reasons but the lack of electricity was

\(^{26}\) German Bavaria and Sweden based on (Evans, 1925), Denmark based on (Christensen, 2009) and (Evans, 1925) respectively, and France based on (Zomers, 2001)
considered a contributing factor in terms of the quality of rural life (general health and comfort) as well as the productive capacity of the farm (economic profitability) (Evans, 1925).

In 1921, the United States Department of Agriculture published a publicized a report about electricity for the farm. The report suggested, “power on the farm has proved to be one of the greatest time and labor savers the farmer knows” (“Drudgery Removed from Home”, 1921). Though the report focused on more towards wealthy landowners by commenting on the affordability of servant help and suggesting that electricity, “the tireless servant,” could be a solution. It did not suggest that the centralized utilities be held accountable for providing electricity to the farm but instead suggested that community plants based on water or wind energy be used to drive dynamos and supply storage batteries (“Drudgery Removed from Home”, 1921). The lack of public outcry for utility power provided to rural communities is likely why the utilities companies to date had not pursued rural electrification in any significant way. Small changes began, however, that same year when the electric power industry, through its trade association the National Electric Light Association (NELA), appointed a Rural Lines Committee to study the issue of rural electrification.

The committee suggested that utilities could benefit from rural electrification due to both increased load diversity as well as avoiding competition (if utilities did not provide electricity to farmers, they would provide it for themselves (Brown, 1980). In 1923, NELA formed the National Committee on the Relation of Electricity to Agriculture (CREA) in conjunction with the American Farm Bureau Federation, American Society of Agricultural Engineers, the Independent Farm Light Plant Manufacturers and the
United States Department of Agriculture (U.S. Senate, 1925). Based on initial research, the organization supported the creation of 13 state committees to take further action at a state level.\textsuperscript{27} Through work with the State agricultural experiment stations supported by state and federal funds, the committees performed investigations and engaged in demonstration projects related to rural electrification (U.S. Senate, 1925). Of the experimental efforts, the Red Wing, Minnesota and the Alabama projects were the most successful. The 156-page report on the Red Wind Project by the University of Minnesota Agricultural Experiment Station touted the benefits of electricity for productive farming as well as domestic use (Stewart, Larson and Romness, 1927). Generally the project was hailed as a success and evidence of the willingness of utility companies to work with agricultural communities, but the special nature of the community (located close to an existing power line, with small acreage, significant use of machinery and emphasis on dairy production (Brown, 1980). While the Alabama project was more representative of typical farming conditions in the country, the costs of the project were higher than could be sustained by private efforts.

Still, there were many arguments made for the rural electrification during the 1920s. There were economic arguments. Profits to utilities during the time period were high and the “cost of money” (risk adjusted borrowing rates) was low such that the utilities should be able to afford to provide electricity to rural communities at reasonable rates and still see a profitable return (Bonbright, 1925). In addition, overall costs for supplying electricity from a technology standpoint were dropping and unique financing structures could support averaging of costs in ways that would make rural electrification feasible (Cooke, 1925). In addition, economic productivity of the struggling agricultural sector would increase via electrification (Morse, 1925). Of course, there were also social arguments that electricity would improve the quality of life and that “without power, the people are poor” (Tripp, 1926) and live in “antiquated conditions” (Williams, 1927). Overall, though, the utility-led efforts in rural electrification during the 1920s did not meet with much success and by 1927 only 7.11% of farms had gas or electric service and only 3.53% of farms had connections to the electric grid (Williams, 1927).

While the majority of farms in many European nations had electricity by 1930, scholars and utility leaders considered rural electrification in the United States to be in the “developmental and experimental stage” (Zinder, 1928). The lack of successful efforts to provide central power lines to rural areas left the door open in the United States for independent power stations in rural communities and on farms. In this environment, wind generated electricity would for the first time be deployed on a commercial scale.

\textbf{3.2.2 Wind energy takes the stage}

Despite the work of Fales and his propeller inspired RATs and very-small-scale propeller based wind electric generator machines, attempts to develop wind driven electric generators in the early 1920s depended largely on American-style windmill rotors. La Cour’s work showed that a reduced number of wind blades to have higher efficiency for electric power generation compared to the multi-bladed

\textsuperscript{27} State committees were present in Kansas, New Hampshire, New York, Virginia, Alabama, Indiana, Illinois, Wisconsin, Minnesota, South Dakota, California and Oregon
American-style type of windmill, but the design of his rotor's were not included in Powell's 1910 and 1918 editions of *Windmills and Wind Motors*. He described la Cour's electrical set-up in detail – pulling directly it would seem from la Cour's 1904 work publication on his work (Powell, 1910; la Cour, 1904). Powell's book also featured chapters on a “tower mill” with 4-blades as well as a “small American type windmill” but his “practical working windmill chapter” again featured an American style wind wheel. As a result, wind generated electricity pioneers in the United States just after the war returned to the American-style windmill as the starting point for their designs. This may have also been due to the large number of American-style windmill companies and windmills that already existed – which would have potentially eased integration and acceptance of the new technology and even have supported retrofitting of existing windmills with electrical equipment.

From the start of World War I in 1914 through 1922, the government issued 44 patents for wind electric generation machines of which 36 involved horizontal-axis configurations. Of these, 25 explicitly described a wind wheel rotor configuration and five more did not list a particular rotor type and presumably used conventional technology of the day (i.e. American style wind wheel rotors). One of these patents belonged to Oliver Fritchle of Denver, Colorado. Fritchle was a well-known inventor responsible for the “Fritchle one-hundred mile car” which could travel 100 miles without recharging and was sold in Colorado between 1904 and 1917 (Righter, 1996). Fritchle had visited Cleveland as a child and seen Brush's giant wind dynamo, and in 1917, he wrote to various windmill-manufacturing companies, asked them if they had wind dynamo units available for purchase, and found that not one of them did (Righter, 1996). He started the "Wind-power Electric Company" in 1919, and in 1920, he filed a patent for his own wind dynamo system that would retrofit to existing windmills. Essentially, a drive chain attached to the rotating hub of the windmill on one side and to the outside of the gearbox on the other that in turn connected to the dynamo armature shaft (US Patent 1391377). The whole system would sit on a plate bolted to the overall windmill bedplate. Fritchle managed to sell 55 wind plant systems that had some success – as expressed by positive endorsement letters from his customers. One customer commented on how using the “free Colorado wind” freed him from the toils of cranking a gasoline engine whenever he needed power – the wind dynamo system was design to operate in an automated fashion similar to conventional windmills (Righter, 1996). Still, 55 systems was a very small number and Fritchle's company went out of business the next year even after the Illinois windmill company Woodmanse (Righter, 1996) had acquired it.

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28 This estimate stems from a search of US patents from 1880 to 1973 using the search technique as described in chapter 2. The other 12 described vertical-axis machines of various types.

29 Of the remaining six horizontal-axis patents that used neither wind-wheel nor propeller-style rotors, two used European-style windmill configurations with multiple sails for the rotor blades. The remaining three used a turbine style of one sort or the other. One used an Archimedes style airscrew, another used a water-wheel style slatted configuration where the machine would be positioned perpendicular to the wind inflow, and the third used a more modern compressed air-intake style turbine with a shroud. Only one patent during the period used a propeller-style rotor configuration.
Other pioneers of unique wind dynamos configurations were more successful. George and Wallace Manikowske of North Dakota filed a patent in 1914 for a wind dynamo system where a large pulley attached to a ring near the edge of the rotor (of American-style configuration) and connected at the base to the shaft of a dynamo (Manikowske, 1916; Clipfell and Manikowske, 1920). The dynamo was set on a platform that shifts position with rotor speed so that the dynamo system acted like a belt tensioner similar to la Cour's "rocker belt" system to absorb gusts and system shocks.

The design was the result of several years of experimentation. A pitching mechanism controlled by a governor kept the machine rotating at constant speed and feathered the blades in high winds. The dynamo system was relatively separate from the rest of the machine design so that it could provide dual-use for both pumping and producing electricity. The machine received significant press when installed at the home farm of North Dakota Governor Lynn Frazier but by 1921; Manikowske has
installed his windmill system on many North Dakota farms and one farm outside of North Dakota (Burns, 1921). Though not a retrofit design, Manikowske understood that pumping water was still the most critical role for a windmill—in particular in the American west where such American-style mills had first been developed—and designed his machine with dual-use in mind. Righter suggests that Manikowske’s career in the wind-business was short-lived, but at least as late as 1927, he was actively engaged in the wind industry—participating in the American Society of Mechanical Engineers (ASME) Annual Meeting in a discussion on the work of Elisha Fales and working for The Aerodyne Company in Minneapolis, Minnesota where they were at that point developing propeller-type wind dynamos.

As with Fritchle and Manikowske, many machines patented through the mid-1920s focused on adapting electricity generation to traditional American-style windmills and even providing dual-use as water-pumping machines (Fessenden, 1917; Herwehe, 1918; Brady, 1918; Yanacopoulos, 1920; Taylor, 1920; Ford, 1927; and Silverstrin, 1927). There were varieties of mechanisms to connect the windmill to the dynamo. A few used rotor-edge-driven configurations. Some were traditional geared configurations with very detailed mechanical design (Fahle, 1918; Overstreet, 1920; Scholes, 1921; Terhorst, 1925; Williams, 1926; Richardson, 1927; and Fisher, 1927). Some involved pulley drive systems based on hub rotation like Fritchle or rotor-edge rotation like that of Manikowske (Howden, 1920; Beavers 1923) while others used the outer edge of the windmill affixed with magnets as the actual generator itself (Heyroth 1917a; Heyroth 1917b). Some devices even envisioned very interesting devices of converting the windmill rotation to translational motion back to the rotational motion for driving the generator to preserve the coupling to traditional pumping mechanisms (Miles, 1924; Somers, 1924) or attaching a device to the pumping line of the windmill (Beeson, 1925).

Figure 3-X: a) The Windmill dynamo device of Casper Miles for converting from rotational to translational to rotational motion for driving a generator (Miles, 1924), and b) The Windmill dynamo device of F. Beeson which attaches the dynamo drive to the pumping line of a traditional windmill (Beeson, 1925).
In addition to compatibility with traditional American-style windmills, some inventors sought to couple storage systems to their windmills including air compression (Ebert, 1919) or pumped hydro (Fessenden, 1917). Other efforts focused on the power regulation aspects of the machine and the electrical controls (Waters, 1915; Manning, 1920; Hoffman, 1920; Terhorst, 1926). In particular, a series of patents by Pittsburgh residents William Snee, John Snee Jr. and Thomas Kerr focused on the power regulation of windmill dynamo systems. The Snee brothers started out in development of wave energy systems that would have appeared at the time to be even more novel than windmill generated electricity. In 1908, they formed the Snee Universal Wave Motor Company and managed to obtain a letter from Pennsylvania Congressman W. H. Graham who suggested that President Theodore Roosevelt himself examined their technology and said that “he hoped [the Snee’s] would install a power plant somewhere along [the] Atlantic Coast, where the hitherto wasted energies of ocean waves and surf could be utilized to the saving of our deposits of coal now being depleted at such a rapid rate all over the country” ("Power Right Now", 1908). By 1910, however, the Snee brothers had turned to windmill dynamos, created the American Power and Manufacturing Company, and filed their first patent (Clements, 1911) related to a windmill-pump design for variable speed operation. Between 1912 and 1915, the Snee’s and Thomas Kerr filed several patents related to windmill dynamo controls for power regulation (Snee and Kerr, 1915; Kerr, 1915; Snee, 1921). It does not seem they ever sold their windmill dynamo machines – primarily focused on electric controls technologies, but it is possible that the power regulation control technology found use via license or other mechanism by windmill dynamo manufacturers during the period.

Various patents during the period also suggested the use of multiple rotor configurations including multiple American-style windmill rotors on a single tower (Mulrony, 1918; Calkins, 1921; and Fullwood, 1922) or even on vertical-axis machines (Brown, 1919; Manning, 1920; Yanacopoulos, 1920; and Fagan, 1925). An interesting novel machine of this type was the first patent that involved the use of a propeller-type rotor for a windmill dynamo. In this case, multiple propellers connected in series inside of a duct. Dew Oliver filed a patent for “Air Motor” machine in 1918 (Oliver, 1920; Oliver 1930) and the resulting “blunderbuss” machine has received criticism (Righter, 1996) but there were a few redeeming qualities of the device. Despite Oliver’s reputation as a “swindler” in the real-estate world in California, he successfully received a patent for his technology in 1920 and set up a demonstration in San Gorgonio Pass in California – now home to 100s of wind turbines. The whole machine was set-up on a track for rotation into the wind but winds in San Gorgonio pass tend to flow in a single direction such that a long ducted turbine would have seemed appropriate. The propellers, however, were spaced so close together and of a size within the tunnel that limited benefit would have accrued form the operation of the downstream turbines. Still, this may have been the first demonstration of a “wind-plant” consisting of multiple propeller-type wind turbines connected to a single electric collection system. Oliver was convicted of fraud in 1929 and his promises to create additional “Air Motors” were never realized, but Oliver’s early thinking about using propeller-style rotors for electricity production machines were at the forefront of developments that would continue throughout the 1920’s and beyond.
Along with start-up innovators, established windmill manufacturing companies entered the windmill dynamo space. Notable among these was the Perkins Corporation. In 1922, a seven-page article in the Farm Light and Power Yearbook, likely written by the company itself, touted the virtues of the “new windmill” for electricity production (“Wind Power Plants”, 1922). It suggested that wind energy technology was as old as the dynamo but the storage battery was necessary to enable the technology’s practical application to farm use. It also suggested early developments of wind dynamos were inadequate and represented the work of “kitchen mechanics that had little or no knowledge of wind pressures, surfaces and speeds... nor... friction” while the Perkins new Aeroelectric machine was designed particularly for electricity production (“Wind Power Plants”, 1922). Just as one would not take an “ordinary stationary gasoline engine, put it on a wagon body and make a practical motor truck,” coupling an “ordinary windmill” with an “ordinary dynamo” was bound to fail for the purposes of electricity production.
The Perkins machine did not appear to be revolutionary but instead included more advanced and tailored versions of current technology. The design included an anti-friction bearing as an interface between the wind-wheel and the gearing mechanism and the generator was specially designed by Westinghouse for the application to be a variable speed compound generator machine operating between 30 and 40 Volts-DC. On top of this, Perkins Corporation recognized the benefit of higher wind speeds accessible from higher heights and designed taller towers for the system than traditional water-pumping machines would use. The generator was rated at 1 kW that would have served as a decent supply for a battery bank used for electricity demand by a single farmhouse. Still, the controls were not as sophisticated as some of the other designs of the time as the farmer still had to reef "the wheel out of the wind when the battery is full charge" – no power regulation for over-charging the batter pack was included though a switchboard was included with the set-up that could disconnect the different electrical connections ("Wind Power Plants", 1922).

![Perkins "Aeroelectric" Windmill Dynamo switchboard ("Wind Power Plants", 1922).](image)

Perkins also offered a 110 V option for those farmers who could afford it (Righter, 1996). The company advertised the Perkins machine in the early 1920s, but by the mid-1920s and after, the use of American-style windmills for electricity production found a challenger from the new propeller-style technology that was influenced by the aviation sector. This new wave of technology represented a linking of the new science of aerodynamics with windmill technology. La Cour had paved the way and others, most
prominently Albert Betz of Germany, provided a new scientific foundation for future wind energy technology development.

3.3 After the Great War: Rural Electrification and Wind Energy in Europe

The installation of la Cour style windmill dynamos and wind motors in Denmark and surrounding areas represented a high point for commercial application of wind-generated electricity in Europe in the first half of the 20th century. As already mentioned, the demand for windmill dynamos and motors in Denmark peaked in the first two years of World War I and started to rapidly decline during the remaining war years and then plummeted after the war ended (Christensen, 2009). Many factories for wind motors in the early 1920s shut down or diversified into services and the production of other technologies (Christensen, 2009). Grid electricity by that time was accessible to 20% or more30 of the rural community in Denmark and there was a growing preference at the time for gasoline independent power plants over windmill dynamos and motors. Still, there were continued efforts in developing wind generated electricity plants in Denmark through the mid-20th century. One prominent example stems directly from the la Cour tradition with the Lykkegaard’s Machine Works that acted as a developer and owner/operator for its windmill dynamos. The DC machines would be placed at power plants and the owners charged power plants a fixed fee for each kilowatt-hour produced and guarantee 80% of a loan for the turbine cost and installation (Christensen, 2009). These production costs tended to be significantly lower than electricity costs at the time (DKK 0.08/kWh plus low daily maintenance costs versus DKK 0.30-0.70/kWh) and 40 Danish power plants used wind electricity as a supplement to other generation (both DC and AC generation systems) (Christensen, 2009).

30 Different projects for rural electrification in Denmark in the early 1920s range from 20% (Christen, 2009) to 50% (Evans, 1925).
Many of the installed windmill motors and dynamos of the early 19th century appeared to survive and operate to the mid-century (in 1945, 12,000 windmills were used on Danish farms of which at least 1,400 were used for electricity production) (Christensen, 2009). The surviving windmills served as a symbol of the Danish tradition in wind generated electricity stemming from the Askov Folk High School and the wind energy actor network created by Poul la Cour.

In Germany and other European countries, there was even less success in the commercialization of wind generated electricity plants. Rural electrification in Germany was even more fast paced than in Denmark with 50 to 60% of rural Germany having electricity by 1930 (Evans, 1925, Nye, 1992). Still, there were successful examples of wind plants in Germany including the installation of a 12 m diameter windmill dynamo in Högel near the Danish border in 1923 (Heymann, 1995). The 9.6 kW dynamo powered 300 lights and 14 engines for the community and continued to operate into the late 1930s. Other rural areas of northern Germany also continued to use wind energy for electricity generation and other purposes (primarily water pumping but also as motors) in the 1920s – a study by one engineer found 13 wind electricity-generation plants in northern Germany (Heymann, 1995). However, the commercial use of wind electric systems in Germany was only part of important role it would play in the history of wind energy technology in the first half of the 20th century. German scientists, in particular Dr. Albert Betz, would bring together modern aerodynamics with the study and design of wind electricity generation systems.
3.4 Aviation Technology meets Wind Energy Innovation in the 1920's

3.4.1 The Rise of Aerodynamics and Early Connections to Wind Energy

In the 1890s and early 1900s, wind electricity generation technology brought together existing windmill technology with new technologies in electricity. Most of the mechanical design of these new windmills did not vary from previously developed wind motors and windmills, but the complexity arose in bridging the design to the electric system and the controls in particular. Solutions for control involved both mechanical solutions (i.e. governors for regulating rotor speed and the la Cour "rocker belt" drive system) as well as electrical systems (i.e. "La Courscher key" and new electrical relay systems). Modern wind energy system design depends on understanding a number of disciplines. In addition to the electrical and mechanical design, the aerodynamic design of the machine is critical to machine performance – perhaps most critical. However, at the turn of the century, aerodynamics as a discipline was still relatively new. The only notable applications of the discipline of aerodynamics to wind energy up to that time were in the experimental and theoretical work of John Smeaton and Poul la Cour as well as the experimental work of Thomas Perry.

Looking back briefly into the history of aerodynamics provides an understanding of what knowledge was available to early inventors of wind electricity generation systems. If electricity was an invention of accidental discovery, human flight was perhaps one of the most purposeful inventions in human history. The flight of birds had long inspired man of the possibility of flight and “tower jumpers” throughout history sought to attain flight through imitation of bird-like features – notably their wings and feathers. Early designs for flying machines also sought to mimic birds via flight mechanisms where the same apparatus provided the propulsion and lift – da Vinci's work showed drawings of several such devices (Anderson, 1997). However, as late as the 18th century, little scientific knowledge existed concerning the fluid dynamics generally and aerodynamics in particular. Concepts of lift and drag comingled as one single fluidic force acting on a body and most interest was concentrated on “resistance” of bodies under the impact of fluid motion. Applications of fluid forces were important for machines in marine environments such as ships and water wheels as well as in air environments such as military projectiles or even windmills. John Smeaton's work, described in chapter 1, was an important step in the history of wind energy technology but also to the overall development of the science of aerodynamics. Firstly, he adapted and improved upon the “whirling-arm” test machine originally invented by Benjamin Robins in the early 1740’s to explore air resistance for projectiles (i.e. cannonballs) (Anderson, 1997). Just 15 years after Robin's work was reported, Smeaton was using an adaptation of the whirling-arm (which included a rotating miniature windmill rotor) to investigate forces associated with windmill operation and how variations in windmill design might affect performance (Anderson, 1997; Smeaton, 1759).
Figure 3-XV: Smeaton’s whirling arm mounted with a windmill rotor (Smeaton 1759).

In addition to showing for the first time the effect of camber (airfoil curvature) on improving windmill performance, he measured the force on a flat-plate perpendicular to the wind and proposed a formula for the force as a function of the area, the square of the velocity and a constant multiplier which became known as “Smeaton’s coefficient,” which, though erroneous, would be used in calculating aerodynamic forces through the early 20th century by the Wright brothers and others (Anderson, 1997; Smeaton, 1759).

In the early 1800’s, George Cayley of England would be the first to propose: 1) separation of fluid forces into ideas of a perpendicular force (now known as lift) and parallel force (now known as drag) relative to the incident wind direction, and 2) the design of a flying machine which would separate in the design of a heavier-than-air flying machine the means of propulsion to provide thrust and the means of providing lift (Anderson, 1997). Cayley first associated the camber of an airfoil with effects on the lift versus Smeaton’s observation on the effect of camber on windmill forces. From that time, scientific interest (both experimental and theoretical) in aerodynamics grew. The word itself entered the English language around the 1830’s (likely stemming from the French word aérodynamique or the German word aerodynamische) and professional societies for aerodynamic related studies were established by the mid-1800s. In the 1800’s there was still quite a gap between theoretical aerodynamics (led by the work of Claude-Louise-Marie-Henri Navier, George Gabriel Stokes, Hermann Ludwig Ferdinand von Helmholtz, Lord Rayleigh, Osborne Reynolds and others) and applied aerodynamics (which largely relied on
empirical findings like those of Smeaton, Cayley and subsequently Francis Wenham, Otto Lilienthal and others).

By the time la Cour performed his wind-tunnel experiments on wind turbines, a significant amount of new understanding about applied aerodynamics was available, and la Cour, who had studied in the fields of meteorology and who was an avid reader of scientific literature, was likely aware of many of these latest developments. The notions of partitioning the resultant aerodynamic force on a wing into lift and drag were well accepted by the late 1890’s having been first demonstrated by Cayley and then measured as distinct entities using vertical and horizontal springs in the first wind tunnel experiments of Francis Wenham and then again by Otto Lilienthal using a whirling-arm device (Anderson, 1997). There was some dispute during the time as the accuracy of new wind tunnel experiments and the validation of the da Vinci’s idea that “the same force as is made by the thing against the air, is made by air against the thing” did not occur until Gustave Eiffel’s comparative experiments in the early 1900s (Anderson, 1997). However, by la Cour’s time, wind tunnels were prevalent in the applied aerodynamics community and he chose to use them for his windmill experiments. Thus, we can evaluate la Cour’s experiments in the context of aerodynamic knowledge in the period.

Chapter 2 described la Cour’s aerodynamic experiments and his novel conclusions that fewer bladed turbines (1-4) would be more efficient at producing power than multi-bladed turbines. La Cour found that the airflow between the blades was also important to the power production and not just the airflow hitting the sails and suggested that shortly after passing by the rotor blade “the air particles... cause a vacuum by their inertia, which accelerates the sails and at the same time decelerates the air particles” (Nissen, 2013). This shows an understanding of the role of differential pressure and in particular the role of suction in producing aerodynamic lift that we know today to be the basic mechanism of wind turbine operation. Ideas of lift and drag where still relatively new concepts that were just gaining traction in the scientific community so la Cour’s interpretation of his results can be seen to be relatively independent of such understandings. Particularly in the millwright community, la Cour’s finding on the advantage of fewer blades was contrary to knowledge about windmills that estimated power production from a windmill as a function of overall sail / blade area (Heymann, 1995; Nissen, 2013). La Cour’s work was novel for the field of applied aerodynamics in suggesting a relationship between a pressure vacuum and aerodynamic machine performance. It is likely he derived this understanding from the work of Danish scientists Johan Irminger and H. C. Vogt who had found that a vacuum existed over the top surface of a flat plat for moderate angles of attack (Anderson, 1997). La Cour was familiar with the work of Irminger and Vogt (spelled Voigt in Danish) and in particular their ideas on suction. He mentions their findings in the description of his airfoil experimental test set-up: “Voigt and Irminger pointed out

31 John Smeaton had also found a similar effect though it was not a well-known component of his work (Heymann, 1995).

32 Horatio Phillips had found in his own wind tunnel experiments in the 1880s that pressure over the top of the airfoil was less than that of the free-stream flow but it was not until Gustave Eiffel performed detailed measurements of pressure on various points of a wind that a formal understanding of pressure distributions on the suction side of the airfoil was understood and found to play a key role in aerodynamic lift (Anderson 1997).
that such pressure is derived partly from Pressure on windward side and partly from the sink on the back side and the latter is often are larger than the first” (la Cour, 1900, p. 31).

Figure 3-XVI: la Cour’s airfoil experimental test stand (la Cour, 1900, p. 31). By adding weight to the scale to counter the lift and drag forces, la Cour was able to measure the resultant aerodynamic force on the airfoil.

Though theoretical aerodynamics had advanced substantially by that period, there were still no methods for using that work to predict actual aerodynamic performance of real machines and understanding about the role of pressure in producing aerodynamic lift was unknown. The best that la Cour could do was to show through his experiments that the previous ideas were invalid – indeed, an experiment which compared wind rose machine with a 6-bladed conical wind motor found a 30% increase in power output for the same rotor area and input wind conditions (Nissen, 2013).

In addition, la Cour also found the a similar result to the work of Cayley and others that concave or cambered sail profiles were advantageous for power production – thus further supporting the work of Cayley and Lilienthal and others who had shown similar results in their own experiments (Anderson, 1997). He did this first by using kinked plates and then curved plates and found in all cases that the loads were higher than in the case of the flat plat for equivalent wind speeds and angles incident to the flow. All of this work led to la Cour to construct his own theory of aerodynamics for windmills though

33 Thomas Perry used a whirling-arm type experiment using carousel to perform similar studies on airfoil shapes that resulted in the concave design of his all-metal windmill the “Aeromotor” (Heymann, 1995). This new design allowed Perry’s company to capture 50% of the wind market by 1900 due to the overall improved efficiency of their machine compared to the traditional flat-bladed wooden concepts. Going to a metal rotor allowed Perry to produce the rotor with the novel shapes inspired by his experimental work.
his findings and resulting theory did not gain recognition from the larger applied aerodynamics community and historical accounts of aerodynamic work in that époque.34

3.4.2 Propeller Design and a New Science for Wind Energy

La Cour’s work represented an important bridge between the new science of aerodynamics and the old technology of the windmill. Another important bridge under construction at the end of the 19th century was that between the science and design of propeller technology (for ship and submarine propulsion) and aviation technology (for propulsion of airships and airplanes). A gasoline-engine based propeller drive system was a critical enabling technology for heavier-than-air flight and work on propeller design was well underway by 1900 (Rosen, 1977). From the Wright Brother’s successful flight in 1903 through the end of World War I and after, the science and design of propellers advanced significantly. By the 1920’s, the state-of-the-art in propeller design would influence a new generation of windmill dynamos.

In the second half of the 19th century, an increasing number of aviation enthusiasts sought to create flying machines with steam-powered propeller-based propulsion systems. The first machines to use the technology for successful (untethered, steerable and controlled flight) were the lighter-than-air ship systems (airships). In 1852, French engineer Henri Giffard flew the first mechanically/steam-powered airship for 17 miles using a three hp steam engine driving a 3-bladed propeller (Rosen, 1977). The propeller blades were very much of the European style windmill with a narrow root and linear taper toward the tip. The overall steam-engine weighed 400 pounds for a power-to-weight ratio of 0.0075 hp/lb. (or 0.012 kW/kg) which is more than an order of magnitude lower than ratios of typical gasoline-fueled internal combustion engines used to power modern aircraft propellers (primarily due to the need for the boiler and condenser sub-systems of the machines). Early heavier-than-air machines such as Thomas Moy’s “Aerial Streamer” also used a steam-powered engine and flew 6-inches off the ground in a tethered flight35 (Rosen, 1977). However, the weight of the steam-engine was a certainly what Thomas Hughes’ referred to as a “reverse-salient” to heavier-than-air flight at that time and the solution to this would be found in the use of new internal combustion engine technology developed in the late 1800s that used the combusted gas to directly drive the motor. The lack of efficient propeller designs at the time was certainly another reverse-salient to heavier-than-air flight at the end of the 19th century.

The “Aerial Streamer” (see image) used two large 12-ft diameter propellers with adjustable slats to pitch the blades for increased thrust (Rosen, 1977). The design of the blades again mimicked European-style windmill propellers of the day with their narrow roots and wide tips in a multi-bladed rotor configuration.

34 For example, Anderson’s 1997 History of Aerodynamics does not mention la Cour though it does mention Voigt and Irminger.

35 There is some doubt as to whether the machine actually cleared the ground.
Figure 3-XVII: The airship of Henri Giffard that flew using a steam-engine powered propeller in 1852. The shape of the rotor is of a European-style windmill though with only three blades.

Figure 3-XVIII: Thomas Moy's "Aerial Stream" that was meant to be powered by a steam engine using two propellers each with six blades with pitchable slats for improving thrust at different speeds.
The propellers of Giffard and Moy were characteristic of propeller designs for flight applications in the late 19th century. However, soon attention would turn towards few-bladed propellers developed using a combination of aerodynamic experimentation and design theory. The experimentation contributed to design through the growth in use of wind tunnels to study the performance of individual airfoil shapes to create lift and drag profiles as well as in testing of the performance of various full propeller designs. The latter was particularly informative at a time when the theory of propeller aerodynamics was still premature. While methods did exist for theoretic design of a propeller, as will be discussed, they had by no means gained general acceptance by the design community. An early book on *How to Build an Aeroplane* suggested that "Propeller theories are nowadays very numerous, and all have good points; but unfortunately they do not always agree in their most important features, and should always be look upon with suspicion" (Petit, 1910). Thus, building and testing a propeller design was the only method to evaluate its performance.

Still, some methods became popular and one in particular found use not just in designing airplane propellers but in designing a new generation of propeller-style windmill dynamos as well. In 1909, Stefan Drzewiecki published his *Des Hélices aériennes, théorie générale des propulseurs hélicoïdaux et méthode de calcul de ces propulseurs pour l'air* that provided a general theory of helical propellers and methods for calculating their performance useful in design. We now know this theory as "Blade Element Theory" and it is one-half of the all-important "Blade Element Momentum Theory" used in analysis of propellers for airplanes, helicopters and wind turbines. English hydrodynamicist William Froude had suggested a similar theory in the 1870s related to propeller design for ships. Drzewiecki, who moved to studying propellers for flight after spending many years working in the submarine space, was likely familiar with Froude’s work. Still, Drzewiecki first made the theory widely accessible with the publication of his methods and their translation into various languages.

Froude was also the first to tie blade element theory for individual blade elements with momentum theory for analysis of overall rotor performance. Momentum theory was first developed for naval applications by Physicist William John Rankine in 1865 and then further developed by British naval engineer Robert Edmund Froude (unrelated to the first) in the 1880s (Leishman, 2002). Momentum theory treats the propeller rotor as an infinitely thin disk over which a pressure difference exists, and that the pressure difference is created by the rotation of the rotor and the corresponding effects on airflow across the rotor plane. German Aerodynamicist Albert Betz adapted this theory to assess the performance of an ideal wind turbine rotor in his 1919 PhD thesis. Similar to Smeaton and la Cour

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36 At the time when the Wright brothers were designing their propellers, they did not have any suitable methods available and created their own similarly relying on a blade element approach. The approach itself was not published or widely publicized but according to Anderson (1997) it was quite sophisticated and allowed an impressive degree of accuracy between theoretical performance predictions and actual performance. The Wright’s also influenced the modern design of propellers by moving from small diameter fast-rotating propellers to large diameter slow-rotating propellers which allowed them to achieve thrust efficiencies of 66% and higher (much higher than typical performance of other propellers at the time) (Rosen, 1977).

37 Also known as Froude’s Momentum Theory, Actuator Disk Theory or Froude’s Actuator Disk Theory

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before him, Betz would look to apply contemporary knowledge in aerodynamics to the study and design of windmills. His work provided the first concrete intersection of modern aerodynamic science and wind energy.

Betz became interested in wind energy early on in his career as part of Ludwig Prandtl’s Aerodynamische Versuchsanstalt (AVA), the premier German aerodynamics laboratory in the early 20th century located at the University of Göttingen. Ludwig Prandtl is one of the most famous aerodynamicists in history and his laboratory for aerodynamics research, the AVA, was the world-center for theoretical aerodynamics in the early part of the 20th century. There is a long list of students who worked with Prandtl (85 doctoral students in total) and many, like Betz, became leading experimental and theoretical aerodynamicists. Betz worked with Prandtl on various topics including lifting-line theory (also known as Prandtl wing theory or Lanchester-Prandtl wing theory) which uses the concept of circulation to predict the lift distribution over a three-dimensional wind (Anderson, 1997). Betz first discussed in a 1917 confidential publication the lifting-line theory to airfoils of arbitrary (non-elliptical) shapes. In 1919, Betz received his PhD for his work in the area of calculating lift for a finite wing with a given shape and angle of attack (Anderson, 1997) and would continue to work in the AVA for much of his career. In 1936, Betz took over Prandtl’s position as head of the AVA and continued to lead scientific work related to aerodynamics and aviation technology for military applications throughout the Second World War. However, due in part to the effect of the World War I coal shortages which “intensified the search for new sources of energy” and “the impression that the lessons learned in aeronautics would produce a considerable improvement in windmills”, Betz focused significant research effort on aerodynamic models of windmill performance and momentum theory in particular (Betz, 1927).

Betz understood that the decision for wind energy was an economic one – a quest “to obtain the maximum output with the minimum investment” in order to harvest the “immense quantities of energy in the great ocean of air” (Betz, 1927). He also identified the same system design challenges that were identified by Nollet including the overarching objective of cost to “make the ratio of the investment to the annual output as small as possible” as well as related objectives of reliability under extreme conditions and the need to provide consistent power through the use of storage batteries – which he recognized also added considerably to the overall system cost (Betz, 1927). All of these objectives (low cost, high reliability and consistent power) had been identified previously but to these Betz also added the recognition of design of the machine for a specific site and wind resource since “it is hardly possible to so construct a windmill that it can utilize both very weak and very strong winds” (Betz, 1927). Wind turbines today are designed for a specific “wind class” that represents a specific type of wind site with similar wind resource conditions; there is no universal wind turbine that performs at low cost for all sites. Betz was perhaps the first to recognize the need to account for geographic heterogeneity in wind system design. He noted that machines should be designed for specific wind velocities (for windmills at heights typical of this period Betz suggest that the velocity would be 3-10 m/s for inland applications with slightly higher velocities near the coast).
Figure 3-XIX: Addition of design considerations that take into account functional and geographic heterogeneity of wind energy system design applications

Whereas la Cour was interested in teaching practical design of windmill dynamo systems, Betz was primarily interested in informing the design of windmills for electricity production with state-of-the-art theories in aerodynamics. His dissertation and subsequent book material provided a basic foundation for the aerodynamics of wind turbines and demonstrated 1) the higher energy efficiency of lift-driven over drag-driven machines, 2) the ideal efficiency of a lift-driven wind machine as 16/27 or 59.3%, and 3) comparison of different types of rotor designs in terms of their lift and drag coefficients and overall energy efficiency (Betz, 1927; Betz, 1926a; Betz, 1926b).

Scientists established the separation of aerodynamic force into components of lift and drag by the early 20th century and practitioners such as Octave Chanute, the Wright Brothers and others (Anderson, 1997) had codified the terms. Betz work on power extraction first began with an example comparison of a sailboat style machine driven first by a flat plat perpendicular to the wind (completely via drag force) and then a more aerodynamic structure driving the machine by lift. Windmills, on the other hand, involved movement in a "closed circuit" and thus the power extraction could be calculated based on the airflow moving through the rotor plane which could be imagined using momentum theory as "a perforated disk, which exerts a retarding effect on the air and thereby extracts energy from it" (Betz, 1927). To simplify the analysis, Betz ignored the angular momentum and tangential forces of the rotor so that his calculations represented an unrealizably ideal case for windmill power extraction. For this, he imagined "a stationary rectifying device installed behind the windmill to restore the air current to its original direction" (Betz, 1927). By considering the mass flow and velocity change across the rotor plane, Betz was able to establish a relationship for energy production as a function of the ratio of initial to final velocity:

$$L = \frac{\rho A}{4} \left(1 + \frac{v_2}{v_1}\right) \left[1 - \left(\frac{v_2}{v_1}\right)^2\right]$$
Where $l$ is the energy per second (power), $\rho$ is the air density, $A$ is the rotor area and $v_1$ and $v_2$ are the initial and final velocities respectively. By taking the derivative with respect to $v_2/v_1$, the optimal ratio comes out to be $1/3$ and overall maximum power could then be found as $16/27$ or $59.3\%$ of the overall power in the wind (Betz, 1927). This provided an important benchmark known today as the “Betz limit” for maximum power extraction of a wind turbine from the incoming air flow.

While the result was theoretically interesting, it did not provide much insight into design of windmills for electricity generation or any other purpose. Perhaps more important from a practical design standpoint was Betz’ extension of his work to analysis of machine rotational speed and dimensioning of the rotor vanes (blades). Betz showed that power extraction from a blade depended on both the blade area and its rotational speed relative to the incident wind (which varied along the span of the blade), and he established an inverse relationship between the lift coefficient for a blade section, the number of blades and the rotational speed of that section:

$$c_t \frac{nt}{2\pi r} \sim \left(\frac{v}{r\omega}\right)^2$$

Where $c_t$ is the average lift coefficient for the blade section, $n$ is the number of blades, $t$ is the thickness of those blades, $r$ is the mean radius of the section, $v$ is the incident wind velocity and $\omega$ is the rotational speed (Betz, 1927). From this it is evident that to obtain a constant lift coefficient along the blade span, the thickness must increase towards the hub similar to what Sperry found in designed his wind driven electricity generator for aircraft. In real cases, Betz noted that it was not possible to design a blade profile near the hub that could generate energy efficiently and indeed rotors at the time had blades that began somewhat outboard of the hub center. Furthermore, the inverse relationship between tip speed (defined as $u_t = R\omega$ for rotor radius $R$) and the overall blade density ($\frac{nt}{2\pi r}$) is evident as well so that for the same thickness to achieve a certain lift coefficient for a certain incident wind speed, the rotational speed necessary will increase for a decreasing number of turbine blades. Today we know that turbines with fewer blades operate more efficiently for higher tip speed ratios – a result first demonstrated by Betz.

This also meant that to achieve a given efficiency, a higher rotational speed and tip speed would require blades of smaller area (which would reduce the weight of the blades and make the windmill “correspondingly simpler”) (Betz, 1927). In addition, Betz also stated that a higher speed windmill would have a smaller gearbox (with a smaller overall gear ratio) to increase the speed to the high-speed generator input shaft. Today, the trade-off between the maximum allowable tip speed design of a wind turbine (which is a significant factor in determining turbine aeroacoustic noise) and overall machine design and cost is still an important design consideration. Betz first recognized this important trade-off in system design. However, Betz also noted limitations of high-speed designs including complexity in airfoil design, higher centrifugal forces on the machine, and higher starting wind speeds. Finally, Betz categorized windmills according to their design tip speed ratios to create a classification system for archetypical windmill configurations that is still in use today. Betz in particular identified four categories based on common tip-speed ratio regimes:
1. \(1 < \frac{U_0}{V} < 2\); low-speed windmills (American-style wind rose windmills which the NACA translation referred to as “wind turbines”)

2. \(2 < \frac{U_0}{V} < 3\); transition-speed windmills (the “old” European-style 4-vane windmills)

3. \(3 < \frac{U_0}{V} < 4\); high-speed windmills

4. \(4 < \frac{U_0}{V}\) (very-high-speed windmills of which Betz only was familiar with a few in existence at the time)

Betz was able to show how his principles worked in practice through a series of tests in the famed Gottingen wind tunnel for very low-speed (wind-rose style), “modern medium type” (few blades), and an “extremely high speed windmill” (two-bladed propeller-style). Preliminary results reflected Betz’ theoretic findings in that the wind-rose machine performed best at lower tip speed ratios and the 2-bladed machine performed best at much higher tip speed ratios. He was also able to show an overall improvement in the lift-to-drift ratio moving to the higher speed machine for improved power extraction efficiency. Similar charts that show lift and drag performance for different windmill rotor archetypes have been used to justify windmill rotor configuration design even today. Below are the charts machine designs and charts from Betz’s 1926 publication.

Figure 3-XX: Betz test turbines with the corresponding design of airfoils at points A and B respectively along the blade span.

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38 The aircraft windmill generators of the time would have fit into this last category but it does not appear that Betz was familiar with such machines at the time that he wrote his thesis and book. There is no mention of such machines in any of his materials and as earlier discussed the technology came to the United States through French influences – likely as part of knowledge transfer in the aviation sector within the Allied Powers during World War I.
Figure 3-XXI: Lift coefficients and drag coefficients at different tip speed ratios for each of the three test windmills. The lift to drag ratios for the 2-bladed design are generally better than both the 4-bladed and 12-bladed designs though as can be seen, the lift for the machine is low until high wind speeds (above 3 m/s) are reached.

Betz’s ideas and in particular his theoretic maximum for windmill efficiency were not immediately adopted or even accepted. In a very public debate, one windmill design practitioner, Kurt Funger, openly challenged the 59.3% finding from Betz work and suggested that efficiencies of 80% were obtainable even by current designs (Heymann, 1995). A “newspaper war” resulted in which Betz and Funger argued their respective points and Funger tried to use aerodynamic principles stemming from the older collision theory to demonstrate why the Betz limit did not exist (Heymann, 1995). In the United States, Fales ran similar tests to Betz on various machine configurations using the McCook Field wind tunnel and found power coefficients upwards of 80% (see figure below from Fales 1927).

However, the equation used for calculation of the power coefficient was not accurate and using the correct equation for power in the wind, the results would be divided by a factor of ~2.1 so that the experimental results for the 2-bladed machine had a maximum power coefficient of ~36% which would have been a reasonable efficiency for an aerodynamically-designed 2-bladed propeller-style machine at the time. In the same paper, Fales states that “Using the Froude momentum theory, the maximum energy recoverable from the wind has been determined by Betz, Munk and Hoff as 0.593 times the kinetic energy of motion” (Fales, 1927). Betz work on windmills was translated as a NACA report in 1928 (Betz, 1926b) though it appears that Fales was familiar with his research even before that report. Still, it would take some time for scientists to accept the Betz’s theory as a “rule” for wind turbine design and others at the same conference (George Manikowske) claimed machine efficiencies of 78%.
3.4.3 Windmill Propeller Rotors in Denmark and Germany in the 1920s and 1930s

This new environment of propeller technology and design helped to shape post-war wind energy technology. The work of Betz did not immediately affect wind turbine design but experimental findings similar to the above would encourage increasing use of propeller-style windmill rotors and their associated design processes. The wind driven generators for aircraft developed during the war in France and the United States were the first example of propeller-style rotors for windmill dynamos but soon after the war, similar technology would start to appear in Denmark and Germany. The Aggrico windmill, developed by Danish engineers Johannes Jensen and Poul Vindig, was perhaps the first aviation technology inspired windmill system in Denmark and could be used directly as a motor, for pumping water or for production of electricity (using either DC or AC power) (Thorndahl, 2009). The machine represented perhaps the first time a windmill drove an AC generator. In one case, an Agrico windmill was used by the NESA electric utility company (now Dong Energy) in Buddinge, Denmark to power a 40 kW induction (asynchronous) generator at a relatively high voltage of 10 kV (Thorndahl, 2009). The windmill still had a relatively large number of blades (5) but the blade design mimicked the aerodynamic design of airplane propeller blades – a so-called “propeller-mill” (Heymann, 1995). It also featured an active yaw control system using two fantails rotors perpendicular to the rotor plane and a centrifugally governed pitch system similar to other windmills at the turn of the century (Thorndahl, 2009). From their familiarity with propeller design, Jensen and Vindig were familiar with the concept of the angle of attack and how the speed of the machine would change this – causing stall as wind speeds grew higher and higher – and the pitch regulation was used directly as a means to counteract the deterioration in performance at higher speeds (Heymann, 1995).
The Agricco windmill had some success even in the post-war period where diesel fuel was particularly cheap. The company sold hundreds in the early 1920s including both in and outside of Denmark — including to colonial establishments as far as Thailand (Heymann, 1995). Perhaps the most important contribution of the Agricco windmill was directing millwrights towards new aviation technology. Tests on the Agricco windmill in the early 1920’s in Denmark showed that the windmill had about doubled the efficiency of both la Cour style windmills as well as American-style wind-rose windmills (Thorndahl, 2009). However, mills was considered to be generally not as good as the la Cour style mills — though the Agricco motors had been under development for a much shorter time period (Heymann, 1995). The Agricco mill developed prior to the publications of Betz relating to windmill performance. German engineer Kurt Bilau, on the other, would benefit from both knowledge of and collaboration with Betz and his “ideal windmill work,” and indeed marks the first case where the formal academic community in modern aerodynamics interacted directly in a mutually beneficial structure.

Bilau was directly inspired by the Agricco machine and filed for a German patent related to aerodynamic blade design (Heymann, 1995) as well as multiple patents in the United Kingdom related to pitch regulation of the blades (Bilau, 1922; Bilau, 1926). Bilau, who came from modern day Poland, was an engineer and soldier in the First World War and became interested in wind energy shortly thereafter. Bilau developed his “aerodynamo,” a 4-bladed aerodynamic propeller-like downwind rotor fit to a 40 ft. thin monopole tower with supporting guy-wires (“Now for the Aerodynamo Windmill”, 1925). The rotor diameter was approximately 9 m and the overall machine power efficiency was estimated at about 40% - about twice the efficiency of la Cour style windmills and 4 times the efficiency of wind-rose style windmills (“Now for the Aerodynamo Windmill”, 1925; Heymann, 1995; Hütter, 1954). The machine
demonstrates many features of modern windmill design including the general blade profile using aerodynamically designed airfoils at each section that increase in (chord) length moving from tip to one-fourth the span/length of the blade and then diminishing to the root. There are fewer blades much like a high-speed machine design of Betz with a tip speed ratio of 3 to 4 and even the use of the monopole with the generator mounted on the nacelle of the turbine with a gearbox for translating the lower speed of the turbine rotor to the high speed of the generator. This is not surprising since Bilau conceived of and designed his machine largely at the AVA through many wind tunnel tests that used knowledge transfer from Betz (“Now for the Aerodynamo Windmill”, 1925; Heymann, 1995). Bilau’s design was even featured in Betz book on wind energy in 1926 and Bilau himself published a book on wind turbine theory and practice in 1927 (Betz, 1926; Bilau, 1927). Whereas in la Cour one found a union of aerodynamics and machine design, Betz and Bilau together provided specialized competence in the respective areas and created a similar network in terms of building the understanding and science of wind as well as promoting its deployment.

Bilau went further to improve the aerodynamic performance of his design and the power regulation in particular though the development in the late 1920’s of the “Ventimotor.” The new machine design again featured an aerodynamic 4-bladed propeller-style rotor but in this case the blades of 25 ft. (7.6 m) in length for an overall rotor diameter of about 16 m were manufactured from aluminum in two separate parts: a front plate and an adjustable aileron-style rear plate (Heymann, 1995). Again, the interaction of Betz and Bilau is apparent in the design. Firstly, the use of the AVA facility for wind tunnel tests provides a direct connection and then there is the aerodynamic design of the blade profile. Beyond this, there is the two-piece structural design of the blade with the adjustable aileron-style rear portion to adjust the airfoil shape for better aerodynamic performance over a range of wind speeds. The use of the two-piece structure introduced a slot into the airfoil shape and this slotted aileron-style airfoil structure happened to be a subject of Betz publications and work in 1927 (Betz, 1927). Rather than a stand-alone machine as with his first design, the new rotor would retrofit to existing tower-mills. It appears that the aluminum construction and overall cost of the machines were prohibitively high and that retrofitting existing windmill structures provided a better avenue for introducing the technology (Heymann, 1995). Many such Bilau-style rotors, such as the one shown to the right below, exist on old tower windmills in Germany even today.
Comprehensive tests compared wind-rose windmills, Ventimotors, Agricco motors and Aerodyamos, and though tests were inconclusive, the new aerodynamic style wind turbines had better overall production per unit area than the older wind-rose rotor machines (Heymann, 1995). Still, Bilau’s efforts never met with large-scale success. There appears to have been patent disputes between Bilau and the Aero-Dynamo Limited company of England that filed a patent based on Bilau’s control technique, and the courts eventually decided in favor of the English company (Heymann, 1995). In the end, Bilau proved to be a champion of wind energy in Germany up to World War II and his firm, where he continued to serve as an advisor until his death in 1941, Ventimotor GmbH would continue to develop wind turbine technologies even after the war (Hüter, 1954). Throughout the 1920s and 1930s, a small contingency of engineers and enthusiasts would continue to promote wind energy technology development and deployment influenced by the new era of propeller-style rotor technology.

Of these enthusiasts, the most prominent (or most notorious) was Hermann Honnef. He was a champion for wind energy technology with many fantastic designs that he patented in Germany, the United States and other countries. The work of Matthias Heymann has documented Honnef’s failed efforts in some detail. In particular, he was able to capitalize on state concerns over German economic self-sufficiency that were catalyzed during the first World War, in the aftermath of the signing of the Treaty of Versailles, and in the global economic crisis at the end of the 1920s and early 1930s. Each of these national crises highlighted energy independence in spite of the fact that by that time large utilities had created a vast centralized grid network in the country (Hughes, 1983; Heymann, 1995). Within this context, Honnef began promoting his ideas for gigantic multi-rotor power plants with towers hundreds
of meters high with diameters of over 100 m providing multiple MW of capacity (Heymann, 1995). The idea was that only very-large power plants could successfully compete with coal-fired electric generation, and thus the leap in size (in all dimensions) seemed justified. Honnef published a book in 1932 giving a full discussion of his plans including detailed economic analysis. In particular, Honnef's analysis emphasized that moving to higher heights would allow access to faster, less turbulent winds that were necessary for wind energy to compete economically with coal (Heymann, 1995). Not only this, Honnef used knowledge of Betz theory and the aerodynamics work of the AVA to design his rotors and was informed by past work on wind energy to design his overall system including the electrical characteristics, dimensioning of all the components, and all other engineering aspects including loads calculations, analysis of materials costs, etc. (Heymann, 1995). It was perhaps due to the extensive nature of his plans and the detailed scientific analysis that he was able to generate significant interest in his plans at the state level.

Figure 3-XXV: Image of one of Hermann Honnef's wind power plant design concepts with a very large lattice tower and multiple rotors each with two counter-rotating individual rotors supporting a ring generator at their intersection. The frame would tilt out of the wind vertically (as shown above) or tilt into the wind horizontally for operation.

The main technical characteristics involved the multiple large rotors on a tall tower that would normally be of horizontal axis construction and where the whole system would be actively yawed into the wind. On each rotor was a ring generator (a concept which had been proposed before in the early 1900s) but in this case the ring generator was driven by two separate counter-rotating rotor sets so that the relatively speed of the generator would be the sum of the magnitude of speed of the two rotors. Such a design featuring magnets along a circumference would no doubt be quite heavy and the overall scale of the system was quite fantastic involving an order of magnitude or more in scaling from current sizes for
windmill electric generation plants. Still, Honnef suggested that a 15-year timeline was achievable in terms of realization of his plan and he presented his views and the corresponding book in various lectures to a wide variety of audiences including community members, academics and even politicians.

His plans, however, were somewhat compromised by the fact that at the same time he was seeking state-support, he was facing charges related to bankruptcy and other economic difficulties. He presented his proposals to the state but received criticism in particular with respect to: 1) the large loads in the system that were difficult to conceive of a priori and led to doubt about the structural integrity of the design, and 2) the ability for the generator design with such a large radius (i.e. 60 m) to maintain in the counter-rotating scheme the necessary air gap (i.e. 25 mm) between the two rings over the entire circumference under all operating scenarios (Heymann, 1995). Further concerns related to having the generator areas themselves exposed to the elements such that the generator would require being enclosed creating further complexity in the design. Various authorities who evaluated the plans repeated these criticisms. Still, over the years, Honnef was able to acquire millions of German marks for the exploration of his ideas – none of which were ever built though some wind tunnel testing at Gottingen apparently took place. He also received several patents for his technology in Germany and the United States that he was able to use to combat other would be wind energy champions in Germany during that period.

He filed his first US patent in 1931 and it displayed all the general characteristics of his plans including the large tower frame supporting multiple rotors with the tilt mechanism and the dual-ring structure for the counter-rotating dynamo (Honnef, 1934b). Subsequent patents filed in the US provided more detail on various features and options to the same basic system including the dynamo structure (Honnef, 1934a; Honnef, 1939b; Honnef, 1940), electrical connections of the generator (Honnef, 1941), and overall integration with a power plant for hydrogen production (Honnef, 1939a). Hydrogen production was another feature of Honnef’s overall plan for using wind energy to create a self-sufficient German energy economy (Heymann, 1995).

Figure 3-XXVI: Patent drawings for Honnef’s "Power Tower" and the ring generator with counter-rotating multi-rotors on a multiple rotor tower (Honnef 1934b, 1934a).
Despite Honnef’s acquisition of patents and general ability to market his ideas to a wide audience, his ideas were never widely adopted at the state level in a way that would have provided him the necessary capital to build one of his wind power towers in the 1930s. Centralized electricity was too widespread and concerns about fuel-shortages were not high enough to merit serious consideration of development of large-scale wind power plants. The case in Denmark was quite similar. As mentioned before, even where the grid was not accessible, diesel power systems had all but eclipsed the demand for wind-generated electricity in Denmark and most factories, with the exception of Lykkegaard, had shut down operations by the end of the decade. Thus, for multiple reasons – whether due to the growth of centralized grid networks or the relatively low cost and accessibility of independent diesel power plants – wind electricity in Europe in the 1930s was becoming a “thing of the past.”

3.4.4 Windmill Propeller Rotors in the United States in the 1920s and 1930s

In the United States, the opposite was the case as the 1920s provided the first opportunity in its history for a stable windmill dynamo market. The development of so-called “wind chargers” would take rural America by storm and provide many families access for the first time to electric power for home radios and lighting. The development of this new technology was influenced by aviation technology but largely independent from the development in Europe of Bilau’s “Aerodyanmos” and “Ventimotors” and the work of Betz. There was only minimal influence of Betz and the AVA on the American wind charger experience through Fales work. Conducted in conjunction with Wright Field test facilities and the military, Fales research and experimentation served as a conduit to the United States the theoretical aerodynamics work of the AVA and Betz. However, Fales was not heavily influenced by Betz’s work and described how for very high-speed machines (i.e. with tip speed ratios greater than 4) that using Drzewiecki method was inaccurate and the only real option at the time for assessing the performance of a particular machine would be to build it and test it in a wind tunnel (Fales, 1936). Thus, wind electricity generation machines in the United States in the 1920s and 1930s tended to borrow more from applied aerodynamics and the use of testing facilities than the theoretical foundations that were still in the early stages of development. This new generation of small propeller-style windmill dynamos came to be known as “wind chargers” and hundreds of thousands of the small machines diffused across rural communities for electricity applications.

As mentioned previously, the first application of aviation technology to wind energy in the United States was through the development of wind driven electricity generation systems for aircraft. Based on patent filings in the United States from 1910 to 1940, a general transition exists from the older wind-rose style windmills towards new aviation inspired propeller-style windmills. The first propeller-style patents came from aircraft applications (Sperry with the earliest in 1916) but by the late 1920s, the number of propeller-style patent applications began to outweigh those of traditional windmills – a trend that continued through the 1930s and after.
Some of the early entrants into the new propeller-style windmill space were not surprisingly those who had experimented originally with windmill dynamos based on traditional American-style wind-rose configurations. One example was George Manikowske who was at the time affiliated with the Aerodyne Company that may have been an outgrowth of the earlier Aerolite Wind Electric Company (Fales, 1927).

In 1927, he was involved with the development of single and two-bladed propeller machines designed to operate in wind speeds of around 8 mph. Manikowske emphasized that the ability to utilize low wind speeds was particularly important in order to provide a consistent enough supply to the batteries to not discharge them to very low levels too frequently (Fales, 1927). It was an interesting argument — indeed most windmill dynamos of the time charged batteries and a machine to operate in lower wind speeds would operate more frequently. Manikowske thus highlighted the trade-off seen by Betz in terms of designing a wind turbine for a particular wind speed regime. However, it does not seem that his propeller-style machines were any more successful than his wind-rose style machines as there is not much of a historical record of the deployment of these Aerodyne machines. In particular, he began investigating and patented an interesting double-rotor set-up with two propellers in series that rotated in opposite directions from one another that from today's perspective would seem a rather odd set-up with complex interaction of the flow and the two rotors (Manikowske, 1933). Only a few years later in 1927, Manikowske filed another patent using only a single two-bladed propeller on a windmill electric generator with a pump attachment for dual-use as a water pumping system (Manikowske, 1934). Eventually his company Aerodyne began to produce a three-bladed machine that became available in two different sizes of 1 kW and 2.5 kW respectively (Wincharger.org, 2016). However, this double-rotor concept would appear in various patents including in a patent filed by Fales as one of several configuration options for of a propeller-style wind turbine (Fales used the term high-speed turbine to
describe his machine) (Fales, 1930; 1936). Fales continued his career in military research and did not apparently have success if he did try to commercialize any of his wind machines.39

A more successful story is that of Herbert E. Bucklen who installed HEBCO machines throughout the west including powering lights for remote airfield landing strips (Righter, 1996). Herbert E. Bucklen Jr. was the son of successful businessperson and medical doctor Dr. Herbert E Bucklen in Elkhart, Indiana. His father had become wealthy for selling a patented medicine the “Arnica Salve” which is similar to today’s “Alka Seltzer” medicine (Kiracofe, 1954). He then used his fortune to invest in real estate and railroads, was responsible for the development of the Elkhart line to Mishawaka, and provided Elkhart citizens a chance to attend the Chicago World’s Fair in September of 1893 (Kiracofe, 1954). It is likely that his son Herbert Jr., age six or seven at the time, would have attended the fair with his father and seen the massive display of windmills at the event. During young Herbert Jr.’s life, his father owned much of the town and named it after himself – including Bucklen Hotel and the Bucklen Opera House. Herbert Sr. passed away in 1917 and his son sold most of his real estate holdings, but he left his son and family as local royalty providing Herbert Jr. with the means to create his own path to success.

![Figure 3-XXVIII: H. E. Bucklen Corporation advertisement for their medicines at the Chicago's World Fair of 1893.](image)

Herbert Jr. would go on to create his own legacy first in automotive trucks, then wind chargers and later in electric switching equipment. In 1912, Bucklen Sr. agreed to fund with his son a new company Bucklen Automotive Manufacturing Company that would produce five different truck models and Bucklen’s first patents relate to automotive engines. The company was apparently eventually renames the H. E. Bucklen Jr. Motor Truck Company emphasizing Bucklen Jr.’s role as the leader of the technology-based company. In He began to manufacture his HEBCO wind chargers in the 1920s under the Herbert E Bucklen Company name of his father and in 1935 would go on to found an electronics switching company, Durakool, which would become a very successful company eventually run by his son.

39 A 1925 patent for a one or two-bladed turbine was assigned to Fales from his colleague H. R. Stuart who had been involved in much of the wind tunnel testing work in the 1920s (Stuart, 1931). The design appears to have been very similar to those promoted by Fales in his papers – a high-speed machine meant to directly drive a small DC generator.
Hebert E. Bucklen the 3rd and then merged with the American Electronics Company, Inc. which would continue to supply their high-performance industrial relays and switches under the Durakool name. Over his lifetime, mainly from the 1920s through the mid-1940s, Bucklen Jr. received nearly 40 patents in areas related to internal combustion engine technology, shock absorbers, wind chargers and electronic switching and relay equipment.

Sometime in the early 1920’s Bucklen had become interested in wind energy and apparently started producing machines under the name HEBCO around 1922 (Righter, 1996). Twelve of his patents (all filed between 1925 and 1930) related to wind energy electricity generation. For perspective, the total patents tied to wind energy electricity generation during the same period were 44 such that over a fourth of these patents were from Bucklen and his partners. Bucklen filed the single largest number of patents relating to wind energy electricity generation up to that time – a number only surpassed by one other US inventor up to the 1970s oil crisis. His first patent in wind driven electricity generation technology in 1925 featured a conventional wind-rose rotor configuration though it hinted that the inventor was considering the use of a two-bladed or three-bladed system in practice (Bucklen, 1929b). In fact, a patent filed by Bucklen the same day for a “windmill drive” featured a two-bladed propeller-style rotor for a pump system (Bucklen, 1930a; Bucklen 1932). The propeller-style rotor and electricity generation mechanisms would converge almost immediately thereafter in his two-bladed high-speed wind dynamo system.

Figure 3-XXIX: US Patent 1699949 (Bucklen, 1929b) features Bucklen’s first wind charger design with an old wind-rose style rotor and his new propeller-style rotor design for a wind pump system (US Patent 1755422, Bucklen, 1930a) filed on the same day.

The main area of innovation for Bucklen’s machine had to do again with the development of the propeller-style rotor. There were a few prior examples or propeller-style windmill dynamos like those of
the aircraft generators and another early patent by North Dakota resident Edwin Olson (Olson, 1928) featured rotors with integrated two bladed propeller shaped from a single piece of wood (for a fixed pitch design). Bucklen’s initial concept appeared to include two separately manufactured blade pieces that could be pitched during operation to achieve a desired angle with respect to the wind inflow. Not only this, his blades were manufactured from a uniform thickness sheet metal which was meant to promote ease of manufacture of the rotor (Bucklen, 1930a; 1932). However, such a metal propeller (as found by Bilau and others) was heavy and increased overall costs. Bucklen proposed another solution in a patent filed in 1926, perhaps the first, for a propeller made of composite material. In particular, Bucklen was interested in overcoming the resistance of the heavy metal propeller to operation in lower wind speeds (8 to 10 mph or 3.5 to 4.5 m/s) and having a lighter rotor that would accelerate faster as wind speeds increased (Bucklen, 1928). Not only this, a lighter rotor had the advantage of lower aerodynamic loads at higher speeds that were better for overall system reliability. His composite propeller involved a mixture of cork and cement that would be formed and set in a mold over an integrated hub and reinforcing arms (made of wood or cast metal) – a relatively straightforward and repeatable manufacturing process.

Still, it was likely that there were issues with this design as another patent was filed by Bucklen with his colleague Harlie O. Putt on a propeller-style rotor design based in this case on glued balsa wood panels that permitted “the proper contour, pitch and camber to be secured without excessive machine work or carving” and provided “an impeller of light weight” with tough outer layers of wood covered in coats of varnish or a metal-spray to improve durable in harsh climates (there was even the suggestion of adding a copper covering towards the tip of the propeller for protection) (Bucklen, 1931a). This new design represented an improvement which could “stand up in wind velocities which wreck the windmills of [Bucklen’s] prior art” (Bucklen, 1931a). The design was also more flexible and lightweight than previous designs (likely the all-metal designs) which reduced loads and costs.

In contrast to earlier patents, the description went into more depth regarding the proper aerodynamic design of the device showing that either Bucklen or more likely his colleague Harlie O. Putt had a basic understanding of new aerodynamic science. Bucklen and Putt had a few US patents and at least four Canadian patents together on the wind power plant technology (all assigned to Herbert E. Bucklen
Company). They expressed the effect of the fluid stream moving past the blades creating “a pressure on the wind side and a suction on the lee side whereby torque is produced and the impeller rotated to deliver power” as well as the overall importance of camber in the design along the blade and at the tip in particular in order to produce “starting torque at low wind values” and “a retardation of rotation of the impeller at high wind values” due to stall (Bucklen, 1931a). It appears the design of the blade was mainly experimental as the authors described tests with different levels of camber and even rotors with no camber. They found via experimentation that the blades with camber had starting speeds were 3-5 mph, 1-2 m/s, lower than blades without camber. The assumed novelty associated with the findings suggests that Bucklen and Putt were not aware of the work in windmill aerodynamics of Fales or the AVA.

The overall design started operating in wind speeds of 4 mph, 1.5 m/s, and could operate up to wind speeds of 25 mph or higher – with stall-control regulating speed at very high inflow wind speeds. Patents filed after this date feature the basic aspects of this propeller design (Bucklen, 1931e) and images of HEBCO machines also suggest that this type of design was used on HEBCO machines going forward (Righter, 1996).

Figure 3-XXXI: a) HEBCO machine in front of a house in Texas (Righter, 1996 p. 83) and b) a brochure from Universal Battery Company featuring the HEBCO style windmill dynamo (Wincharger.org, 2016).

From that point on, Bucklen and Potts generally focused on other aspects of the system design including surviving extremely high wind speeds by tilting the rotor out of the wind (Bucklen, 1931b, 1929a, 1930b) as well as various aspects of gearing, power regulation and organization of the overall power plant system (Bucklen, 1929c, 1931e, 1931d, 1931c). The electrical features of the system – in particular the relays and electrical controls – were quite sophisticated and work in this area was what led Bucklen to start the successful Durakool company in 1935. Bucklen’s first relay patent (in collaboration with Putt) was a current cut-in relay to “in order that the maximum amount of power may be obtained from relatively feeble winds and also in order to prevent the battery discharging through the generator” (Bucklen, 1929d). However, it was not necessarily the technology alone that brought success to the
Bucken wind chargers. Perhaps having learned from his very successful father, the company promoted the HEBCO windmill dynamo heavily using a variety of clever marketing techniques and Bucklen was able to secure a contact with the government to supply his machines for lighting beacons at U.S. Post Office owned landing fields across the country (Righter, 1996). The HEBCO brochures touted the uniqueness of the propeller and even claimed it was the same one as used by Charles Lindberg in his cross-Atlantic flight (Righter, 1996). The HEBCO brochures “surpassed its competitors in hyperbole” with language about how amazingly strong the machine was and how for such a low cost it could provide all the domestic electricity needs on a farm (Righter, 1996). At some point in the 1930s, perhaps when Bucklen went on to found Durakool, he sold his wind charger business to Universal Battery Company of Chicago that would continue to produce and sell the machines for some time thereafter (Windcharger.org, 2016). It is unclear how many HEBCO wind chargers the company produced and deployed, but it appears they were under production for some 20 years between the Hebert E Bucklen Corporation and the Universal Battery Company.\textsuperscript{40}

The HEBCO machine represents perhaps the first successful wide-scale deployment of windmill dynamo technology due in significant part to the evolution from a wind-rose style rotor to the propeller-style rotor. Other companies followed suit and a new generation of windmill dynamos was born. These new “wind charger” machines would charge batteries in particular for powering radios across rural America. For many technologies of household convenience, electricity was more a luxury than a necessity — and indeed, electricity for rural homes was considered a luxury in the United States through the First World War. However, radios were a new technology entirely dependent on electricity for power and the storage batteries that supplied their power needed charge from some generation system. Though radio was still young in the 1920’s, with the first broadcasting stations in the country going into service just after the war, the technology promised a new opportunity for rural areas to receive information about the world at a faster and higher rate than ever before. In particular, vacuum tube based amplifying radio sets appeared in the mid-1920s that replaced the older crystal radio sets but required battery power. In the 1920s and 1930s, hundreds of thousands of small wind chargers diffused across the world in particular for applications relating to powering radio batteries but also expanding to supply electricity for various other uses such as lighting and machine power (Hütter, 1954; Fales, 1937; Righter, 1996). An estimated 70,000 such wind chargers were sold in 1935 alone (Fales, 1937).

\textsuperscript{40} In the late 1930s, the Universal Battery Company was employing engineers to address issues related to speed control of wind chargers showing evidence of continued development of the HEBCO machine (Watkins, 1937).
Many such “wind charger” companies sprung up in the late 1920s to provide systems for charging batteries to power radios in particular.\textsuperscript{41} Some of them, like Perkins Corporation, transitioned from the propeller-driven technology to geared systems. The vast majority of successful approaches (including the HEBCO, Wincharger, and Jacobs machines) used geared systems similar to today's modern wind turbines. However, many configurations for drivetrain/power take-off were explored including a gearing mechanism in series with the generator, connected to the generator via a chain-link or other pulley system (Haugen, 1932; Plucker, 1936; Betts, 1937; Litton, 1938; Grohmann, 1939), some combination pumping/electricity production machine with the generator at the base of the tower (Potts, 1929; Willenbring, 1930; Buchser, 1932; Miller, 1930; Penton, 1937; Moon, 1938; Vater, 1939; US Fumagalli, 1939) or even some direct-drive applications assumedly with a very-large generator (Rime, 1933, Davis, 1934; Cullin, 1939). Over time, more patents featured geared and direct-drive systems than the pulley systems and an emphasis on how to control the machines. Whereas HEBCO machines had an integrated propeller which used stall to govern the machine at high speeds, many designs featured the pitching mechanism for constant speed compatible with the constant speed DC generators of wind chargers. Additional mechanisms based on the thrust of the wind to activate flaps provided braking for the machine in high winds (Miller, 1936) and employed by Russell Swanson in his relatively well-known “Wind King” model (Windchargers.org, 2016). Another somewhat novel approach used generator torque (Watkins, 1937) that modern machines use as a speed control mechanism to maintain optimum power efficiency in modern machines though it was used here as well as a means of matching the speed for the variance in generator power due to temperature fluctuations in particular. Power regulation involved controls for the overall electric system including the switching and automated control mechanisms for charging the battery pack and providing power to various loads (Constantin 1930; Hunt, 1931; Weeks, 1938; Claytor, 1939a; Weeks, 1939). However, the electronic control systems for such charging plants...
traditional windmill markets and introduced their own propeller-style windmill. Perkins already produced their relatively well-known “Aeroelectric” machine based on older wind-rose rotor technology but by 1930s, they had acquired a patent for a new propeller-style wind charger with a relatively sophisticated electrical control system for charging the battery and connecting the system to the loads (Hunt, 1931). An electronic control system automatically turned the machine into the wind when the battery was discharged between a certain level and a panel could be used to control the overall power system. It is unknown whether the specific design was produced but Perkins Corporation was also acquired by the Universal Battery Company in the 1930s which continued to supply wind chargers based on both the HEBCO and Perkins Corporations designs (Wincharger.org, 2016).

Many other companies produced the wind charger systems but perhaps the Wincharger Corporation was the most prominent of all since with hundreds of thousands of units being sold in the 1930s and 1940s – many as a package deal with radios sold by Zenith Radio Corporation which owned a 51% stake in the company. Many (restored) Wincharger units can still be found operating today across the United States as well as in Europe and other locations – a testament to the scale of production of the machine which was referred by some ranchers as the “Chevrolet or Model T of wind energy” due to its affordability and the range of models that were offered (Righter, 1996). The company was started in the late 1920s by John and Gerhard Albers as the “Albers Propeller Company” who had been tinkering on their family farm in Cherokee, Iowa to create a wind energy system to charge 6-Volt radio batteries (“Windco Inc”, 2016). Both Albers brothers had been working on their father’s farm since they were young; Jonathan only completed an 8th grade education while Gerhard had completed high school (US Census 1940). Both were also too young to fight in World War I though the older brother Gerhard Albers had registered for the draft and so their education was primarily a practical one through working on the farm and gaining experience with the machines that were there. They continued working on the farm through the 1920s and sometime around the middle of the decade, they were inspired to build a wind-charging unit for a vacuum tube radio on the farm. Having initial success selling the resulting product to friends and family, the company grew and eventually adopted the name of its main product and became the Wincharger Corporation.

Then in 1934, the Zenith Radio Corporation approached the company with an order of 50,000 units and acquired the 51% stake in the company – effectively putting the company on the map as the largest producer of wind charger units in the world (Wincharger.org, 2016). Why Zenith picked the Wincharger company over some of the others is unclear – HEBCO had a significant present in the Chicago area where Zenith was located. The fact that Zenith went to Wincharger is evidence of how popular the machines had already become by that time. Eventually, Zenith bought out the entire company and would continue to sell the units until 1953 when the factory in Sioux City, Iowa was destroyed by a large flood (Wincharger.org, 2016). By then, however, the market for wind chargers was dwindling and Zenith sold off the entire company in 1968; by that time the company had diversified to produce generators, engines, and other small power equipment (“Winco Inc, 2016). An estimated million or more existed by that period including both the measurement and controls aspects that were “well known in the art” which explains why such features were not key parts of patent applications during the period (Hunt, 1931).
Winchargers were sold across the United States and internationally during the late 1920s, 1930s and 1940s – the most of any wind charger company in the world.

![Image of a Wincharger system design](image)

**Figure 3-XXXIII:** Image of the typical Wincharger system design with the integrated two-bladed propeller and the airbrake arms extending perpendicular to the rotor in the rotor plane (Wincharger.org, 2016).

Overall, the Wincharger technology was very much like that of HEBCO. It was a two-bladed 6 ft. diameter propeller designed to operate upwind. A later version, the “Giant,” featured 4-blades but most of the produced units were of the two-bladed configuration. The initial system used a direct connection to drive a 6-Volt 100 W DC generator (sized to charge a single 6-Volt battery for radio but also with enough power for 8 to 10 household lights) (“Electric Plants Offer Power to Everyone”, 1938). Assuming a maximum tip speed ratio of 8, then in 20 mph (9 m/s) the turbine would be rotating at about 750 rpm – a very fast speed similar to the earlier ram air turbines also meant for high-speed direct drive operation. Both active and passive control systems were popular including a tail vane to passively yaw the system into the wind during operation; similar to other windmill designs the vane would fold to the side in high-winds to avoid damage to the rotor. A key patented feature of the machine was the use of air brakes to maintain constant speed operation about 20 mph. Jonathan and Gerhard Albers along with their colleague Ernst Arndt42 of the Wincharger Corporation held upwards of 15 patents related to their wind electricity generation system design – eclipsing Bucklen and Putt’s 12 patent record from the early 1930s. Some patents related to the design of the propeller itself (Albers 1939; Albers, 1941). The Wincharger propeller design emphasized manufacturability carving the propeller out of a single piece of wood (typically Douglas fir known for its high strength-to-weight ratio) which avoided issues that may have arisen with HEBCO’s balsa-wood gluing based approach where weaknesses in the glue would likely have developed over time.

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42 Ernst Arndt moved between several windcharger companies including Parris-Dunn, Ruralite and the Wind Power Light Company. However, he appeared to assign his early patents appear to the Wincharger Corporation.
Some consideration of aerodynamics is part of the design, but the overall design focused on relatively straight edges again to ease the manufacture—Winchargers were a relatively low cost wind charger compared to the Perkins or Jacobs brands (Righter, 1996). Eventually, designers used more aerodynamically rounded airfoil shapes with a slightly negative pitch on the blade design to ensure the machines would be self-starting\(^{43}\). The rigidity of the wood and the use of thicker airfoils in certain sections of the blade also apparently prevented flutter and vibration at high speeds. The company tested the machines at the factory under high-speed operation of 2-3 times their operational speed in order to demonstrate reliability.

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\(^{43}\) An early patent of them company focused on providing a starting means for the early design which was not self-starting by using the generator initially as a motor (US Patent 2086279).
Still, neither of the Albers brothers appears to have a strong background in aerodynamics though Gerhard did take on the role of their design and is the inventor on the blade patents. Advanced propeller design was not the strongest aspect of the machine and the patents do not provide evidence of significant study of aerodynamics principles. More so, the design developed through trial-and-error as Gerhard Albers uses language “I have found” in both patent applications that suggests an experimental approach. Generally, low-cost was the key consideration. Using a high-speed direct-drive machine with an integrated two-bladed propeller led to an overall system that was reliable enough at a very low cost. Such a system in 1937 cost $44.95 USD which was indeed fairly affordable (around $700 in 2010 USD) but would only cost $15.00 USD with the purchase of a 6-Volt Zenith radio due in a bundled pricing scheme (Wincharger.org, 2016). The price included the overall machine and a 5 ½ ft. tower but excluded the batteries. The larger “giant” 32-Volt system rated at 650 Watts sold for $69.95 (around $1000 in 2010 USD) but was still much cheaper than the cheapest model from competitor Jacobs wind which sold 32-Volt 2500 Watt system in the late 1940s for $490 (around $300 in 1937 USD) with the tower sold separately for $175 USD (an extra $100 in 1937 USD) (Wincharger.org, 2016; Righter, 1996). Winchargers were cheap and indeed the parent company Zenith no doubt saw the wind charger as a companion technology for promoting their core product the Zenith radio to rural residents who still did not have grid access. In addition, if a new Wincharger was too expensive, one could build their own using a complete set of instructions published in Popular Mechanics in July of 1938. The pamphlet provided details about how to build everything from the generator to the air-brake governor and pivoted vane – everything but the “scientific” rotor could be acquired and built easily at home on the farm using common parts and tools (Crowley, 1938).
The field coils are wound on a rectangular form. Fig. 10, the size of which will be the same as the inside dimensions of the old field coils. Four coils of 125 turns each of No. 18 enameled wire are required. When each coil is finished, remove it from the form and bind it with cotton tape, as shown in Fig. 9. Shape the coils to fit the contour of the frame by inserting them in place and bending them to fit. Then remove them and impregnate with varnish or shellac. When dry, connect them in sequence.

Figure 3-XXXVI: Excerpt from Popular Mechanics 5 page article with complete instructions on building all parts of a Wincharger except for the rotor - including mechanical and electrical diagrams of all main sub-systems and pictures of assembly and instructions on testing (Crowley, 1938).

The inexpensive and simple nature of the machine design that lent itself to a “do-it-yourself” system is surprising since Albers and other Wincharger employees filed a number of patents. Jonathan Albers, who eventually became chief engineer of the company, filed the majority of these, and the patents largely related to machine control and safety. Indeed, one of the unique features of the machine was speed regulation mechanism covered under US Patent 2277011 and US Patent 2480687 (Albers, 1942; Albers and Albers, 1944). The earliest Wincharger systems did not have the braking feature though they may have had an internal breaking system conceptualized by Ernest Arndt that could be manually set by pulling a chain when the winds were extremely high (Arndt, 1940).

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44 Some of John Albers patents were related to overall system design including aerodynamic design of the nacelle or drivetrain housing (Albers, 1941), mounting system design (Albers, 1940a), electrical controls for the battery system (Albers, 1943b), centrifugally activated control of the generator field resistance (Albers, 1944a) for improved power extraction, auxiliary power systems for prime movers (Albers, 1943a), a dually-pivoted configuration for passive yaw and pitch of the entire machine (Albers, 1944c), and even a multi-rotor plant configuration (Albers, 1945).
It is likely that the early machines that did not feature speed regulation were prone to failure by either subjecting the generator to excessive speeds or causing the turbine itself to enter into some unstable operating regime with excessive vibration. As with previous windmill dynamos, power regulation of the system was important for overall machine reliability as was providing a predictable and relatively constant speed to the input shaft of the generator.\textsuperscript{45} Albers suggested mechanisms for doing this with the fixed-pitch integrated propeller design included centrifugally activated tip brakes (Albers, 1948), a centrifugally governed mechanism to limit the generator speed, torque control, in particular for alternating current generator applications (Albers, 1944b), and even a centrifugally governed tilting mechanism to slowly turn the system vertically out of the wind as wind speeds grew higher (Albers,

\textsuperscript{45} Many patents regarded speed regulation approaches of a variety of types. Speed regulation mechanisms specific to the new propeller-style rotor technology were developed that would automatically adjust the speed above certain levels using a variety of means generally using centrifugal forces to control the overall blade pitch (Haidle, 1934; Youngberg, 1934; Rovik, 1935; White, 1936; Swanson, 1937; Burkhartsmeier, 1937; Renquist, 1937; McColly, 1938; Harley, 1938; Hood, 1938; Cable, 1938; Wiste, 1940) or sometimes to use ailerons similar to the approach used by Bilau (Allen, 1939). In one important case, George Jean Marie Darrieus (inventor of the “Darrieus concept” vertical-axis wind turbine which will be described) proposed a stall-regulated design whereby stall would be induced on the airfoil above a certain critical angle of attack so that the drag would be increased and eventually overcome the lift (Darrieus, 1931a). This “stall-regulation” principle became very important in the development of small modern wind turbines from the 1970’s onward.
The winning concept, at least the one implemented on the standard Wincharger design, was that using flaps perpendicular to the propeller in the rotor plane. An early design of these used flaps which were attached at the hub and centrifugal forces which would turn the flaps from a parallel to the inflow to perpendicular in order to introduce drag on the system (Albers, 1940c). Another benefit of this setup was that the flaps were aerodynamically designed and could assist in starting the machine at low wind speeds. The design used in practice, however, was again two flaps but in this case, the flaps remained parallel to the wind inflow at all times and were either parallel to the direction of rotation of the machine during normal operation or perpendicular to the direction of rotation at speeds in excess of 20 mph (Albers, 1942; Albers and Albers, 1944). In the latter case, the flaps would interfere with the flow and cause the machine to maintain a constant speed. As with most other control mechanisms, the flaps activated from centrifugal force using springs.

Figure 3-XXXVIII: a) the flap mechanism for starting and speed control of John Albers in US Patent 2215456 (Albers 1940c), and b) the winning concept for the Wincharger speed control design, the air-brake system invented by John and Gerhard Albers.

Figure 3-XXXIX: The Wincharger air-brake governor featured in an advertising brochure.
With the introduction of the air-brake governor, the main components of the Wincharger system were complete and the standard design appears in brochures throughout the 1930s and into the 1940s. However, the governor design was not without criticism. Marcellus Jacobs of Jacobs wind energy described the approach as “holding the throttle down on your car while you step on the brakes to slow down” (Plowboy, 1973). By using the Wincharger mechanism, the pressure on the blades would still grow as wind speeds increased and Jacobs commented that he had “replaced hundreds of those plants when storms just pushed their blades right into the towers” (Plowboy, 1973). Ideally, designers would avoid this destructive process by the second safety feature of the Wincharger that was a pivoted-vane (common on many windmill machines). When excessive force overcame a spring-load, the vane would swing parallel to the rotor causing the system to rotate out of the wind to a maximum of 90 degrees. A person could also control the mechanism by a hand pulley when the batteries were already charged. Still, the instability in the two-bladed fixed-pitch design may be one reason that out of the hundreds of thousands of Wincharger machines produced, only a small number survives today.

The company also produced a more stable four-bladed design where two integrated propellers were mounted perpendicular to one another and one of them attached to a centrifugal governor to feather in high winds and thus acts as the air-brake system. The larger “Giant” machine provided enough power for an overall electrical system for a household and many of these larger Winchargers with 4-blades have survived in a refurbished form to current day.

Figure 3-XL: Brochure for Wincharger systems featuring the "Giant" system with four-blades on the right. The “Wincharger Electric System for Every Income” is reminiscent of the Alfred Sloan’s slogan for General Motors: “A Car for Every Purse and Purpose.”
Almost all of the patent designs for propeller-style rotors featured two-bladed machines similar to the HEBCO and Wincharger designs. This likely reflected the direct application of two-bladed airplane propeller technology to the wind energy space. However, such two-bladed designs faced certain design challenges and at the time no teetered two-blade systems (stemming from helicopter technology) existed. Speed control was handled in various ways (as mentioned above) but as will be discussed later, modern two-blade wind turbines have a teetering hub which acts to mitigate the asymmetric loading of the machine as the blades pass through wind shear, turbulence and tower wake. While pitch regulation of the machines was a well-known technology for producing constant speed operation, teetering was not and thus the two-bladed machines at the time would have experienced significant fatigue loads and unstable vibration. A few companies featured three-bladed machine designs, Russel Swanson's Wind King Company for example which became a successful company as did the Wind Power Light Company that employed Ernst Arndt as the engineering manager after he transitioned from Wincharger and the Parris-Dunn company. The Wind Power Light Company was unique in particular because their machine was of a downwind construction using passive-yaw to rotate the three-bladed rotor away from the wind as well as the active pitch control of the individual blades using a centrifugally governed activation system (Windcharger.org, 2016). The design had good performance and reliability though the lattice-tower on which it was mounted provided a significant source of interference to the wind inflow today known as “tower-wake.” Modern downwind design configurations (mostly of the small-scale wind turbine size range) mitigate the tower wake effect by using a monopole construction.

In addition to the Wind King and the Wind Power Light Company, the other major three-bladed system in the wind charger market was the Jacobs Wind system — and it became perhaps the most famous wind charger company from the period with a renewed form of the company still operating even today. Many have written about the Jacobs Wind Company and on its principle owner, Marcellus Jacobs, who was a champion for wind energy from the 1930s through the 1970s. The oil crisis took place in October of 1973. John Albers had passed away in 1966 and Gerhard Albers lived through only a small portion of the event — passing away in July of 1974. Herbert Bucklen Jr. had also passed away in 1966 and had not been involved in the wind industry for some time at that point as he had moved on to run Durakool. Few leaders of wind charger companies lived through both the peak of wind charger deployment in the 1930s and the resurrection of the industry in the aftermath of the oil crisis. Marcellus Jacobs was an exception and in the 1970s re-entered the wind industry almost 20 years after shutting down production of the original Jacobs Wind Company machines in 1956. Due to the reliability of Jacobs Wind machines, many were still in operation and Jacobs on several occasions spoke about his successful wind charger business and machines. Thus, in Jacob’s case there is a unique opportunity to understand the background, design and deployment of their famous 3-bladed upwind wind charger systems.

47 Paris-Dunn Corporation featured a design based on a gyroscopic governor meant to “slip the wind” very similar to the patent by Albers of Wincharger. William Dunn had about 7 patents on his wind charger system that all related to his tilt control system (Dunn, 1936c, 1937, 1936b, 1941; Malme, 1939; Dunn, 1938, 1936a) the Wind Power Light Company) which continued to produce the Dunn style wind chargers into the 1950s.
Marcellus Jacobs and his brother Joseph, the elder by 5 years, together founded and ran what was to become the Jacobs Wind Company. The brothers, born in 1903 and 1898 respectively, grew up in Montana on a ranch where their father worked as a rancher and butcher. Joseph only completed an 8th grade education while Marcellus went on to complete high school and a year of electrical training in Indiana as well as a 6-month course on electricity in Kansas City (Plowboy, 1973). Marcellus had already been quite interested in electricity in high school and had read many books on the topic; in high school he built and sold radios that operated on storage batteries (Plowboy, 1973). In the early 1920s, Marcellus, likely along with his brother Joseph, converted a secondhand engine to run a DC generator for the first source of electricity on the ranch and coupled it to some batteries to power electric lights – but it did not supply enough power to run a motor attached to a hand forge (Plowboy, 1973). Not only that, gasoline to supply the engine involved a three-day trek and involved crossing the Missouri River (Righter, 1996). It was then that the brothers first turned to wind energy and like other before them, they started by taking the rotor from an American-style wind-rose windmill water pump and mounting it onto a wheel-shaft connection of a Ford Model T rear axle with the tail vane mounted to the other side; the drive shaft was then extended down to the ground where it connected to the generator (Plowboy, 1973). To make it work, Marcellus “just locked the differential with a pin so that as the wind turned the fan it would drive the shaft” (Plowboy, 1973).
Like others, Jacobs recognized early on that a rotor designed for pumping water was not efficient for power production. Jacobs noted that:

A water-pump has to “lift water right from the instant it begins turning [and] needs a lot of starting torque... and that’s why it has so many large blades. Once the wheel gets some speed, however, about 80% of those blades get in each other’s way. They begin fighting each other. In fact, a water-pumping windmill needs all the power it generates just to run itself in an 18 or 20 mph wind. You can pull the pump rod loose and the wheel won’t run away. It can’t. The force of the wind during a storm may blow the wheel into the tower and push the tower over... but the fan won’t over-rev and tear itself apart.” (Jacobs quoted in Plowboy, 1973)

From there, the Jacobs brothers, like others before them moved to investigating machines with fewer blades – inspired by the two-bladed propellers of new airplanes. In 1926 or 1927, Marcellus Jacobs learned to fly and this gave him the idea of using a two-bladed propeller as a wind generator (Plowboy, 1973). Jacobs noted that at the time most airplanes used two-bladed propellers and the Jacobs brothers started with that and experimented with three- and four-bladed machines as well, but Jacobs realized that there were “vibration problems” with a two-bladed machine that were not present in a three-bladed design – in particular when the machine yawed during operation (Plowboy, 1973). In airplanes at the time, most curves were gradual such that two-bladed propellers were not affected but when an airplane was “kicked into an abrupt turn” as with Curtiss-Wright aircraft designed for military purposes in World War II, then the two-blade propeller systems became unstable which led to a series of crashes (Plowboy, 1973). Eventually Curtiss-Wright adopted three-bladed (and even four-bladed) propellers for their military aircraft including the P-90 “Warhawk” and the SB2C “Helldiver.”
As mentioned earlier, there are issues with two-bladed high-speed machines under certain operating conditions. Like an airplane performing a fast turn, a two-bladed high-speed wind turbine may yaw abruptly as the wind changes direction which in free yaw (where the turbine orients itself automatically without the use of controlled gearing and motors) would introduce instability without the use of a teetered-hub (Jamieson, 2011). The Jacobs experimented with two, three and four blade machines before deciding on a three-bladed design which didn’t have the balance problem of one blade, the vibration problems of two blades and captured just as much energy (according to their measurements) as a four-bladed machine (Plowboy, 1973). In a 1961 presentation to a UN conference, Jacobs gave a nice plain-language description of the vibration and why it led his brother and him to select a three-bladed configuration:

“The three-blade propeller was found to be necessary (as compared to the two-blade type) to prevent excessive vibration whenever the shift of the wind direction required the plant to change its facing direction of the tower.

The periods of vibration which occurred, on the two-blade propeller, every time the tail vane shifted, to follow the changes in wind direction, were found to be caused by the fact that the two-blade propeller when in a vertical position, offers no centrifugal force resistance to the horizontal movement of the tail vane in following changes in wind direction. However, when the two-blade propeller is in the horizontal position, its maximum centrifugal force is applied to resisted horizontal movement of the tail vane; thus the tail vane is forced to follow wind direction changes by a series of jerks, causing considerable serious vibration to the plant.

The three-blade propeller was developed by us in 1927 to correct this condition. When in operation the three-blade propeller creates a steady centrifugal force resistance, against which the tail vane reacts with a constant pressure and produces a smooth shifting horizontal movement of the plant facing direction.” (Jacobs, 1961).

Even though the maximum centrifugal force of their three-blade system (1600 lbs. or 7117 N) compared to that of their two-blade system (1100 lbs. or 4893 N) was larger, it was relatively constant for a given
operating condition whereas the two-blade system centrifugal force fluctuated from roughly 0 to 1100 lbs. twice per revolution). Thus, unlike most wind charger manufacturers, the Jacobs system had a three-bladed rotor.

The Jacobs brothers then focused on the rest of the system design including power output and machine control and regulation. Whereas the HEBCO and Wincharger machines were intentionally designed to be small, producing initially just enough power to run a few lights and charge the 6-volt radio batteries, the Jacobs were drawn to wind energy with the initial idea in mind of providing power for farm equipment and essentially all the power needed on their ranch. A larger machine was already on their minds and they understood that power depended on the rotor area or diameter of the wind machine. Their first machine had a 3-bladed 15 ft. (4.6 m) diameter that provided in excess of 1 kW of power connected to either 32-V or 110-V system (Plowboy, 1973). The machines were larger than HEBCO and Wincharger machines (with their small 8 ft. diameter and 100 W power systems) by a factor of 10 and would continue to be some of the largest machines on the market.

The other subsystem design concerns involved the generator design and speed regulation. Speed regulation was a concern for all wind chargers and unlike many of the two-bladed designs with an integrated propeller (as the Wincharger cut from a single piece of wood); the Jacobs design featured three distinct pitchable blades. The Jacobs system accomplished this through a centrifugally governed pitch mechanism and this allowed the turbines to sustain winds of a hundred miles an hour (Plowboy, 1973). The first patent filed by the Jacobs brothers, featured a governor system such that “when the speed of the drum reache[d] a predetermined figure, approximately 275 revolutions per minute, the governor weights [were] forced outwardly, due to the centrifugal action, to provide for the shift of the gear... and causing the blades to turn more edgewise into the wind... This regulate[d] the speed” (Jacobs, 1931). The Jacobs brothers filed relatively few patents compared to Bucklen and the Albers brothers and almost all of them were related to their control mechanisms including different pitch control methods (Jacobs 1949, Jacobs 1950) including pitching just the tips of the blades (Jacobs, 1937) and also methods for adjusting the tail in extreme winds (Jacobs, 1933, 1936).

![Figure 3-XLV: Blade pitch governor mechanism of early Jacobs wind machines (Jacobs 1931).](image-url)
Joseph Jacobs in 1929 filed the first patent on pitch control as a sole-inventor and later he would go on to be president of the company for an unknown number of years. Marcellus, however, was likely responsible for the design of the generator which was unique to the machine. The maximum rotational speed mentioned in the patent was 275 rpm and later 225 rpm. No generator of around 2000 Watts was available that could work in that speed range and thus a special generator was designed for the machine which had a load increase commensurate to the increase in power extraction from the propeller up to the design operating speed of 18-20 mph (8 to 9 m/s) (Plowboy, 1973). To do this, a special alloy-material in the field poles of the generator allowed the generator load to fit the output power curve of the propeller over the entire range of wind speeds up to 24 mph (11 m/s). They never patented the design and likely held it as a trade secret. Another trade secret had to do with the brush design and commutation. The commutator, as discussed before, was often problematic even in normal fixed-speed operation but in variable speed operation, the device would be prone to sparking as the “neutral zone” of the machine shifted. Commutation is a method to mechanically rectify the current flow in a DC machine. The brushes for a machine must be located in the magnetically “neutral zone” in order to avoid an induced voltage in the commutator loop when contact is made with the brushes – else damage will occur reducing the life of the brushes. In a variable speed machine, the “neutral zone” is constantly changing so that a priori design of the brush location is difficult – an issue that plagued all wind chargers and not just Jacobs machines (Plowboy, 1973). The Jacobs solution was the development of entirely new brushes involving layers of graphite and carbon with a very high cross-sectional resistance avoiding current flow perpendicular to the brush contact direction and providing a much longer life span for the brushes – up to 10 or even 15 years that was a very long life span at the time (Plowboy, 1973). The introduction of these new brushes was important in particular for a wind generation system since its location on the steel towers high above ground meant they were more susceptible to static discharge and the influence of charge build-up from nearby lightning events (Jacobs, 1961).

The controls system for the machine was another important feature in order to charge the batteries with relatively constant power output in order to not “burn the storage cells out” and to charge at a slower rate when the batteries were near full (Plowboy, 1973). Again, Marcellus’ background in electrical technology allowed him to apparently develop a solution that eluded most of their competitors – a voltage regulation process that would slow the charging when the batteries were near full by inserting a resistance into the generator field that reduced the output (Plowboy, 1973). This “Master Mind” system also contained a “reverse current relay” which ran DC current opposite to the main flow in order to open the main circuits when necessary to avoid issues associated with arcing in a system that would cycle on-and-off with relatively high frequency (Plowboy, 1973). Marcellus created most of the electrical component design himself because at that time “there weren’t any experts on slow-speed electrical generation. There were no experts on voltage regulation... There were no books on the subject.... When you [had] a problem... you just [stuck] with it until you [found a solution]” (Jacobs quoted in Plowboy, 1973).

This same experimental approach applied to the design of the rotor itself. They did not discuss the blades in detail, and from Marcellus Jacob’s account it appears that the actual blade-design (as with
Wincharger machines) were based more on experimentation than knowledge of aerodynamic theory. As mentioned before, they tried various numbers of blades and different materials as well – even “stamped out” aluminum but frost on the metal blades caused imbalance leading to unstable vibrations (Plowboy, 1973). Instead, they used “aircraft-quality, vertical grain spruce” which was selected personally by Marcellus and then brought to the factory where they were cut into the airfoil shapes, dried and sanded down into final shapes which were then coated with an asphalt-based aluminum paint (Plowboy, 1973). They found the actual design of the propeller through a trial-and-error process that evolved first from a propeller design very similar to an aircraft propeller into the three-bladed concept where they used an iterative process to find a propeller with the resulting target tip-speed-ratio of 125 mph in 20 mph winds (Plowboy, 1973). All of the system design described above was relatively stable by the early 1930s – only growing in size to a maximum of 3 kW (Jacobs Wind Company Website, 2016).

The Jacobs Wind machine differed from the Wincharger and others not just in its system design but also in the overall approach of the Jacobs Wind company to marketing and commercialization of their technology. The general approach taken by the Jacobs to sales was “word of mouth” with Marcellus traveling to fairs and other events across the mid-west to advertise the technology and recruit dealers for future sales (Righter, 1996). Jacobs Wind depended on their reputation for reliability over all else, and their “Cadillac” of wind chargers was “built... to last a lifetime” (Plowboy, 1973; Righter, 1996). The plants themselves were not cheap – a 2500 Watt 32-Volt plant $490.00 for the wind power unit, $360.00 for the 21 kW storage battery, and $175.00 for the lattice-tower ($1025 USD for the full system around the late 1940s as quoted by Jacobs in a 1961 report – the company had shut down in 1956 and it is unclear for what year the reference costs are provided) (Jacobs 1961). However, the Jacobs were marketing their wind chargers as a reliable home electric plant more than just a charger for small electronics. For this reason, they not only sold the power system but also manufactured a series of home appliances meant to operate on 32-V DC power. The overall series of electronics manufactured by Jacobs Wind included “everything you’d need on the ranch – fans, motors, electric irons, toasters, percolators, freezers, refrigerators,” etc. (Jacobs as quoted in Plowboy, 1973). Similar to Edison and other “system builders” the Jacobs Wind Company was intent on supplying rural America with a complete and reliable power system from the free fuel of the wind to end-use appliances. Two anecdotes sum up the reliability of the Jacobs machine: an African mission bought a plant in 1936 and in 1972, a replacement order for brushes was sent (the first request for parts in the entire 36 year-period) (Plowboy, 1973). In another amazing story, a Jacobs Wind plant was installed at the South Pole in 1933 by the explorer Admiral Richard Byrd and it was still operating (the blades were still turning) during a return expedition in 1955 – with the ice covering the whole camp except for the top 10 ft. of the 70 ft. tower (Plowboy, 1973; Righter, 1996).
Figure 3-XLV: the 2.5 kW Jacobs Wind charger at Admiral Byrd's “Little America” camp in Antarctica in 1934.

On one end of the spectrum, Winchargers represented the need for a lowest possible capital cost solution for providing electricity to rural Americans who had no other form of access. The vacuum tube radio was a critical technology that propelled rural demand for electricity and the Wincharger, popularized by Zenith Radio Corporation, was possibly the cheapest route to acquiring the new technology. Because of this, the small units were manufactured on a mass scale and hundreds of thousands were sold from the time the company got going in 1927 through the 1950s when the factory was flooded and demand had subsided. On the other end of the spectrum, the Jacobs Wind machines represented a holistic solution to providing significant quantities of electricity to a farm in an overall power plant solution including a relatively large kW power system with a sophisticated set of controls and a variety of end-use appliances. For rural Americans, like the Jacobs, who did not have grid access, found transport of gasoline for a diesel-engine plant cumbersome, and had enough wealth to afford a full-plant solution, the Jacobs Wind system was a great option. This is perhaps why that despite the price, the company produced tens of thousands of Jacobs Wind plants from the early 1930s to 1956 when the plant closed. Both companies found a market niche for the better part of three decades and likely would have continued to exist were it not for the growth of centralized grid network electricity supply to rural areas from the late 1930s onward.

Perhaps most interestingly, the contrast between the technology and approaches of the two companies provides the first glimpse of a debate that would continue into the modern wind era. Generally, there are trade-offs in the system design between upfront costs and long-term reliability and operational expenditures. The Jacobs model was touted for its minimal operational expenditures of less than $5/year over 10 years with another $36/year for the battery system (to save up for the replacement every ten years) and the overall reliability and long-lasting nature of the machine. The Wincharger however was much more accessible and low-cost to begin and was perhaps “sufficiently reliable” for the applications of interest. Thus, each technology represents a distinct system design approach, and only
through overall system analysis in cost of energy can we really evaluate one with respect to the other. It is difficult to perform such a task given the lack of cost and performance data on the turbines from the period. However, given the data from the UN report we can estimate the circa 1950 cost of energy for a Jacobs system. Using a reasonable fixed charge rate of 10% and excluding the battery (including only the wind charger at $490 and the tower at $175) and assuming from the UN report the annual operating costs of $5 and an average monthly output of 450 kWh, then the overall cost of energy can be calculated from:

\[
COE = \frac{F \times CAPEX + OPEX}{AEP}
\]

Where COE is the cost of energy, F is the fixed charge rate, CAPEX is the overall capital expenditures, OPEX is the operational expenditures and AEP is the net annual energy production. The overall cost then for the Jacobs Wind system (excluding battery and other miscellaneous electrical costs) comes to $0.019 / kWh that would be about $0.14 / kWh in 2010 USD. Then, assuming that the fixed charge rate and a similar capacity factor of 0.25 (450 kWh/mon * 12 mon/yr / 8760 hrs/yr * 2.5 kW), in order to have cost of energy parity, the $69.95 Wincharger 650 W 32-volt system would have to have annual operating expenditures of about $16 for the same overall cost of energy. Operating costs for the Wincharger would be difficult to come by and could have been quite substantial if the claims of Marcellus Jacobs were true concerning the reliability issues associated with both mechanical and electric systems, but again, without more information it is impossible to draw any conclusions about the relative cost of energy of either system. In addition, the value of reliability in terms of not having to work with parts procurement and replacement is not necessarily solely economic. Depending on the user, the ability to put the turbine up without maintenance requirements year after year could be quite valuable compared to the hassle of dealing with constantly repairing a system that frequently breaks down. It is hard today for us to imagine the decision between a “Chevrolet” and a “Cadillac” of wind charger technology. Electrons today are in developed countries as a commodity – a very cheap commodity at that. But to a rural farmer in the 1920s, the choice of an electricity generation system likely had a number of considerations from upfront purchase and installation cost, to overall reliability and long-term costs, to ongoing maintenance requirements and automation, even to noise (diesel generators were known to be noisy) and convenience (regular access to fuel for diesel generator for example or the comparative noise of two different wind chargers). The choice of an electric power supply had to do with many competing factors. A system level perspective to assessing technology performance and cost is important to a wind project developer today but was just as important to a farmer in the 1920s selecting a system to generate electricity for his home - often for the first time. Based on the sales of wind chargers in the 1930s – upwards of 100,000 per year – it would appear that generally wind chargers were a good solution to electricity on the farm. Fales stated that some 70,000 of the small radio wind chargers were sold in 1935 alone, but in that year, the Rural Electrification Administration (REA) formed and would usher in a new centralized-grid based era for rural electricity. Just as in Europe,

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48 Note, the battery and other electrical costs would normally be included, but here we are just interested in comparison of the Jacobs wind charger to the Wincharger system.
DC wind electricity solutions for rural power would eventually lose ground to new centralized AC grid hook-ups and all the complementary AC electronics to go with them.

3.5 A Note on Innovation in Vertical-Axis Designs

New concepts in aerodynamics and propeller-technology did not only affect horizontal-axis wind energy generator technology. In the 1920's, several new vertical-axis technologies were introduced including the concepts of Sigurd Savonius, George Jean Marie Darrieus and Ernst Schneider (Paraschivoiu, 2002; Savonius, 1929; Darrieus, 1931b; Schneider, 1928). The Savonius technology (named after the inventor) took advantage of new theoretical understanding and experimentation related to the “Magnus Effect” in aerodynamics while the Darrieus (named after the inventor) and Giromill (developed by Schneider) concepts adapted propeller technology for rotation around a vertical axis. These concepts would serve as important and controversial influence on modern wind technology development efforts from the 1970s moving forward.

The Savonius wind turbine is of particularly simple construction but involves a more nuanced set of physics than traditional drag-driven vertical-axis machines. In 1852, German scientist Gustav Magnus published a paper in which he described an effect by which a force would act on a rotating cylinder (or spinning projectile) perpendicular to the direction of incoming flow for a fixed object (or the direction of the flight path for a projectile). Now known as the “Magnus effect,” we commonly observed it in sports like tennis, golf or baseball where a fast-moving rotating ball deviates from its path due to the effect of spin. In the late 1800s and early 1900s, AVA researcher Martin Wilhelm Kutta and contemporaneously by Russian scientist Nikolai Zhukovsky (commonly spelled as Joukowski) both studied the effect in detail. Their work resulted in the Kutta-Joukowski circulation theory of lift that is still today a fundamental theorem in aerodynamics in which knowledge of circulation an airfoil leads to a direct calculation of the lifting force on that airfoil (Anderson, 1997). Savonius referenced both the Magnus effect and the AVA work on the topic in his 1925 US Patent filing for his new rotor design which combined the drag-driven features of traditional vertical-axis windmills with the “Magnus effect” lifting force for an overall higher efficiency vertical-axis rotor design. The concept of operation is somewhat complex and Paraschivoiu’s 2002 book on wind turbine vertical-axis designs describes it in some detail. The basic design (as pictured) includes two halves of a cylinder offset from each other so that a broken “S-like passage” allows for flow between the cylinders (Savonius, 1929). Savonius found that either semi-circular or spiral rotor configurations performed the best in testing.

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49 He had filed a patent in his home country of Finland the prior year.

50 Savonius in his own patent referenced a more conventional design that used the Magnus effect for translational motion. Concepts using the translational motion (for instance on a track) has been proposed as well as in the “Madaras experiments” in New Jersey in 1933 (Paraschivoiu, 2002). In that case a full-scale rotating cylinder 27.4 m high and 8.5 m in diameter had been tested to measure Magnus effect forces but an actual electric generation plant based on the design was never built.
According to Savonius himself, “an unsymmetrical Magnus flow is produced in the surrounding layer of air... which causes a vacuum at [the left side] of the rotor. As the inner surface and central portion of the rotor vanes rotate almost in the direction of the wind, the resistance of the over pressure will mainly meet the outer portions of the blade only and thus act as cross-drive” (Savonius, 1929). Generally, the Magnus effect is creating a vacuum on rotor that introduces lift at the outer edge of the rotor in the direction of rotation. The construction requires a lot of material but the simplicity of the design means that all one needs is a barrel sawed in half and the machine can be constructed relatively easily – indeed many applications of the country have been in rural areas and developing countries where the simplicity and cost readily enable construction.
Also in the 1925, French Aeronautical Engineer Georges Jean Marie Darrieus\textsuperscript{51} was experimenting with lift-driven vertical axis machines using a more direct application of propeller-technology. In 1925 he filed a patent for his new wind turbine technology in France and filed a patent for the same technology in the US in 1926 (Darrieus, 1931b). Darrieus acknowledged the limitations of conventional vertical-axis windmill rotor technology (it is unlikely that he was aware of the new work from Savonius at the time of the filing) and proposed a new technology where the rotor was composed of airfoil-designed vertical blades which would, just as their horizontal-axis counterparts, use the lift force to propel the turbine around the axis of rotation. The rotor forms the shape of a “Troposkien” which is Greek for “turning rope” and approximates “the shape of a perfectly flexible cable” which “minimizes inherent bending stresses” (Paraschivoiu, 2002). The Darrieus concept was very influential in later efforts in several nations to commercialize large-scale vertical-axis technology. One drawback of the Darrieus machine is that it is not self-starting. In recent years, concepts have combined Darrieus and Savonius rotors together to solve this issue.

Finally, a related concept to the Darrieus machine is the self-starting Giromill which similarly uses airfoil-design vertical blades but in this case, the blades do not curve as in the Darrieus case and instead are vertical bars attached to rods which connect them to the shaft of rotation. Such a design was contained in Figure 6 of Darrieus’ patents but a more complete representation of the Giromill concept was contained in the 1926 US patent filing (1925 home country patent filing in Austria) of inventor Ernst Schneider (Schneider, 1928). Schneider’s version of the giromill is a special case known as a “Cycloturbine” which is a design constructed in particular to allow for constant circulation around the blades during their entire path of rotation by allowing each blade to rotate around a preferred axis. Unlike general Giromill and Darrieus machines, Cycloturbines are self-starting but they have

\textsuperscript{51} Darrieus also contributed to the design of stall-regulated wind turbine rotors.
considerable added mechanical complexity due to the mechanical adjustments of the blades and blade-shafts.

There is not a lot of evidence that such aerodynamically influenced vertical-axis wind motors diffused on a large-scale during the 1930's and 1940's. More importantly, as will be discussed in later chapters, the design concepts themselves were influential in the wind turbine technology developments in the 1970's and after.

3.6 Discussion

World War I started out as a boon to wind energy actor networks in Europe. Demand for windmill dynamos based on la Cour designs were boosted coal shortages in Denmark and Germany at the start of the war. However, the boom would be short lived and already by the end of the war, demand for wind motors and dynamos was subsiding – all but disappearing by the 1930s. Wind motor and dynamo producers cited the availability of inexpensive and dependable gasoline-based independent power plants for rural applications as the key factor for the decline. Also in Germany and Denmark, rural electrification rates were relatively high and climbing already by the 1920s and even more so in the 1930s. The availability of alternative power sources that were less costly ultimately served to destabilize the once strong windmill dynamo actor-network in Denmark in particular. Poul la Cour had passed away and though his legacy had lived on through the 1910s, the courses for rural electricians were cancelled by the 1920s due to new requirements in testing for electrician certification and a new emphasis on AC systems over the DC systems that were the primary focus of the classes and the windmill dynamo technology at their core. Legacy members of the network, particularly Johannes Juul, would serve as links between this era of Danish wind energy history and modern wind technology but by the 1920s, few traces of the network would be visible excepting the la Cour windmills still dotting the Danish landscape.

South of the Danish border in Germany, la Cour's technology was also visible in many places but the network was less solid during the early 1900s. Instead, an industrial-academic complex with Bilau and Betz at the center championed wind energy in Germany. The German story marks the first link between
theoretical aerodynamics and the development of wind energy technology embodied in the rotor designs of Bilau. However, Bilau was fighting an uphill battle and while he was relatively successful in using the new technology to keep alive waning tower mill systems, the technology was never commercially successful as a stand along product for new electricity demand. Again, the advanced state of rural electrification in Germany would limit the need for DC based windmill dynamo systems in the country. However, of that era, legacy components of the Bilau-Betz network would survive in particular in the form of foundational scientific theory on wind energy in the form of Betz’s advancement of momentum theory applied to wind energy and the general body of aerodynamic knowledge of the AVA regarding propeller design and theory.

These theories of propeller performance would influence thinking about the new “wind charges” in the United States through the work of Fales and others in the military who were interested in wind generators for aircraft electric power. By the late 1920s, Fales was already aware of Betz’s work and the theoretical limits for windmill propeller efficiency and there were even links between this knowledge transfer from Germany and wind charger entrepreneurs in the United States – for example the exchange between Manikowske and Fales at an annual American Society for Mechanical Engineers conference in 1927. Still, general design for wind charger design in the United States depended on experimentation and experience. The Albers brothers and Jacobs' brothers represented typical wind charger designers from the period. Their education typically did not extend past high school and it was their practical education working with and building technology for use on their respective farms that led them to develop interest in wind-generated electricity. The approaches of the Albers and the Jacobs to wind charger design was quite different – with the Albers seeking the lowest possible upfront design cost with reasonable reliability and the Jacobs seeking to build things that would “last forever.” Still, in the United States in the 1930s there was certainly room for both design philosophies. The depression had come to the United States and at the same time, rural electrification rates were very low.

At the same time, however, rural Americans began to seriously demand electricity for their homes and in particular the new radio technology that would connect them with the world in a ways that they had never experienced before. Radios and lighting represented the first main drivers for electricity needs on farms – something that small wind charger systems coupled to batteries could easily provide. Radio companies, Zenith in particular, saw the potential in the technology and actively joined the actor network – in Zenith’s case through direct acquisition of a wind charger company and co-marketing of products for a full “system solution” to rural electricity needs based on its radio and battery products along with the Wincharger generator system. On the other side, wind charger developers sought to promote their product through the development of compatible DC appliances – such as the Jacobs refrigerator and other products. Thus, while the market for windmill dynamos in Europe was already in decline from an early 20th century peak, the market for wind chargers in the United States was just developing and would reach a market size never before seen for the technology. Tens of thousands of machines were sold annually which created a relatively stable (albeit geographically spread out) network of wind energy actors including the wind charger producers, DC appliance makers, dealers and end-users on farms, ranches and many other places. By the mid-1930s, the actor-network for wind chargers in the United States, which extended to international sales in Canada, Europe and elsewhere as well,
was stable and flourishing. Unfortunately, just as in Denmark and Germany beforehand, at the same
time, the mid-1930s saw a significant shift in thinking about national support for rural electrification
with the creation of the Rural Electrification Administration (REA). Just as the network had become
stable, a new force embodied in the rural electrification movement would threaten its existence.

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### 3.7.1 Patent Citations


4 Big Systems from the 1930’s through the 1960’s – Centralized Grid Power for Everyone and the first Utility-Scale Wind Turbines

The dominance of the large centralized power system serving rural cooperatives from the late 1930s onward largely displaced the use of independent power plants for farms – including wind chargers. However, this new paradigm for electric power systems inspired a redirection of wind energy technology development efforts towards one that was compatible with large-scale electric power supply. These latter efforts would serve as points of accumulation of experience and knowledge in wind energy technology and would provide key sources of influence for subsequent development in the aftermath of the OPEC oil crisis.

4.1 Rural Electrification in the United States: The Grid versus Wind Chargers

A 1938 Popular Mechanics article about independent power plants, with significant focus on the Wincharger, suggested that even at that time about 1/3 of the 31 million homes in America still lacked grid-electricity and of these about half (5 million) were located on farms (“Electric Plants”, 1938). Census data from 1930, 1940 and 1950 show that the number of rural homes with electricity grew from 13% to 33% to 78% respectively (accompanied by similar growth in homes with radio sets from 21% to 60% to 92%) (Craig, 2009). In the 1930s, the market for wind chargers in rural communities was vibrant but from the beginnings of World War II and after, the market all but disappeared. There were many contributing factors to the decline, but the primary source was the growth of centralized grid power service in rural areas. Franklin Roosevelt’s New Deal in 1935 used the Emergency Relief Appropriations Act to create the Rural Electrification Administration (REA), and over time, REA would catalyze the extension of centralized grid power across the countryside and largely displaced the use of independent power plants including wind charger systems.

We organize the history of the development of the electric power system in the United States and Europe into a series of époques (Hughes, 1983). The first époque involved the introduction of electric power stations like Edison’s famous New York Pearl Street Station that began operation in 1882 and generally used a specific generator set to serve a specific load-type. These generally urban stations early on powered incandescent lights or arc lamps or streetcars or motors but typically not a combination of loads. The particular make-up of the network (AC versus DC, frequency and voltage levels) depended largely on the type of load they served. They were relatively small and isolated systems when compared to today’s large integrated networks.

The second era, according to Hughes, involved the development of the “universal system” for power that was first showcased by Westinghouse at the Chicago World’s Fair of 1893. As mentioned before, the system displayed how a variety of loads could be served from the same generation sources – potentially via back-to-back motor-generator sets but also through the introduction of the new rotary converter technology. The rotary converter, or mechanical rectifier/inverter, allows the conversion of AC to DC power and vice versa as well as converting between different frequency and voltage levels. Rotary converters and motor-generator sets, along with transformers, allowed for the use of large-scale generators to supply a variety of loads across an expanded distribution network. Samuel Insull of Commonwealth Edison in Chicago championed this type of system in particular. He led the way in the
United States by acquiring several smaller generator stations, turning the smaller stations into substations (retiring older generators) and supplying the whole system from new coal-fired steam turbine generators of 5000 kW and even 12000 kW in size (compared to 1000 kW size turbines which were considered very large at the time) (Hughes, 1983). To provide DC power to older sub-networks, systems used rotary converters and motor-generator sets.

Hughes defined the third era of development of the electric power grid as then the integration of various urban networks into larger regional networks – an effort largely driven by electricity demand associated with World War I and scaling up electricity-based industrial production for the war effort in 1917 and after. The coupling of different networks together provided the ability to take advantage of “load diversity” across different networks where different types of end-users typically demanded power at different times which thus meant that less overall capacity would be needed to meet peak demand for the region and a smoother electricity demand profile could be obtained. While this integration certainly had economic benefits, the initial driver for integration across separately owned and operated companies was the security of supply needs for supporting the war effort. In some cases, government entities ordered integration due to concerns with supply shortages after the winter of 1918. The technical distinctions of this époque compared to the last included the use of multiple types of generation facilities to provide electricity for a diverse set of loads across an integrated transmission and distribution network – the form, more or less, of the modern electric power system. These integrated systems required complex control systems to ensure in particular network stability and more generally a matching of demand with load. Inventors developed various technologies to support the central dispatching system including sophisticated relays, circuit breakers and switches for direct control of machinery as well as a telegraphy based communication system with a large array of measurement technologies to monitor equipment at all points on the network (Hughes, 1983). This third époque also saw the development of public holding companies and very large-scale grid development that meant consolidation and creation of the grid system that would persist throughout the middle of the 20th
century and even today in many areas. This latter effort was the result of risk diversification at an institutional level rather than a physical level as in the third époque. By having assets across greater and greater geographic regions, utilities could mitigate against risks of downturn in demand in one area (due to weather factors like drought etc.) by having assets in other regions with dissimilar risk profiles.

Table 4-1: United States Electric Power System Époques

<table>
<thead>
<tr>
<th>Époque</th>
<th>Years of Coverage</th>
<th>Technical Characteristics</th>
<th>Institutional Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>1882 - 1893</td>
<td>single generation / single load-type systems</td>
<td>Integrated equipment / utility companies</td>
</tr>
<tr>
<td>2nd</td>
<td>1893 - 1917</td>
<td>Large single generation / multiple load-type systems</td>
<td>Integrated equipment / utility companies and utility companies</td>
</tr>
<tr>
<td>3rd</td>
<td>1917 - 1935</td>
<td>Multiple large generations sources, high-voltage transmission, and diverse distribution systems with centralized control of operations (the modern grid)</td>
<td>Mergers and consolidation leads to large public holding companies separate from equipment manufacturers</td>
</tr>
</tbody>
</table>

Various aspects of this development process would affect the wind charger markets and actor-networks that had developed in the late 1920s through the 1940s. Firstly, there was the general trend toward consolidation in the electric power systems with the creation of larger and larger institutions to manage a diverse portfolio of generation, transmission and distribution assets across a complex integrated system. Independent systems with wind chargers or diesel-generators at their centers did not fit in within this large-consolidated system paradigm. Nor technically were the two systems inherently compatible. First, there was the matter of the wind charger technology that was predominantly DC-based technology. As mentioned, the Jacobs Wind Electric Company sold not just the charger system but also a portfolio of products to operate on the 32-V DC wind-charger/battery system. These included the special refrigerators and freezers designed by Jacobs as well as various other kitchen appliances and motors and tools – some designed and built in-house and some provided by electric appliance companies and distributed/sold by Jacobs wind charger dealers (Plowboy, 1973). What Jacobs provided was a complete electricity supply system for the home. Other companies, like Wincharger Corporation, which had originally developed 6-V wind charger systems to power batteries for radios and a small number of electric lights, also had begun to offer a 32-V wind charger system to use with a large number of appliances.

A rotary converter with some switching and control mechanisms would have made it possible to use either grid power or battery power to provide electricity for the DC appliances from a wind charger home system. However, the technical compatibility had not just to do with the end-user but the overall network whereby a sophisticated central control system constantly monitored load and supply in a
delicate balancing act. What is now known as “distributed generation” where small generation networks exist on the distribution side of the network, was very much outside of the paradigm at the time where large centralized generation stations provided power to transmission networks and ultimately to downstream distribution networks. In hindsight, it is hard to say how those early systems for managing energy balance and security on the grid would have accommodated distributed generation from wind energy across various nodes in the network. At the time, utility networks were struggling with understanding and maintaining stability on the largely unidirectional system and some early precursors of the digital computer, such as the “continuous integraph” developed at MIT or the “differential analyzer” developed at the University of Pennsylvania, specifically addressed the analysis complex non-linearities in power system operation (Hughes, 1983).

Still, the presence of a few 32-V wind chargers at the end of a distribution network would not have noticeably affected the load profiles of these large regional power systems. The bias against non-utility generated power was systematic and affected not just distributed wind energy systems but also much larger cogeneration facilities. The idea of using waste heat energy from power production for additional power production (called cogeneration) was already common with the use of steam power. Thomas Edison’s Pearl Street Station used as early as 1882. Cogeneration for production of district heating was actually quite popular in the early days of electric grid development where power plants were located near to end-users and thus the heat supplied nearby buildings (Pierce, 1995). Before World War I, there were supposedly 400 non-utility companies selling heat and power from cogeneration plants. However, by the 1920s, utility rates were so low (due to the growth in economies of scale by holding companies as well as direct efforts by those companies in some cases to reduce rates where cogeneration plants existed) that cogeneration made less and less economic sense (Pierce, 1995). The growth of centralized grids in the third époque favored large central generating stations providing system power located near coal mines in order to improve scale economies by creating very large generation plants and also to avoid issues associated with coal-transportation to generation plants (which induced critical power shortages in World War I) (Pierce, 1995). These “Steam condensation plants” typical of current coal-fired power plant configurations condensed the exhaust steam in a closed-loop system rather than using the exhaust for heating as was done with cogeneration district heating systems. In order to push out other independent cogeneration plants, utilities apparently provided more attractive electricity rates to industrial customers with attractive cogeneration opportunities (Pierce, 1995). This trend continued into the 1930s and after even with the introduction of gas turbine technology which was more compatible with industrial cogeneration – the number of cogeneration plants (including utility-owned) remained roughly constant from 1950s to 1970s (Pierce, 1995). Thus, from the 1920s onward, a bias existed in the electricity sector towards utility-owned large-scale centralized electricity generation regardless of the electricity source. Note that by 1949, less than 2% of overall generation came from non-utility sources, and independent generation continued to fall until it had all but disappeared in the early 1970s.
Electricity Generation from Non-Utility Sources as a Percent of Overall Generation in the United States from 1949-1972

Figure 4-11: EIA Data for Electricity Generation from 1949 to 1972 from Non-Utility Sources as a Percent of Overall Generation (U.S. Energy Information Administration, 1993).

4.1.1 The Rural Electrification Movement

Returning to wind generated electricity in the 1930s, system compatibility was not necessarily a concern to farmers in rural America in the 1920s. Farmers who bought wind charger systems in the 1920s and 1930s typically did not have the option of access to centralized power. As mentioned before, roughly, 10% of rural Americans had electricity from centralized grid networks in 1920 but by 1945, that number had increased to about 50% (Brown, 1980). This grew largely by the creation at the federal level of the Rural Electrification Administration and its direct funding of rural electricity cooperatives that would buy power wholesale from utility companies and would own and maintain their own distribution systems.

By the end of the 1920s and in the wake of the great depression, there was a great deal of dissatisfaction with the holding companies and their perceived abuse of market power. When it came to rural electrification, Senator George Norris of Nebraska suggested, “universal electrification of both homes and industry [was] being postponed only by the exactions of a little group of selfish monopolies. [The utilities were] foolish indeed if they think they can stop the demand for cheap electric current by floods of misleading propaganda” (U.S. Senate, 1929). Norris was a strong champion of rural electrification on the federal level and worked with the Roosevelt administration and others to promote utility reform and rural electrification. Experience and knowledge about electricity for rural areas came from other countries in Europe (such as Germany, Denmark and France) where they typically had a combination of subsidies and rural cooperatives as well as from Canada where there were some initiatives involving public power projects (Brown, 1980). The perceived role of electricity in rural life
had changed and US President Franklin D. Roosevelt himself stated that electricity was no longer a luxury (Brown, 1980). There were even successful examples of rural electrification and public power in the United States – most notably the creation of the Tennessee Valley Authority and the establishment of the Alcorn Cooperative in 1934. In World War I, the consolidation of electricity that led to the third époque of power in the United States also inspired the idea of large comprehensive energy networks. As part of the consolidation and development of large supplies of electricity for the war effort, the “Muscle Shoals” project involved the development of Wilson Lock and Dam on the Tennessee River in 1918.

Figure 4-III: Wilson Lock and Dam on the Tennessee River near Florence, Alabama (US Army Corps of Engineers).

After the war, there was political dispute about what to do with the dam and Henry Ford even offered to buy the dam in order to establish an industrial park (Hughes, 1983). However, President Franklin D. Roosevelt was against any privatization of the dam and his campaign platform promoted reform in the utility sector and protection of national power resources against private interests. As president, he saw the formation of the federally owned Tennessee Valley Authority that still today manages the resources of the dam and larger valley region. There was little direction on how to operate the newly formed TVA and the Alcorn Cooperative was an outgrowth of collaboration between new TVA officials and the local townspeople. Not only did the cooperative work on hooking up rural communities to new lines but the community had increasing access to electrical appliances through the federal “Electrical Home and Farm Authority” that worked with manufacturers to standardize specific electrical appliances and financed their purchase (Brown, 1980). This view of publically owned power was very much in line with the ideas of Morris Cooke, the first leader of the Rural Electrification Administration. During World War I and after, Cooke proposed “Giant Power” for the state Pennsylvania where generation was provided by large publically-owned generation stations and utilities then bought the power and served it to customers (with a mandate for providing power to rural areas). On the other hand, utilities in Pennsylvania and elsewhere favored a “SuperPower” system that continued under private ownership and where rural users would have to pay for a portion of the cost of extending lines to serve them (Brown, 1980; Hughes, 1983). The growth of super power to rural areas was vital not just for providing electricity on existing farms but also for growing industrial activity in rural districts (Tripp, 1926).
Cooke was not against private ownership of transmission and distribution, but he felt that rates were too high based on how utility estimated asset values (generation in particular) were used to specify rates. By 1930, the top 16 holding companies controlled over 75% of the entire electric power industry and there was strong belief that the companies abused their market power position (Hughes, 1983). This led to the Public Utility Holding Company Act (PUHCA) of 1935 that increased regulation and forced divestiture of uneconomic utility assets and to the establishment Rural Electrification Administration (REA) in that same year. The passing of PUHCA created a “forth époque” for the electricity grid in which the holding companies were streamlined and regulated at a federal level to prevent the abuses of market power that the companies were responsible for in the 1920s and earlier. This époque persisted into the 1970s and thus prescribed the dominant form of the electric system during the better half of four decades.

Table 4-2: United States Electric Power System Époques

<table>
<thead>
<tr>
<th>Époque</th>
<th>Years of Coverage</th>
<th>Technical Characteristics</th>
<th>Institutional Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th</td>
<td>1935 - 1978</td>
<td>Multiple large generations sources, high-voltage transmission, and diverse distribution systems with centralized control of operations (the modern grid)</td>
<td>Federally regulated utility companies operating in contiguous territories</td>
</tr>
</tbody>
</table>
PUHCA redefined the utility industry and sought to eliminate waste and abuses by requiring them to register with the SEC, consolidating balance sheets across all operating units, and justifying a variety of financial decisions (U.S. EIA, 1993). Critically, PUHCA also flattened utility holding companies structure to avoid abuses associated with “pyramiding” that were characteristic in particular of super holding companies (holding companies for a set of utility holding companies) (U.S. EIA, 1993). Furthermore, PUHCA included the “death sentence clause” which gave the SEC authority to shut down or force divestiture of utilities with uneconomic assets. Thus, the new world of PUHCA focused on heavily regulated large integrated utility systems.

The previously cited poor economics of building power lines to remote sites coupled with the impact of this “death sentence” clause of PUHCA resulted in an environment where utilities had little incentive to cooperate with REA. Because of this, Cooke, the new head of REA, used the initial funds of $15 million granted to the agency to start working with newly establish rural cooperatives to build lines and purchase wholesale power from nearby utilities (Brown, 1980). REA operated on a loan system whereby the government granted loans to either fund development of transmission and distribution by cooperatives or re-wire individual properties of cooperative members. Despite initial attempts by utilities to thwart REA’s efforts, the agency gained momentum and by 1945 when REA’s charter was up for renewal, about 50% of rural Americans had access to centralized electricity. Over the next 10 years, REA ensured that the rest of rural America had access and by the 1960s, centralized power systems supplied nearly 100% of the country.

The original leader of the administration Morris Cooke summed up what REA meant for small independent power plants and said, “if service is established, then the Delco people can come in and make almost as much in selling refrigerators and other apparatus that uses the high lines as selling their own plants” (Righter, 1996). Delco was a company that produced gasoline-powered independent power plants – Wincharger and other wind charger companies offered mechanisms for coupling a wind charger with a Delco gasoline-powered plant. Delco, and by extension the wind charger companies, were not included in REA plans – independent power was simply not part of the REA solution for rural electrification. The loans from REA went to the cooperatives and the customers of cooperatives – not to individual farmers for individual plants. This was something that one wind charger industry member, Robert F. Weinig, sought to change when the government reevaluated the charter for REA in 1945. Weinig moved from serving as the head of farm radio sales to general manager of Wincharger Cooperation for Zenith Electronics Corporation in 1940 (“Weinig Heads Wincharger Corp”, 1940). Weinig was aware that continuation of REA activity would mean a continued shrinking market for independent power plants and wind chargers specifically.

52 Private utilities had strong ties to state legal communities and regulatory authorities and would often use power to slow approval of new cooperatives; in addition, “snake lines” or “spite lines” were often built by utilities to serve only the most lucrative customers in rural areas which made it difficult for cooperatives to become financially solvent or even stopped their development altogether if laws prevented them building lines within certain distance of utilities lines (Brown, 1980). Ultimately, the courts weighed in favor of REA and the cooperatives and the efforts of private utilities to stop cooperative development were thwarted.
In 1945, Weinig testified before the Subcommittee of the Committee on Interstate and Foreign Commerce of the House of Representatives in order to propose an amendment to House bill number 1742 concerning amendments to the Rural Electrification Act of 1935. Specifically, Weinig suggested amendment of section 3 of the Rural Electrification Act of 1935 with the following additional italicized text:

“SEC. 3. (a) The Reconstruction Finance Corporation is hereby authorized and directed to make loans to the Administrator... [provided that] such obligations incurred for the purpose of financing the construction and operation of generating plants, electric transmission and distribution lines, or systems including wind or engine driven generating plants, towers, batteries and other necessary generating, transmission and storage equipment for use in connection therewith shall be fully amortized over a period not to exceed twenty-five years...” (U.S. House of Representatives, 1945).

He went on to note a precedent set in Canada that provided 10-year state financing of wind charger plants (U.S. House of Representatives, 1945). Weinig bolstered his argument by using information from the administration’s own economists that had suggested repeatedly that profitable cooperatives were possible where there were three customers per mile of line. Cooke himself was famous for quoting the three customers per mile to bolster his arguments that rural electrification was economically feasible for a large number of potential rural customers. Weinig, in turn, suggested that west of the Mississippi, there were some 1,000,000 unelectrified farms located in areas were the density was less than 1.1 farms per mile; such farms could benefit from loans for individual electric plants if REA cooperative loans for building lines to those areas were uneconomic. Weinig suggested that at present, there were not loan terms of sufficient length to allow farmers in these areas to properly finance such wind charger plants. A loan of $896 USD over 10 years would sufficient to finance the entire individual power plant (whereas average line cost for REA lines were $970 USD at the time based on total loans over miles of line built).

His ideas and suggestions gained a decent level of interest from the committee including California Representative John Carl Hinshaw and Arkansas Representative Oren Harris. Both men asked a wide array of questions about the physical operation and cost of the technology as well as the potential market. Representative Hinshaw in particular seemed to embrace the potential of independent power plants and suggested that “sometimes when you look for area coverage you are going to have situations develop in which to cover the entire area you would have to increase the cost of power to all of the users of the power if the costs were to be spread uniformly over all of those who use the power, and that perhaps to confine actual production of electricity and sale of electricity to those farms that could be economically served by power lines and then fill in the space with some wind- or power-driven equipment in the other places might be an economic benefit to the ones in the area served” (U.S. House of Representatives, 1945). However, on further questioning Representative Hinshaw seemed to convince himself that the maintenance of such equipment would pose a significant challenge and Mr. Weinig did not seem to provide him with a sufficient response to how REA might manage such a system of equipment maintenance. Throughout the rest of the hearings, there did not seem to be subsequent appeals for the inclusion of individual power plants or discussion by the committee on their inclusion in an amended Rural Electrification Act.
Ultimately, the effort was not successful and REA continued to interpret the language of section 3 to concern only centralized power systems and not individual power plants. In 1948, Claude R. Wickard further affirmed that the agency solely focused on centralized power when asked at a committee hearing on the use of REA funds for farmers in “sparsely settled areas.” (U.S. Senate, 1948). REA turned down some of them for loans based on the remoteness of their locations and Wickard believed that better power sources or consolidation of territories would be the solution to help such farmers. Senator Edward Gurney of Florida asked him if REA might loan farmers funds for “wind charger machines” under such circumstances to which Wickard replied, “I do not believe that our legal people have said we could do that, because the act specifies that we are to make loans for the purpose of bringing central-station electricity service to unserved people. It is our opinion that “central-station electric service” would not include the individual plant.” (U.S. Senate, 1948). Wickard’s associate Mr. K. Wilde Blackburn supported this and testified that a question on the subject submitted was to the Attorney General who ruled that a wind charger was not a central-station service entity. Senator Gurney then asked that regardless of legality if the government could save money by funding independent plants (like wind chargers) rather than investing in lines to sparsely settled areas and whether Mr. Wickard would recommend Congress approving such authority. Mr. Wickard replied that he would not and in his experience, he found that the overall cost for wind charger systems were $2000 USD fully installed – significantly more than the $896 USD figure suggested by Weinig – and that same $2000 USD could be used to build 1 or 2 miles of line (U.S. Senate, 1948). He further criticized independent power for lacking functionality of central-station service in providing the growing electricity needs for farmers for a variety of functions and the operational costs for such a plant (in particular the batteries which required replacement every few years as well as other maintenance costs). Senator Gurney was not satisfied and further pushed the issue as a temporary solution for very remote locations, but Wickard insisted that building high-lines was the best course of action even in such circumstances even though Wickard firmly suggested that central power was not economically feasible at the time for all rural locations. From the dialogue, it is apparent that REA officials were staunchly opposed to independent power and wind chargers.

Still, even without REA support, there was no mandate for farmers with existing plants to join cooperatives nor was there anything prohibiting a farmer from choosing an independent power plant over joining a cooperative. While the economic terms of REA certainly made joining a cooperative attractive, particularly farmers who already had independent power plants did not have the same incentives to join up with a REA cooperative. But, Wickard again seemed to indicate that there weren’t any farmers who would fall into that category and that the only reason that a farmer was not hooked up to REA by 1948 was for lack of resources from REA to distribute to new cooperatives. In a congressional hearing in 1948, Wickard suggested that wherever a REA “hi-line” was present, the farmers chose to apply to hook up to it. When asked if any had not applied, Wickard replied, “They are rare. I do not know of any group of farmers today any place in the country who are not demanding this service. Moreover, most of them are very much disappointed because they cannot get it or have not gotten it before. There might be one or two farmers some place who do not want electric service, but I could not find one…” (U.S. Senate, 1948). Not only that, REA favored funding cooperatives on the transmission and distribution side of the grid that would purchase wholesale electricity from centralized utilities. Wickard illustrated their policy by suggesting that REA was “anxious to use all the funds [they could] for
building of lines to distribute electricity and not put[ting] any more than necessary into the generation of electricity. [REA’s] borrowers [were] buying 90 percent of their power from [utility] suppliers” (U.S. Senate, 1948). The focus of REA on building “hi-lines” and not generation reinforced the growing paradigm of regional power systems with large central generation that supplied large-scale transmission to distribution networks on the end of the system – in other words, one-way power flow. REA acted as an agent to reinforce the technical paradigm of the modern electric grid while independent power plants (by design) challenged it.

With all these momentum towards large modern centralized grid systems, there was little space for the wind charger to continue to develop. However, the limits to further development of wind charger power plants were not just institutional. It seems, that there many technical limitations of wind charger power plant that encourage farmers to abandon them in favor of REA cooperative high-lines. A few perspectives on life with a wind charger hint at the limitations (italics added in all cases):

“In 1940 or 1941 Daddy put up a wind charger which provided enough electricity to operate a radio and to have electric lights if we used both very conservatively. It has a large battery to store the electricity and of course we had to use the lights sparingly unless the wind was blowing, and our listening to the radio was more or less allotted time... occasionally we had enough electricity to listen to ‘Mystery Theater’ or ‘Kraft Theater,’ dramas that came on once a week... We used 25-watt bulbs to conserve electricity. Today we might think that they would be impossible to read by, but compared to kerosene lamps they seemed very bright. We tried to save the electricity so that we would have light for homework. We finally got electricity provided by the REA when I was in high school and then we could use the radio and lights more regularly, keeping in mind the cost of electricity.” (Wood, 2010).

“In later years Aunt Bud and Uncle Ira had a wind charger, and all it was, was a generator with a propeller on it. It’d charge that wet-cell battery and that would just run the radio, was all it was good for.” (Sitton, 2003).

“For decades after real electricity came to the community the wind chargers remained in place, locked solid with rust or fanning loosely from one breeze to the next. Every farm kid I knew was forbidden to climb the wind charger, and the iron ladders leading up to the narrow platform on top always had the first section covered or removed to keep us off. We all got pretty good at it. Perhaps they were left in place because they filled a need in that relatively treeless landscape, some vertical element to balance the flat reach of prairie. More likely the huge angle-iron A-frames remained like crossed arms, waiting for the newfangled electricity to fail for good. Call it practicality or pessimism, it was common sense to expect the worst... [after losing a series of crops] Dad picked up what work he could, leaving his own place to run a digger for the REA as the power poles marched south and the lines went up.” (Blunt, 2003).

“One of the first questions that people ask me when they hear I grew up in rural western Nebraska is, “Did you have electricity?”... My answer is always, ‘Yes and No.’ I do not remember our household without electricity... at some time, following the end of the depression, Dad put up a wind charger west of the house. This provided electricity to the house but not to the barn or any of the other outbuildings... The wind charger provided electricity for the house. When we did get the REA we got electricity in the barn and a big powerful yard light. It was a dusk to dawn
light that lit the entire outdoors around our place. At this time the wind charger was removed.” (Oldweiler, 2008).

The above stories from personal experiences illustrate that while a wind charger brought electricity to many remote farms, there were still challenges with the technology in the intermittent nature and small sizes of the systems that meant having to conserve electricity for only a few uses—namely electricity and lights. These systems were most likely smaller 6-V wind charger systems since the vast majority of systems sold were of the smaller configuration. Those with larger size wind charger systems, such as the 32-V Jacobs wind system, may have had a different story to tell and indeed, there were some individual who did choose to stick with their wind charger systems over hooking up to REA lines (Righter, 1996). In addition, wind charger manufacturers did try to promote their technology as a viable alternative to REA power. A national advertising campaign by manufacturers of independent power plants including wind chargers and battery storage systems was begun in 1935 and lasted through around 1939 (Richardson, 1961). The campaigns featured slogans like “No Tax on Wind. It’s free!” and “More Electricity than we can use” and touted the ability to supply a farm’s total power with a 32-V wind charger system so that “city light” was no longer necessary. The Rural Radio journal ran an article “How to get Free Electric Energy from the Air!” promoting independent power and wind chargers for radio applications since over five millions homes still did not have electricity and even under REA, there would still be four million “unwired” at least through 1945 (“How to get Free Electricity from the Air!”, 1938). The article contained detailed instructions for how to set-up such systems including controls, home wiring and quite a bit of information on the battery systems.
How to Get FREE ELECTRIC ENERGY FROM THE AIR!

In the United States today there are still over five million unwired homes, and if the REA program of Rural Electrification progresses twice as rapidly as it has during the past year there will still be over four million unwired farm homes in 1946.

Where the farmer is not fortunate enough to obtain rural high line service, the modern 6-volt wind-driven battery charger is coming into its own. Years of experiment plus scientific engineering and designing have brought constant improvement until today the 6-volt wind-driven charger is a far cry from the crude early models.

Contributing to the development of the 6-volt charger is the remarkable contribution of radio engineers, namely, the 6-volt all-electric farm radio, using no dry batteries, obtaining all of its power from a 6-volt wet battery.

These two units go hand in hand and give to the farmer the same modern all-wave radio reception that is enjoyed by his farmer friends having high line service available. Furthermore, they give to the farmer the same modern all-wave electric farm radio, using no dry batteries, obtaining all of its power from a 6-volt wet battery.

The generators employed on present-day chargers are especially designed to cut-in and start charging in winds of low velocity. They are precision machine made. They are thoroughly efficient and under average working conditions will last and give service at practically no upkeep cost for ten to fifteen years. Modern engineering has contributed highly successful governing devices which efficiently control the propeller speed in winds of high velocity and "slip the excess wind" thus making it entirely practical to mount the charger on the farm home.

Knowing that hundreds of thousands of these wind-driven chargers and 6-volt farm radios have been and will be used by our farmer friends, Rural Radio gives you an explanation of their installation and use.

GOOD INSTALLATION

The first requirement for successful operation of a wind-driven, battery charger is the correct foundation, where the charger has the free area away of the wind will be uninterrupted within 15 feet of the height of the charger, within a distance of 100 feet.

Figure 4-V shows a good and a fair installation as well as two poor installations.

CORRECT WIRE SIZES

| NO. 8 WIRE | Size B & X Gauge for use when distance from the generator to battery is under 50 ft. |
| NO. 6 WIRE | Size B & X Gauge for use when distance from the generator to battery is 50 to 100 ft. |
| NO. 4 WIRE | Size B & X Gauge for use when distance from the generator to battery is 100 to 150 ft. |
| NO. 2 WIRE | Size B & X Gauge for use when distance from the generator to battery is 150 to 250 ft. |

It must always be remembered that 6-volts require a low pressure current. A low pressure electric system is similar to a low pressure water system. A low pressure water system will work very successfully providing large enough pipes are used. Low pressure water systems, using a large enough size of pipe is used. Do not assume that any wire, regardless of size, material, or type of insulation will be satisfactory. Only heavy, weather-proof insulated copper wire should be used. Note wire chart showing the correct size of wire to employ for a given distance.

Figure 4-V: Rural Radio article touting the benefits for wind chargers for rural areas without REA lines ("How to Get Free Electricity from the Air!", 1938).
Figure 4-VI: Late 1930s advertisements for wind charger systems that feature the advantages of independent power including the "free wind and no taxes" (right) and the claim that a wind charger can provide farm electricity for 50 cents a year (left).
These campaigns, however, did not result in significant growth even though some farmers did indeed choose to purchase their own power plants instead of hooking up to REA (Righter, 1996). By the end of the 1940s, when Mr. Weinig testified, some 400,000 wind chargers had been sold worldwide although most were the smaller 6-V systems and only 25,000 were the larger 32-V systems which would provide power for an adequate range of farm electricity needs (U.S. Senate, 1948). Similarly, Jacobs estimated that they sold 50,000 wind plants through the 1950s when the plant closed (Righter, 1996). Thus, of the 1,000,000 or so potential farms in sparse rural areas, optimistically up to around 100,000 of them had sizeable wind charger power plant systems or only 1% at the peak.

By the end of the 1950's, nearly 100% of rural America had access to centralized power — much of the growth catalyzed or funded directly by REA. The lack of dramatic accounts of resistance to REA in favor of individual power plants is evidence that generally, rural communities were eager to receive centralized power. The “hi-lines” brought attractive features of near limitless power for a growing number of electric machines on farms without any of the maintenance and care needed for an independent power plant. Wind chargers needed constant “fussing” according to some accounts and a large number of farmers did not have training in electrical machinery needed to properly maintain an independent power plant (Righter, 1989). One claim is that the spread of television in the late 1940s and 1950s was the iron in the coffin for wind energy since television sets required AC power and could not run off the 32-V DC systems of independent power plants (Righter, 1989). As time went on, it also became more and more difficult to find DC appliances as the AC based grid system all but dominated the central power systems.

**Percentage Rural Electricity Coverage by Year in the United States**

![Graph showing percentage of American farms with centralized electricity service](image-url)

*Figure 4-VII: Percentage of American farms with centralized electricity service (Hunter, 1982).*
There were indeed many advantages to centralized power for rural America. Yet, some farmers initially resisted adopting the “hi-line systems.” However, even those who were not jumping at the opportunity to connect to the grid were eventually convinced otherwise. The REA engineers and representatives were zealous in their charge and there is evidence that they worked hard to convince owners of independent power plants to join the cooperatives and give up their plants (Righter, 1996). It is hard to say what might have happened if representatives Hinshaw and Harris had included the suggestions of Mr. Weinig in amended the Rural Electrification Act to include independent power. Certainly, we know the history that resulted from their inaction – by the 1950s, all of the wind charger companies, including even Jacobs Wind Electric Corporation and the Wincharger Corporation, had gone out of business or redirected their efforts towards other manufacturing activities. REA – the champion for rural electrification in the face of resistance by public utilities – had all but ensured the decline of the wind charger and independent power plants for rural America by reinforcing the large centralized grid system at the same time not offering any support for the development of independent power plants in the most rural areas.

4.1.2 Revisiting Rural Electrification in Europe and the Decline of Wind Motors

The decline of wind chargers in the United States in the late 1940s and 1950s due to the growth of centralized power systems supplying electricity to rural areas mirrored similar developments in Europe from a much earlier period. Rural electrification was a focus of national efforts in Germany and Denmark long before the creation of REA in the United States and is reflected in the high rates of rural electrifications in those countries already by the 1930s (from 30 to 90% depending on the source of the estimate). Because of this, the challenges faced by wind chargers in the United States much earlier thwarted the development of the technology in those countries – the most notable case being the rise and fall of la Cour style wind turbines in Denmark that peaked in World War I and declined continuously thereafter. The inability of Bilau to make substantial inroads with his technology in Germany is another example of how early development of rural electricity systems in Europe cannibalized the market for independent power and wind energy. In many ways, it is not surprising that the more population dense regions of the Europe had rural electrification much earlier than the United States. Cooke and others highlighted repeatedly that a good rule of thumb was that at three farms per mile, construction of utility lines would be economically feasible and certainly most farms in Europe likely met this criteria.

Still, Europeans were more proactive in early considering the coupling of wind power plants with fossil-fuel based generations. Previously, we saw that la Cour plants sometimes integrated to central DC-based generation facilities in order to serve as supplemental power. Similarly, in Germany, there were plans that suggested wind power could operate in parallel to coal power as an energy saver (as coal shortages were a known issue in Europe). However, already this brought up concerns about cycling of the large coal-fired boiler based power systems when compared to the potential of gusty winds that ramped up and down frequently (Heymann, 1995). Wind energy did not appear to have much potential for development as large predominantly coal-fired power plants grew in size and number to supply the bulk of electric power in northern Europe. The spread of AC based power systems in Europe reinforced these challenges. But unlike in the United States, where the market for DC-based wind charger power plants did not appear to adapt to the new AC-based world, in Europe, there were several
developments looking at AC wind power plants that could be compatible with the large AC power plants and AC appliances that used the electricity.

Already mentioned was the Agricco motor designed by Johannes Jensen and Poul Vindig in 1919. The Agricco wind motor could operate with either a DC or an AC generator and was installed at a generation facility of the NESA electricity company near Copenhagen in 1921 (Thorndahl, 2009). At the site, the induction generator did not hook up directly to the grid; instead, a Professor Absalon Larsen suggested the use of DC-AC motor-generator set to convert the DC power of the Agricco wind motor to the AC system at the grid frequency (Heymann, 1995). Apparently there were many issues with the DC-AC motor-generator set including significant noise, vibrations and power surges and the system so that the system was abandoned already by 1922 (Heymann, 1995). DC-AC motor-generator sets were cumbersome. A rotary converter was a possibility as well, but the key to compatibility with the AC systems was an asynchronous or induction generator that would allow the windmill to operate at variable speed through the principle of “slip.” Thus, it would provide energy still nominally at the grid frequency when connected to a large central grid system that would act as the “speed regulator” of the turbine. Similar ideas existed in Germany in the 1920s with the idea of using induction generators for grid-compatible energy production not just by wind motors but also by waste energy from industrial plants and other facilities that produced a large amount of heat (Heymann, 1995). Both small-scale industrial cogeneration of waste energy and wind energy could use induction generators to operate on a large grid system. Still, there were concerns for wind energy in particular again with sudden gusts and overloads on the generator from the wind turbine, voltage drops on the grid side, and other concerns which would require sophisticated control systems specifically tailored to a grid-connected wind motor (Heymann, 1995). Some questioned the idea of connecting a wind motor to the grid, however, by noting that such action went against the essence of wind motors that was there ease of installation and attributes of independence (Heymann, 1995). Such perspective, similar to that of the REA leaders, put wind power in a fundamentally different category from grid power – wind power was for small independent applications whereas the grid was for large centralized systems.

Throughout the early 1920s, efforts continued in Germany to research the adaptation of wind motors to interconnect with the centralized grid systems. University and research organizations such as the AVA where Bilau and Betz were performing aerodynamic experiments on wind turbines promoted these ideas, and there were proponents in power systems research on the topic of grid-connected wind power plant systems with induction generators (Heymann, 1995). However, even by the end of the 1920s, support for research and development of wind motor systems had subsided in favor of large centralized power systems supplying power for everyone.

4.1.3 Summary of Wind Chargers and Rural Electrification from the 1920s
The disappearance of wind motors and wind chargers in Europe and the United States from the 1920s on stems from the spread of large centrally controlled and developed electric power systems. Firstly, there was the tendency of electric utilities to displace all independent generation systems – not just wind energy but also cogeneration plants – as they sought to increase their economies of scale. Mechanisms for reducing rates for customers who might otherwise pursue co-generation are stark examples of utility bias against other forms of generation on the grid. The bias is also evident in the
United States proposals for “Superpower” and “Giant Power” which proposed large central coal-fired condensing power plants near mining operations with large transmission systems to move the power to end-users. Secondly, there was the development of rural electrification in Europe and the United States and the expansion of the grid system into remote areas. While, rural electrification in the US lagged Europe by a large margin, the effect was the same: there was no room for independent power plants including wind motors and wind chargers. Whether adverse to the technical limitations of integrating small distributed generation plants with the grid or whether simply for the economic reasons of serving as much energy to as many customers as possible, rural electrification efforts over time displaced wind energy plants. There is evidence of overt bias against wind chargers by the REA in the United States as can be seen in the congressional testimony of REA head Claude Wickard in 1948. But the decision to move from wind charge systems to the grid was not just pushed for by REA, there is evidence that farmers enthusiastically shifted to “hi-line” power given the consistent supply, the ability to add additional end-use machines as needed, and the avoidance of maintenance issues associated with the independent power plants – in particular the batteries. Thus, even though wind pioneers like Marcellus Jacobs and others had overcome significant technical obstacles to develop reliable and capable wind charger systems, they simply could not compete against the grid as its tentacles spread further and further into even the most remote areas of the country.

4.2 Utility-Scale Turbine Development Efforts in the 1940’s through the 1960’s
By the 1940s, it was clear everywhere that large regional power systems and countrywide centralized grid networks were going to be a permanent fixture in society. Any efforts for the development of wind energy technology thus had to conform to this new paradigm. The wind energy actor-networks in both Europe and the United States had all but disappeared. In Europe, the days of la Cour and Bilau were long gone and in the United States, sales of wind chargers were on the decline and World War II would only exacerbate the situation as wind charger manufacturers shifted their production to aid in the war effort. Indeed, even the Wind Charger Company (now known as WinCo) shifted production to airplane technologies – dynamotors to supply power for aircraft communication systems (not RATs as were discussed in the last chapter, but alternator type of equipment which could be driven by auxiliary system connected to the airplane drive shafts).
At this point, the history of wind energy technology could have been complete, but there were a few individuals and organizations that sought to resurrect wind energy technology in a completely new form. In the 1940s and 1950s, we see the first introduction of large-scale wind turbines for AC power generation compatible with modern electric grid systems. These modern wind turbines were developed as separate and independent initiatives across several nations including the US, Russia, England, Denmark, France and Germany. The proposed configurations were reasonably similar, propeller-rotor horizontal-axis turbines and were all striking technological developments in terms of their large sizes,
ranging from 100 kW in Russia, France and Germany to 200 kW in Denmark, and to 1250 kW in the US (Putnam, 1948; Schmid and Palz, 1986). Putnam, lead engineer on the Putnam-Smith turbine, did an extensive survey on wind energy technology prior to selecting the configuration for his own design. The bibliography of his book alludes to “a partially annotated bibliography of upwards of a thousand references dealing with the prior art” in wind turbine technology (Putnam, 1948, p. 213). He was well aware of the work of those wind pioneers discussed in the previous chapter including designs using the Magnus effect (Flettner and Madaras), vertical axis (Savonius), and horizontal-axis (Darrieus, Fales, Bilau and Honnef) (Putnam, 1948). The most significant of these efforts with respect to larger size turbines developed in the 1930s were that of French engineer Georges Jean Marie Darrieus and a state-organized Russian engineering team. The Darrieus machine was a 20 m diameter 2-bladed downwind machine with fixed-pitch (stall-regulated) on a lattice tower according to his US patent for the design (US Patent 1820529). The design had very thin blades that straightened under the centrifugal loading of the turbine in operation – thus balancing the thrust from the wind in the other direction. The machine operated at a high tip speed ratio of 10:1 and stall regulation controlled the rotor speed at high wind speeds (Darrieus, 1931; Putnam, 1948). A prototype of the machine was built in 1929 in Bourget, France.

The second key wind technology demonstration in the 1930s took place in Balacava in Crimea, Russia. Putnam was heavily influenced by the design and thus his book featured a relatively detailed description.
of the key design features including a 100 ft. (30.5 m) diameter 2-bladed rotor with a 100 kW induction generator with centrifugally activated pitch control and an electronic yawing system (Putnam, 1948). The strut also served to transfer thrust loads to the ground. While the pitch control mechanism was similar to that seen by other systems before, the induction generator and electronic yaw control system were quite novel. As discussed, the induction generator allowed the machine to operate over a range of speeds (due to induction slip) while seamlessly interconnecting with a larger grid system (it was connected with the peat-burning power station). The electronic yaw system included a 1.1 kW motor that responded to wind direction changes electrically signaled from a wind vane on top of the nacelle. The advanced yaw system for this larger size machine was necessary since the machine operated upwind. The machine included quite bulky and the tip speed was much lower than the Darrieus design (4.75 versus 10) so that the overall efficiency of the machine was quite low – 24% at its maximum speed of 30 rpm (Putnam, 1948). But, perhaps due to the bulky design, the machine apparently operated for quite some time (up to a period of 10 years or more) (Nielsen, 2010). Putnam reasoned that the bulky design was in part due to the lack of access state-of-the-art forged steel parts and gearing due to the Russian state interest in the project. This Russian design heavily influenced the Putnam design - the first multi-megawatt turbine built and grid connected wind turbine in the United States.

Figure 4-X: the 100 kW wind turbine built in Russia in 1931 was the largest built to that time and one of the first large turbines to be grid-interconnected (Putnam, 1948, p. 106).
4.2.1 Utility-Scale Turbine Development in the US: the Smith-Putnam Turbine and Percy Thomas' grand plans

In the United States, Palmer Putnam led an effort in the 1940s to scale up from tiny radio wind chargers to huge multi-megawatt machines. The humungous prototype wind turbine stood atop Grandpa's Knob in the Green Mountains of Vermont with plans to develop a series of similarly large turbines in the works. The Smith-Putnam embodied the latest science and technology developments of the period and the project provided an important source of influence for modern design of wind energy system.

Influenced by the Smith-Putnam project, Percy Thomas of the Federal Power Commission developed plans for even larger machines. While Thomas' work is less influential, it is a second point of comparison to European efforts that, as shall be seen, focused on the development of much smaller machines with greater emphasis on gradual scaling of technology.

4.2.1.1 The Smith Putnam Turbine

Following the Russian and French projects, the Smith-Putnam wind turbine sought in the United States to provide electricity generation compatible with large-scale centralized electric power systems that dominated the electric sector already by the 1940s. The engineer Palmer Putnam who conceptualized the project gave a detailed account in his book *Power from the Wind* published in 1948. Various aspects of the project have been discussed in terms of how the turbine design influenced later efforts particularly by the United States NASA wind turbine research program in the 1970s (Gipe, 1995, Karnoe and Garud, 1999; Heymann, 1995; Heymann, 1998; Garud and Karnoe, 2003; Nielsen, 2010). The project indeed was grand in size and hubris. In the academic work described above, the later efforts influenced by the Smith-Putnam turbine have been critiqued including many of the design features of the Smith-Putnam turbine itself (Heymann, 1998; Nielsen, 2010). Still, the project highlights the intersection of state-of-the-art pre-World War II science in aerodynamics, structures, and electrical engineering with a quite modern utility-scale grid-integrated wind turbine. In addition, many design features of modern machines are part of the Smith-Putnam turbine design and merit discussion.

Indeed, the Smith-Putnam wind turbine was the first modern wind turbine to be designated as such. Even the French and Russian examples of medium-sized wind turbines were called "les moteurs a vent" (wind engines), "eoliennes electrique" (electric windmills), and "aero-electric units" (Lacroix, 1929; Sectorov, 1933). As early as 1940 in project reports, the terminology of "wind-turbine" was used to classify the large wind electricity conversion system (Putnam, 1948). Putnam's first patent submission on the project submitted in 1935 used the terminology "aero-electric power plant" (likely borrowed from the Russian usage) while the two patents submitted in 1941 on the comprehensive design used the term "wind turbine" (Putnam, 1938, 1944a, 1944b). No other patents up to that time had used such terminology to describe a wind electricity conversion system. Instead they had used words like windmill, wind charger, wind motor, wind engine, wind driven power plant, wind operated power plant, aero-electric generator, wind generator, wind wheel generator, wind propelled generator, windmill electric generator, wind power machine and others. It is likely that the common term for the technology today, the wind turbine, originated from the Putnam project.
The conception of the project began with Palmer Coslett Putnam who had graduated from MIT in 1924 with a degree in geology. He came from a well-to-do family. His grandfather, George Palmer Putnam, had started as a junior partner with the publishing house Wiley & Long in 1834 and subsequently a partner at the firm under the new name Wiley & Putnam (Wiley.com, 2016). Under George’s efforts, Wiley & Putnam became the first American publishing house to have a significant presence in Europe and John Wiley & Sons, Inc. continues to be one of the top book publishing companies in the world. George, however, sought to create his own mark by leaving Wiley & Putnam to form G. Putnam Broadway. Palmer’s father George Haven Putnam then took over the company when George Sr. passed away and renamed G. P. Putnam’s Sons publishing – a publishing force that has continued operating into the present day though now as part of Penguin Random House (Penguin.com, 2016). Palmer took over the family publishing business after he graduated in 1924 from MIT. Palmer’s father, mother and siblings received recognition for their scholarly work primarily in the areas of history and his cousin George Palmer Putnam (named after his grandfather) was a scholar and explorer most famous for being married to female aviator Amelia Earhart.
Palmer Putnam, in contrast to many in his family, was quite oriented to modern technology more than scholarly history. In 1934, with the wealth from his publishing company work, Putnam had a house built on Cape Cod. It was at that point that he was set himself to develop a wind electricity generation system. The cape region of Massachusetts had used wind power in the production of salt in the early 1800s and the consistently high winds along the coast coupled with high electric bills inspired Putnam to look to wind generated electricity for his new home. The 1930s represented a high point for sales of wind charger systems but on inspection, Putnam decided such units were much too small to provide the electricity he needed for his home (Putnam, 1948). It is unclear if he was aware of larger Jacobs Wind systems, but certainly, the radio-style wind chargers such as the Wincharger machines would have been too small for his “all-electric” house. Through a few inquiries, Putnam eventually got in touch with Elisha Fales, discussed in the previous chapter for his work on wind tunnel tests of small wind chargers for RATS as well as rural applications. Fales provided Putnam with one of his own two-bladed test units for exploring the wind conditions on his site; during this time, Putnam spent a great detail of time researching wind energy development efforts up to that point (including the French and Russian efforts described above) (Putnam, 1948).

It was during his review of the other machines and experimentation with the Fales machine that Putnam began to conceptualize his own design influenced by primarily the French and Russian designs. He filed an early patent on one such design that demonstrated his lack of depth in technical knowledge but a general understanding of key design criteria. However, unlike past wind electricity generation efforts, Putnam focused from the beginning on a grid-integrated system. This opened up the question, as stated by Putnam, “is it possible to convert gusty wind into alternating current so steadily that it will be acceptable to the dispatcher of a utility high-line?” (Putnam, 1948). Rather than concerning himself with storage of the energy generated intermittently by the wind turbine, he focused on how to provide that electricity to the larger grid system. In addition to this new concern, Putnam focused on addressing perennial concerns of wind electricity generation including constant power supply via speed control and system safety/reliability through a series of protection methods. In addition, whereas Betz had introduced the notion of variation in system design based on different geographic conditions, Putnam early on focused site selection that would properly support maximization of power production.
Low maintenance requirements / automated operation

Wind Energy System Success

Low maintenance requirements / safety

Low overall system cost (cost / kWh)

Maximizing power / site specific design

Constant power supply via speed control

Grid interconnection stability

Putnam's US Patent 2106557 shows the importance of these criteria in his early design process (Putnam, 1938). Much of the patent focused on the control system that included an electrically controlled pitching mechanism to keep the blades at a constant angle of attack and a set of controls between the induction generator and the grid for stable grid interconnection. The blade pitch mechanism activated by force from solenoids that responded to a temperature signal from the generator. High speed would cause more resistive losses in the windings that would increase temperature – beyond a certain threshold then, the pitch mechanism would activate to adjust the pitch of the blades and keep speed roughly constant. For the grid interconnection, a centrifugal governor would activate a switch to connect the generator to the grid when the speed of the machine was within a certain tolerable range (i.e. when the slip of the induction generator was relatively small). Beyond this, the patent features Putnam's interest in using gusty high-speed winds in energy generation due to the dependency of power generation on the cube of the wind speed. This latter interest was reflected in site selection for the Smith-Putnam machine on top of a hill in an effort to capture the speed-up of gusty winds over the structure.

After a few years of reviewing literature on previous wind electricity machines, talking to technical contacts on design and working with Fales small test turbine, Putnam had developed his design enough to capture the interest of MIT Dean of Engineering Dr. Vannevar Bush. Dr. Bush, an important catalyst in the development of the Manhattan Project and many other US military technical programs in addition to many career accolades in aerospace and information technology developments, was so impressed with Putnam that he recruited him to join him at the Office of Scientific Research and Development in 1940. In 1937, Bush connected Putnam to MiT Department heads in meteorology (Dr. Sverre Petterssen) and civil engineering (Dr. John B Wilbur), and then Putnam was further connected with Thomas Knight, the Commercial Vice President of the General Electric Company in New England, and Theodor von Karman, Director of the Guggenheim Aeronautical Laboratories of the Guggenheim

Figure 4-XII: Design criteria as seen from Palmer Putnam - replacing adequate means for energy storage with grid interconnection stability and site / function design variance with maximizing power extraction
Aeronautical Institute (Putnam, 1948). This set off a formal effort to turn Putnam’s vision into a reality. In 1939, through connections from GE’s hydroelectric specialists, Alan Goodwin, to hydraulic turbine manufacture S. Morgan Smith Company’s New England representative Howard Mayo. The president of the company, Beauchamp E. Smith, was already looking to broaden the company’s product portfolio and Goodwin and Mayo were able to sell him on the project (Putnam, 1948). The company was facing a tough economic climate for its hydraulic turbine business in the wake of the great depression and was hoping to use a new wind turbine business to bring work new work into its factories (Smith, 1981). In addition, Goodwin was able to leverage his connections to the utility industry to sell the project to Walter Wyman, President of the New England Public Service Corporation, who arranged for interconnection of the turbine to its Vermont subsidiary – a utility that used predominantly hydropower and could benefit from the wind-generated electricity to balance its hydro reserves (Putnam, 1948).

From that point, a formal process for development of the turbine was underway now named the Smith-Putnam wind turbine project. The S. Morgan Smith Company revisited Putnam’s cost calculation to inform the bulk dimensions of the turbine and found that a 1500 kW turbine with a rotor diameter of 200 ft. (61 m) on a 150 ft. (45 m) tower would be the most economical from a large scale production standpoint (Putnam, 1948). Ultimately, likely due to constraints on available generator configurations, the Smith-Putnam turbine had a 1250 kW generator, a rotor diameter of 175 ft. (53 m) and a hub height of 120 ft. (36.5 m) above the ground (located on the 2000 ft. (610 m) Grandpa’s Knob hill in Vermont (Putnam, 1948). Remembering Putnam’s emphasis on strong gusty winds, the design philosophy was to seek out hilly areas where speed up of the wind over the hill would allow the machine to capture more power at lower heights. Putnam had reviewed German Hermann Honnef’s designs for very tall-towers with multiple rotors and had decided that Honnef “had exaggerated the importance of height” (Putnam, 1948, p. 108). That is, Putnam assumed that the wind shear (increased wind speeds moving vertically from the ground since the wind is less retarded by the friction of flow interaction with the earth’s surface) was not significant. Of course, we have to look at this exaggeration from Putnam’s perspective. From a very early point, the project focused on the peaks of the Green Mountain Range in Vermont for use as a test site. Putnam was certain that the speed up of wind over hilltops was essential for economic success of a large-scale wind project since it would allow the project to achieve high wind speeds nearer to the ground. In fact, Putnam assumed that the wind speeds due to speed-up would be higher than could be achieved by going to very high heights above ground.
Putnam acknowledged that in 1939 at the time of project design that there was a great deal of uncertainty in the knowledge surrounding the wind resource either free-stream or affected by topography. Estimates on the speed up for different ridges in 1939 were inconclusive based on both site measurements and a large series of wind tunnel tests so that the selection of the Grandpa’s Knob test site was done in advance of a major data collection and analysis campaign that took place from 1940 to 1945 (Putnam, 1948). The turbulent flow from interaction of winds with complex terrain can have a strong interaction with the wind turbine structure—inducing significant loads and vibration in the machine. Putnam and his colleagues assumed that the compression of the airflow streamlines over the ridge would tend to dampen turbulence and thus they used statistics on turbulence over flat land in their design process for the turbine. Thus, the Smith-Putnam turbine was perhaps the first turbine in history designed for very specific site conditions in terms of estimated wind velocities, the turbulence profile, and the wind orientation due to flow distortion over the summit. The orientation of wind flow over the summit influenced the rotor orientation and the inclination of the rotor-nacelle-assembly in an effort to position the rotor parallel to the direction of the flow—12.5 degrees which also included consideration for the sizing of the main shaft (Putnam, 1948). For an upwind orientation, the blades deflected towards the tower even with no inclination. To turn the rotor perpendicular to the direction of the free stream wind directed upward over the hill, the rotor would have had to tilt downward and would further exacerbate the danger of tip deflection and potential for the blades to strike the tower (tower-strike). The only option, from Putnam’s vantage point, then was to orient the turbine downwind in operation. Thus, the emphasis on designing the wind turbine specific for the hilltop location determined the orientation—one of the most important design features.

The physics of wind flows in particular around complex terrain (such as hills and other structures) can introduce significant amounts of turbulence.
Having selected a site, basic design features for the system were selected and rigorous system design followed. The first design decision was the power capacity of the machine. A small-scale test machine of 1/7 scale was briefly discussed as an option for an initial design and built but was dismissed based on the lack of inertia that such a small unit would provide when interconnected to the grid (Putnam, 1948). While generator inertia is an important mechanism for maintaining stable grid frequency for large grid systems, the lack of inertia from one small test unit on the system would likely not have had significant impact—the decision based on this rationale seems somewhat unfounded. Still, it highlights the cautious approach of traditional utility engineers towards the integration of a variable resource even at that small a scale. In addition, the move towards large centralized power systems favored synchronous generators and integrated large-scale generation and his General Electric project partner Thomas Knight told Putnam that utilities favored synchronous machines (Putnam, 1948). However, synchronous machines operate at a specific speed or frequency while wind turbines by nature operated with variable speed. The gearbox and the generator used a hydraulic coupling in order to allow for “slip” between the low speed and high-speed sides of the drivetrain. The synchronous machine, once grid connected, would continue to operate at the grid frequency and speed while the turbine, operating at a range of speeds, would transmit its power to the synchronous generator. Thus, the design had a size of 1250 kW using a synchronous generator.

The second key configuration parameter for the machine was the rotor size—this was determined primarily based on the optimization studies that the S. Morgan Smith Company had performed and came out to a diameter of 175 ft. (53 m). Combining the rotor size and the generator speed, 600 rpm, the team could calculate general dimensions for the gearbox and other drivetrain components. In late 1939, the S. Morgan Smith Company was overwhelmed with orders for its hydraulic business as the US entered into wartime production mode once again for World War II. They outsourced the project to the Wellman Engineering Company of Cleveland, Ohio and Putnam became project manager. Just over 6 months later, however, Putnam left the project to join Dr. Vannevar Bush in DC at the Office of Scientific Research and Development and Dr. John Wilbur, Dept. Head of Civil Engineering at MIT, took over the project as Chief Engineer (Putnam, 1948). Given Putnam’s lack of engineering experience (as shown in his 1935 patent), it is likely that much of the specific design and even key architectural attributes were
made by Wilbur and other collaborators on the project. In particular, Putnam mentions Dr. Theodor von Karman in many of the discussions surrounding the design of key system features. Still, Putnam appears to have been involved in many of the decisions about the system architecture.\textsuperscript{54}

The key architectural decisions for the turbine included the generator type and size as well as rotor diameter size as previously discussed. After that however, there were a number of other architectural decisions starting with the number of blades. Von Karman's work on rotor performance showed that 2 blades were nearly as efficient as 3 blades for producing power (only a 2 percent difference) and thus, 2 blades were selected in order to reduce system mass and cost (Putnam, 1948). Another key design feature associated with the rotor was allowing the turbine to cone. Putnam had seen fixed coning in wind turbine designs such as that of Darrieus and smaller windmills – the technique reduced the moments and stresses on the blade roots in particular. In the Darrieus system that had a horizontal shaft, the coning provided additional stability for the system during yaw – though Putnam was convinced that the inclined shaft was superior and necessary especially for application on ridges that were the focus of the project (Putnam, 1948). Putnam was further convinced that because of the gradient in wind flow across the rotor for large turbines that a variable coning would be needed to allow each blade to cone separately at an angle that to reduce the moments and stresses (Putnam, 1948).

Each blade experienced different wind speeds due to both wind shear as well as the influence of the tower on the wind flow. A centrifugal speed governor controlled the pitch of the blades for regulation at higher speeds. The rotor connected to the low speed side of the drivetrain that included two main bearings on the low speed shaft connected to a gearbox connected to the hydraulic coupling via a flexible coupling. Finally, the entire rotor-nacelle-assembly balanced on the pintle girder, oriented via pintle shaft rotation, and turned on the pintle driven in yaw by an electric motor controlled set of bull gears (Putnam, 1948).

Even today, many of these key design features would be considered novel (the downwind coned two-bladed rotor), others have become common design practice (the use of an electrically-controlled / geared yaw system and a 4-pt geared drivetrain configuration and electronic pitch control) while others are outdated at the moment (the use of lattice tower structure), and others just seem bizarre (the pintle support structure and some particular aspects of the pitch and coning mechanisms). Regardless, the complexity of the entire system is evident and the design of such a turbine would have been a great challenge in particular given the state of knowledge in atmospheric science, aerodynamics, structural dynamics and other fields. Through networking primarily via Vannevar Bush, Putnam was able to bring together some of the leading scholars in the country and the state-of-the-art science and engineering of the time was brought to bear on the particular physical aspects of the design as well as its testing and operation.

\textsuperscript{54} The two patents on the wind turbine design were taken out by Putnam but signed over to the S. Morgan Smith Company
4.2.1.1.1 The Science and Engineering of the Smith-Putnam Turbine

While Putnam was involved with the general design of the turbine, Dr. Theodore von Karman and Dr. John Wilbur respectively oversaw the major engineering of the rotor aerodynamics and structure of the machine. The latter, Dr. John Wilbur, was a professor in the civil engineering department of MIT at the start of the Smith-Putnam project and later became the head of the department from 1944 to 1960 when he retired. In contrast to Putnam, he came from a modest background. His father was a public school teacher in New England (first Maine and then Massachusetts) and John went on to attend MIT for his bachelors, masters and doctorate – then becoming a professor and working his entire career at MIT. As a civil engineer, he designed several large projects in the New England area – primarily bridges – and was part of the Freemasonry in Boston (webmuseum.mit.edu, 2016). He worked with Dr. Vannevar Bush on a follow-up project to the “network analyzer” mentioned early for analyzing operations of new large-scale electricity networks. His “Wilbur simultaneous equation calculating machine” (the Wilbur machine) was a large mechanical system for solving systems of equations (up to nine simultaneous linear equations) that could add in the analysis of both mechanical and electrical systems (webmuseum.mit.edu, 2016, Wilbur, 1936). The machine was similar to differential analyzers (a mechanical computer for solving differential equations) built Dr. Vannevar Bush and represented a precursor technology to the electromechanical and all electric computers developed from the late 1930s onward. Such machines were useful for studying complex physical systems and the Japanese built a copy of the Wilbur machine for their own use in aeronautical research during World War II (Princeton.edu, 2008).

The wind turbine project intrigued Wilbur early on and performed some of the preliminary stress analysis on the machine to size the various mechanical components (Putnam, 1948). Once the project was underway, Wilbur became even more involved as a consultant and then the Chief Engineer of the project once Putnam left for DC. The design of the overall machine was then distributed across various parties, including Harvard, MIT, the California Institute of Technology Guggenheim Aeronautical
Institute, S. Morgan Smith Company, General Electric, the Wellman Engineering Company and American Bridge Company and overseen by Wilbur (Putnam, 1948). Wilbur oversaw the mechanical design of all major components across the geographically dispersed set of institutions – a systems engineering feat novel for any technology let alone an experimental technology like a wind turbine. The task was complicated by the shifting emphasis towards wartime production brought on by World War II. One of the key limitations in the design process, and the one that ultimately would lead to the machine’s destruction, was the structural design of the blades. Because of the impending war, initial estimates of aerodynamic loads on the blades had been used to size-out many machine components and orders were rushed through to build them (Putnam, 1948). Complete analysis even in advance of the turbine being built showed that the structural design of the blade (the blade shank and shank spar) would be dangerously weak but a large blade shank and shank spar would require a new aerodynamic blade design using a thicker blade (Putnam, 1948). Neither a new blade design nor new forgings for the blade shank spar were possible to acquire and work proceeded for fabrication of the rest of the machine components and the erection of the overall machine.

Accurate estimates of the loads and potential stresses on the different components for such a large machine were difficult due to several factors including the huge uncertainty around the science of aerodynamics for wind turbines and the related branch of physics of aeroelasticity (the science that looks at the static and dynamic interaction of fluid flow (like wind) with structures (elastic bodies) that can respond to that flow). Even so, the Smith- Putnam project had the benefit of a close collaboration with Dr. Theodore von Karman of the Guggenheim Aeronautical Institute at the California Institute of Technology. Dr. von Karman had come to the institute from Germany in 1930 due to his fears concerning the rise of the Nazi party. He was born into a prominent Jewish family in Budapest and went to Germany to study under Ludwig Prandtl at the University of Gottingen. There he began what would become a very successful career in the new field of theoretical aerodynamics with a long list of contributions to theory development and translation of that theory to inform practical machine design. Many studies tout the influence of the Guggenheim Aeronautical Institute and von Karman’s intellectual leadership as the fundamental enablers in the success of US aerodynamics and aviation – catching up from the lag behind European countries after World War I - while others suggest that the catch-up was already well underway by that time (Eckert, 2006). Von Karman’s mark on US aviation and aerospace science and industry is strong. Beyond his academic accomplishments, he was a co-founder of the Aerojet Company in 1943 and helped establish a number of scientific organizations including the NASA Jet Propulsion Laboratory in 1944. He overlapped with Albert Betz one year at Gottingen but was no doubt aware of the work that Betz was doing on wind turbines during the late 1910s and 1920s. In some sense, von Karman was the conduit for transferring the state-of-the-art in wind turbine science and design from Germany to the US that manifested itself in the form of the Smith- Putnam project. While Fales was aware of Betz work and referenced it in his papers on his small wind turbines, it had not influenced (as far as is known) general practices in wind charger design. The Smith- Putnam project, on the other hand, benefited from the accumulation of wind energy science starting from la Cour’s time through Betz’ time up to the late 1930’s.
From correspondence, it appears that von Karman became interested in Putnam’s wind turbine ideas very early on in the effort and his name is mentioned several times regarding fundamental design choices of the machine in Putnam’s book on the project (Putnam, 1948). He was responsible for all the aerodynamic design and calculations for the machine (though others were involved in the final selection of the rotor aerodynamic design) and engaged with Putnam on many other design issues including the pitch control system, coning and rotor orientation and inclination (Putnam, 1948). He oversaw wind tunnel tests on various models of the blades, small-scale machines and even the hill landscapes to understand better the fluid flow around the different hilltops of the Vermont Green Mountains (Putnam, 1948). Von Karman was able to draw on his knowledge of wind energy developments in Germany as well as recent advancements in aerodynamics related to propeller theory driven by interest in improving airplane propeller performance as well as enabling the success of new technologies including autogyros (using wind power for lift) and helicopters (lift from a rotor driven by an engine).

The fundamental aerodynamic theory for wind turbines and propellers is the blade element momentum (BEM) theory mentioned in the previous chapter. Almost every research paper and book that uses or discusses BEM theory cites the work of British aerodynamicist Dr. Hermann Glauert (1934) which references the work of Albert Betz. Von Karman, a contemporary of both men, would have been familiar with this work and Putnam’s 1948 book on the project includes Glauert’s book as a key reference – the only reference on aerodynamic theory. The Smith-Putnam project was able to benefit for the first time from an integrated and comprehensive approach to calculating the power, thrust and torque for different wind turbine designs for different wind speeds. As discussed in Glauert’s book, the aerodynamic design focuses on three major aspects of the wind turbine blade: 1) the airfoil profiles along the blade (and in particular their lift and drag characteristics), 2) the blade plan form or more commonly the variation in chord (distance from the leading to trailing edge of the airfoil), and 3) the twist (or inclination angle of the blade sections from the blade’s primary axis) (Glauert, 1934). Varying these parameters given a target operating condition can help maximize the production of power. In 1939, von Karman worked to design a series of blades with different airfoil, chord and twist profiles, and he tested models of each in a wind tunnel to validate the calculations of performance (Putnam, 1948).

In designing the blades, von Karman leveraged the comprehensive work of the National Advisory Committee for Aeronautics (NACA) in developing various airfoil designs with different lift-drag profiles. Max Munk, another German transplant from Prandtl’s Gottingen group, worked with NACA in the late 1920s to develop a variable density wind tunnel that would remedy the issues associated with understanding airfoil characteristics that depended on the Reynolds number. The Reynolds number, as mentioned in the previous chapter, the Reynolds number is equal to the air density multiplied by the air speed and the characteristic length (typically chord length) over the air viscosity. By varying the air density, one could obtain a Reynolds number for a small-scale model of the airfoil that would be equal to that obtained for a full-scale model. This allowed measurements of airfoils lift and drag profiles in a consistent way that would be relevant for analysis of large-scale machines. By 1929, NACA created a numbering system as a standard for categorizing airfoils (the first digit was the maximum camber, the second where the maximum camber was located along the chord, and the last two the thickness of the airfoil as a percent of the chord). NACA then completed tests on a large number of airfoils in the 1930s to create large-families of airfoils of different archetypes (Bilstein, 1989). Von Karman was able to use
these airfoils in his design process for the Smith-Putnam blades. From the beginning of the project through 1943 (after the turbine was built), four studies were performed around turbine design. In each of first three studies, von Karman used BEM theory as the basis for design while in the fourth study he used the more advanced vortex theory (Putnam, 1948). Based on the second design study, von Karman designed the actual blade using BEM theory.

Likely due to manufacturing constraints, the ultimate design was of constant chord as mentioned using a constant airfoil profile of NACA 4418 with 4% camber at 40% chord and a 18% thickness relative to chord size (which was 11 ft. 4 in or 3.45 m) (Putnam, 1948; Wilcox, 1973). The ultimate blade design had about a 5-degree difference in twist between three sections of the blade (Putnam, 1948; Wilcox, 1973). The latter study above shows much cleaner chord profiles for the blades that reflect an anticipation of ability to manufacture more complex and even non-linear profiles. The blade length was 65.5 ft. plus an additional 21.75 ft. for the hinging mechanism for an overall rotor diameter of 175 ft. as mentioned before (53 m). At the rated speed of 30 mph (13.4 m/s), the turbine operated at 28.7 rpm for an estimated velocity of the tips of the blades as $28.7 \text{ rpm} \times \pi \times 53 \text{ m} / 60 \text{ s} = 80 \text{ m/s}$ which is a typical tip speed for rated operation of today's multi-megawatt utility scale turbines. Taking the rated
speed of 13.4 m/s, this gives a tip speed ratio of six, low compared to what theoretical recommendations for a 2-bladed or even 3-bladed turbine. Given the constant chord profile of the blade and only three sections of twist, the lower efficiency and tip speed are not surprising; one would expect the aerodynamic efficiency of the blade to be low – though there was not enough operational data to do a thorough investigation of the actual efficiency of the design (Putnam, 1948).

From the structural side, the material of choice was stainless steel for the skins and the spar was made of Cor-Ten (weathering) steel (Putnam, 1948; Wilcox, 1973). This again had to do with manufacturing and sourcing – due to the use of the American Bridge Company and Budd Company which worked primarily with stainless steel (versus the potential alternative of aluminum) (Wilcox, 1973). The selection of heavy steel material meant a relatively heavy blade of eight short tons (7.25 metric tons) (Putnam, 1948). As a comparison, a blade of similar length (20 m) using today’s composite materials would likely weight 2 tons or less. The heavy blade meant the loads on the blade roots would be even more significant. Based on the aerodynamic design and estimates of blade weight and mechanical properties, von Karman was then able to calculate the loads (thrust and torque) from the rotor that the rest of the system would need to sustain. Wilbur and the larger design team used these loads to dimension all of the components – from the internal blade structure to the foundation of the tower. However, according to Putnam, the comprehensive analysis on the aerodynamic loads were incomplete prior to finalizing the specifications on the blade design and this was what led to under sizing the blade shank and shank spar.

4.2.1.1.2 The Smith-Putnam Turbine in Operation
The ultimate fate of the Smith-Putnam is commonly known to those who have studied the history of wind turbine technology. The turbine was subject to about 1100 hours of test operation after erection in late summer early fall of 1941. The first tests involved running the turbine at rated speed with no-load (generator decoupled) in order to test the turbine in particular for flutter – an aeroelastic phenomena that was made famous in 1940 as the source for the destruction of the Tacoma Narrows bridge. On October 19, 1941, the turbine was finally grid connected and provided up to 700 kW of power to the Central Vermont Public Service Corporation (Putnam, 1948). Putnam touted this as the first synchronous generation of a wind turbine feeding into an electric grid (as opposed to the induction-based systems of the Russian and French efforts) (Putnam, 1948).

However, not all was smooth in the initial hours of grid operation – vibration quickly surfaced as a critical issue. The vibration was both side-to-side and up-and-down, the latter due to motion from the pintle shaft and girder while the former stemmed from forces from the yaw system in combination with torque around the inclined axis (Putnam, 1948). The yaw gearing was unexpectedly prone to small movements and a spring-loading system had to be added to secure it in place. The source of those forces primarily stemmed from the coning of the rotor that introduced cyclic loading to an extent not anticipated during the design process – softening the damping of the coning system alleviated the impacts of coning on vibration though some vibration was unavoidable (Putnam, 1948). Another early issue surfaced with the use of mercury-relay switches in the controls system for the turbine. Many of the switches were part of safety mechanisms that would cause the turbine to shut down during normal operation because vibrations in the system would cause the switches to activate or deactivate (Putnam,
Ultimately, the team replaced the mercury switches with mechanical switches. The downwind bearing (which would have absorbed the bulk of non-torque loads) overheated early in operation and had to be redesigned and replaced and over-heating of the hydraulic coupling required the addition of expensive cooling equipment in the nacelle (Putnam, 1948).

About 9 months into operation, problems that are more serious began to surface. During an inspection, the skin of the blade near the blade root over the spar showed cracks in several places. This indicated that the spar was too weak to carry the full load to the hub, and the team made repairs by placing a heavy box around the root section of the blade – via arc welding to the original structure (Putnam, 1948). The turbine continued to operate in testing mode until early 1943 when the redesigned downwind main bearing failed. It would take 2 years to procure a new main bearing for project during which reanalysis by Wilbur and his team showed that of the experimental data showed that the loads were higher than the design loads used in 1940 for dimensioning the various system components (Putnam, 1948). Wilbur immediately recommended decommissioning of the turbine to the S. Morgan Smith Company. This was in December of 1944, but in January of 1945, with the new main bearing finally available, a decision was made to run the turbine and it began operating again March 3, 1945. Just 3 weeks later on March 26, a catastrophic failure would bring the project to a sudden end (Putnam, 1948):
“On March 26th the midnight to 8 a.m. shift came on duty to find only about 5 miles per hour of wind. About 2:30 a.m., the wind freshened, and at 2:50 a.m., there was sufficient wind to start the unit. The unit was phased-in to the line at 2:55 a.m., when it was carrying from 50 to 475 kW of load.

At 3:10 a.m. Harold Perry, the erection foreman, was aloft, standing on the side of the house away from the control panel and separated from it by the 24-inch rotating main shaft. A shock threw him to his knees against the wall. He started for the controls, but was again thrown to his knees. He tried again, and again was thrown down. Collecting himself, he dove over the rotating shaft, reached the controls, and, overriding the automatic controls which were already functioning, he brought the unit to a full stop in about 10 seconds by bringing the remaining blade to full feather.

One of the 8-ton blades had let go when in about the 7 o’clock position [calculated by von Karman], and had been tossed 750 feet, where it landed on its tip.” (Putnam, 1948, p. 131).

The technical sources identified for the failure were the stress concentrations at the blade root that ultimately caused the blade to fail. Von Karman analyzed the underlying sources of failure and found several: 1) the weak initial design of the spar, 2) the arc welding of the box reinforcement to the spar, 3) perhaps most importantly, the loading on the failed blade when the turbine was down for two years (Putnam, 1948). During the downtime of the turbine, the blades did not rotate and the failed blade was consistently under load from the wind and gravity - waving in the air like a “fish pole” (Putnam, 1948).

Before the failure, the S. Morgan Smith Company in collaboration with the Central Vermont Public Service Company had started looking into a production run of turbines with an upgraded design. The new design addressed some of the known shortcomings of the test turbine including the underestimation of the loads and the interaction of forces from different parts of the system contributing to the vibration seen in the test unit. The primary design changes suggested in Putnam’s 1948 book included changes to address vibration including modifications to the coning system and hinge angles as well as a redesigned pintle shaft and girder (Putnam, 1948). They also included changes to blade structure and the hub / blade root interface even before the ultimate blade failure occurred.

However, by 1945 following the failure of the test unit, plans for production of more machines and the overall test program were suspended.

The Smith-Putnam project involved applying the best knowledge and resources to the development of a new modern wind turbine - one compatible with the new paradigm of central grid power. However, even with the best resources and knowledge at hand, the uncertainty and inexperience with large-scale wind turbines made success of the project unlikely. The new field of aerodynamics had only begun to witness the complexity of interaction of fluids and structures - largely through flutter but also other aeroelastic phenomena - and the sheer size of the machine and loads on such a machine in a dynamic environment like wind flow was well-beyond anything that the engineers on the project would have encountered previously. From today’s perspective, the failure of the blade at the root and failure of the main bearings do not seem surprising - these particular areas of the turbine experience complex loads that the wind industry research community is still trying to fully understand. Many accounts present the project as a failure that would foreshadow the perceived failure of future US government efforts in development of large-scale research turbines (Gipe, 1995; Karnoe and Garud, 1999; Heymann, 1995; Heymann, 1998; Garud and Karnoe, 2003; Nielsen 2010). Another way to look at the project is as a success in using the best available knowledge at the time to tackle a major engineering research
challenge from which we learned a lot and that knowledge transferred to the next generation of wind energy researchers. Perhaps the most critical aspect of the project focuses on the decision to go with a full-scale test unit prior to having any experience with smaller scale machines – with the second-largest wind turbine ever constructed 1/10th of the size of the Smith-Putnam project. The decision to go with such a large test-unit is perplexing and does indicate hubris or perhaps naivety on the part of the project leaders. It is certainly possible to argue that nearly as much could have been learned from a much smaller turbine given the novelty of the technology itself – it is likely that many of the same problems would have surfaced and more could have been learned by a series of different designs. This, as we will see, is closer to the approach of Europeans Johannes Juul and Ulrich Hütter.

Figure 4-XIX: The anemometer tree and turbine on top of Grandpa's knob (Voaden, 1943).

4.2.1.2 Percy Thomas and Plans for Big Wind Energy
One last effort sought to bring grid-connected wind energy to the United States and it came from an unlikely source. An engineer employee of the Federal Power Commission and MIT graduate, Percy Thomas, was an eager enthusiast for wind generated electricity and closely followed the Smith-Putnam project. He was able to obtain approval from his manager William Warne to study wind turbine electricity systems starting in 1943 through 1951 (Lines, 1973; Righter, 1996). His visions for wind energy were of a grand scale and in many ways mirrored those of Hermann Honnef of Germany. Like Honnef, Thomas never realized his designs, and the period after Thomas' failed efforts is the final stabilization of the large-scale centralized grid system from the end of World War II through the early 1970s.
By 1945, Thomas had already filed his own patent for one of his grand wind turbine concepts, the "aerogenerator tower" and it featured dual rotors for an overall output of 6500 to 7500 kW using 3-bladed and 2-bladed rotors respectively (Thomas, 1950; Wilcox, 1973). The tower was the unique part of the structure featuring "a revolving bridge" much like today's yaw systems or historically the tower windmills of Europe. The machine would balance so that the center of gravity for the entire nacelle would be within the bridge area in order to mitigate against the overturning moment on the tower structure (Thomas, 1950). The failure of the Smith-Putnam turbine did not deter Thomas — instead, he was critical of the main recognized failure of the turbine blade as a design flaw but still suggested that wind turbines (with his dual-rotor system) should between 5000 and 10000 kW in size in order to reach the right economies of scale for grid-integrated electricity generation (Wilcox, 1973).

The technical aspects of Thomas's design were never tested. In 1951, Thomas, with support of the Federal Power Commission, had a bill introduced to the House of Representatives (House Bill 4296 82nd Congress 1st Session) for a $2 million grant to support the construction of one of Thomas' giant machines.
Just as with the Smith-Putnam turbine, the effort did not include first developing smaller machines for testing. The committee that heard Thomas’ testimony was critical of the failure of the Smith-Putnam wind turbine project but ultimately was supportive of Thomas’ plans for development of a new large-scale test unit. The justification for such large machines centered around two primary national concerns: saving fossil-fuel energy and decentralization of power production for security reasons (Righter, 1996). The former would alleviate energy shortages seen during World War II where governments used gas rationing when supplies of petroleum became thin, and the latter was meant to address the growing concern around the threat of the Soviet Union and the start of the “Cold War” (Righter, 1996). For the Smith-Putnam project and in Thomas’ early work, project advocates touted wind energy as a complement to hydropower - an energy resource able to offset water usage - but it was also useful for offsetting use of what at the time were limited petroleum resources. In addition, the now assistant secretary of the Interior, William Warne, noted that wind energy plants could be spread far apart so that they would be less vulnerable to an attack if the US were to go to war again (Righter, 1996). Warne also tapped into arguments surrounding national pride in terms of the US not losing a competitive edge in the development of wind power (Righter, 1996).

Ultimately, the plans were not successful. The failure of the Smith-Putnam project certainly would have influenced house members, but ultimately, Righter (1996) pinpoints the reason for the bill failing as the national imperative for development of a “nuclear age.” In 1945, following World War II, the US Congress passed the McMahon bill to establish the Atomic Energy Commission and push for the development of a new primary energy source for the country. By 1953, the commission’s capital investment was over nine billion dollars that was more than that of General Motors, US Steel, Du Pont, Bethlehem Steel, Alcoa and Goodyear combined (Righter, 1996). Nuclear power also complemented the existing centralized grid structure as it involved large-scale generating plants that would provide base load power similar to coal. In that environment, Righter suggests that the success of the bill for Thomas’ wind plants were unlikely even without the scar of failure from the Smith-Putnam turbine project. It is perhaps fortuitous that Thomas did not realize his grand visions – given the scale of the technology and the knowledge limitations already mentioned around the Smith-Putnam project, the development of the Thomas turbine would likely have met a similar fate. As will be seen, the more modest approaches of Europeans Juul and Hüter resulted in wind turbines that were operational for several years or more without any catastrophic failures.

4.2.2 Utility-Scale Turbine Development in Denmark: from FLS Aeromotors to Juul’s Gedser Turbine

The onset of World War II had even more severe impacts on energy concerns in Europe and Denmark in particular. Similar to the last, the second world war meant another round of coal shortages – coal imports to Denmark were cut in half and oil imports were down to a quarter from pre-war levels (Christensen, 2008). Wind energy was yet again a way to provide electricity for a country that lacked its own indigenous energy resources. This meant the development and deployment of wind electricity generation systems both on small and large scales. The technologies involved reflected the early 20th technology of Poul la Cour as well as new aviation inspired propeller style technologies. The Lykkegaard Machine Works continued to make la Cour style wind plants for back-up power generation at power
plants through 1957 (Thorndahl, 2009). However, wind charger technology – seemingly inspired by the wind chargers of the United States – also inspired a new generation of small-scale wind turbines in Denmark. Richmond Trading out of Copenhagen began to produce such wind chargers in 1940 with a battery storage system and the ability to provide power for lamps and motors for small-scale power generation (Thorndahl, 2009). The model featured in particular the patented air-brake system of the Wincharger turbine that suggests that there may have been some technology licensing involved from Wincharger Corporation. Earlier it was discussed how hundreds of thousands of Wincharger style machines were sold during the 1930s through 1950s, and many of these were produced and sold outside of the United States.

4.2.2.1 F.L.S. Aeromotors

With the extreme coal and oil shortages imposed by the war, one company began to consider wind energy on a utility scale – that is, for providing energy to large industrial units and even to whole communities. The Danish F.L. Smidt & Co. A/S (FLS) was involved in a variety of industries with an emphasis on cement production, machinery and related technologies (F.L.Smidth & Co. A/S., 2016). With the German occupation of Denmark from April of 1940, the company could no longer export and ceased 96% of the company's business (Westh, 1974). The loss of export capability coupled with the knowledge of fuel-shortages (imports of diesel energy all but ceased at the same time) pushed the company to look for opportunities to keep business alive. Key staff noted that large scale wind turbines could be useful for supplying energy to diesel-based DC power system that were common in more isolated regions of the country (Westh, 1974). An early company memo from the responsible project engineer Helge Claudi Westh on subject in May of 1940 highlighted the reasoning for their focus on larger utility-scale machines: “We estimate a priori, that a multitude of small machinery manufacturers will join in on the manufacture of small wind engines, so that this will not be able to provide for FLS remunerative employment while there may be a chance of remunerative employment for the larger units in the region of half a hundred kW and above, those units that could set in very large farms, smaller industrial installations outside the cities, Dairies etc. ...” (translated from F.L. Smidth & Co. A/S, 1940a; Christensen, 2008). This first memo did discuss any specifics of machine design but a second memo written only days later discussed the relative advantages of the “flap-sailor” type of mills of the la Cour tradition in comparison to the newer “propeller-style” type of wind mills that gave about “30% more energy for the same sail area” (translated from F.L. Smidth & Co. A/S, 1940b). The references cited studies performed by a government committee on equipment (akin to a standards committee).

The memo also suggested that a 5-winged (or bladed) propeller style machine would be the best design since machines of 6-blades or more began to behave more like wind-rose style machines rather than propeller-style machines (translated from F.L. Smidth & Co. A/S, 1940b).

Westh, like many of the engineers of FLS, was a civil engineer. The company, as mentioned, focused on cement production and related equipment such that wind machines and the related aerodynamics were well outside of their expertise. Fortunately, the firm was a shareholder in the firm Skandinavsk Aero

55 Benny Christensen of DVS has written several articles on the FLS Aeromotors and much of the account here is based on his work and the associated archival material from DVS.
Industri A/S – a small aircraft firm in northern Jutland. Engineers Viggo Kramme and Karl Gustav Zeuthen co-founded the firm in the late 1930s, the former had a long history in aviation in the Danish Navy that included extensive experience in airplane repairs and the latter had been educated at the Technical University of Denmark as a civil engineer but developed an expertise in aerodynamics. Zeuthen became the key designer for the airplanes built starting in the late 1930s through the 1950s. Due to his expertise in aerodynamics, FLS asked him to design an initial test turbine in 1940. There is little information about Zeuthen’s educational background, but it is very likely given his education and role as airplane designer that he was familiar with the latest advances in aerodynamics from Prandtl, Betz and others. He applied this knowledge to designing the rotor for the FLS Aeromotor machines. With the addition of Zeuthen to the design team, the company constructed a prototype turbine and followed quickly with the commercialization and deployment of several 17.5 m 2-bladed propeller-style DC machines that could interface with the DC grids and independent power plants of factories and utilities in more remote parts of the country.

Just as with the Smith-Putnam turbine, the FLS Aeromotors team used latest knowledge in aerodynamics and mechanical systems in the design. However, unlike in the Smith-Putnam turbine case, little information remains about the design process involved for either the rotor or the rest of the machine design. In particular, there is no account of the thinking behind some of the key design decisions for the system. The only possible approach, then, is to use the information about the machine design itself and the few accounts that exist about the key decisions in the design process. Thus, here we must infer about those decisions based on the final product. Firstly, there are decisions surrounding the basic configuration – an upwind design with a two-bladed and then a three-bladed rotor. It is possible that given the predominance of upwind wind engines across Denmark at the time, both wind charger and flap-sail styles, that a downwind orientation was never part of the consideration set. Even for the prototype machines on lattice towers, the orientation was upwind. Secondly, there was the basic control scheme that involved the use of flaps for regulating the speed above rated power. Apparently, the pitch mechanisms of smaller machines had been investigated but were deemed too complex and the team selected the spring-actuated flap mechanism instead (Christensen, 2008).
Figure 4-XXI: FLS Ullerselv 2-bladed Aeromotor drivetrain and blades at the D.V.S. archives. Left: Hub mount for FLS 2-bladed aeromotor and picture of flap-actuator mechanism at the hub center. Right: the flap control mechanism attached to the blade flaps on the leading edge of the blade.

The team based the general sizing of 50/60 kW for the smaller machines and 60/70 kW for the larger machines on the desire to build machines of significant size for production of energy for factories and even small communities. As mentioned before, the desire was to use the machines to supplement power for predominantly diesel-based DC power systems in rural parts of Denmark. Given the extreme shortages of diesel-fuel in Denmark after the German occupation in WWII began in 1940, the deployment of DC wind turbines to these small power systems was a good business proposition for F.L. Schmidt and reduced some of the strain on these systems during the wartime. The original prototype machine (a 2-bladed 17 m diameter blade built in 1940) used a DC generator for power production but was coupled to an DC-AC rotary converter at the base of the tower that fed into a larger grid system (Westh, 1974). However, for the latter machines at factories and rural utilities with DC power systems, the DC generator fed its power directly to the local grid.

The hub and drivetrain had a relatively unique configuration by today’s standards. The hub was metal plate attached to shaft that passed through the gearbox with a main bearing support on either side so that it was a somewhat integrated drivetrain design (Christensen, 2008). Having selected the generators and the rotational speed of the rotor, the gearbox had a ratio to provide the step-up in speed needed to translate the slower rotor speed to the higher generator speed. The gearbox involved two parallel stages to step up the speed with a ratio of 1/15 for the 17.5 m diameter two-bladed machines that operated optimally at rated wind speeds of 10 m/s or more at 65 rpm for an overall generator speed of about 975 rpm. For the three-bladed machines, the design featured a similar gearbox configuration with a ratio of 1/25 for the 24 m diameter machines that operated optimally at rated wind speeds of 8.5 m/s or more at 57.7 rpm for an overall generator speed of about 1440 rpm (Christensen, 2008; Hilsen, 1942). F.L. Schmidt had a lot of experience designing geared systems for their cement and other material production factors (Christensen, 2008). For braking, several mechanisms protected the
machine against over speed conditions including the blade flaps mentioned above as well as a mechanical brake on the high-speed shaft (similar to modern machines). The yaw system design used a somewhat traditional design from Danish flap-sail style wind engines and traditional Dutch-style windmills for several decades. It involved the use of two transverse wind-rose style small turbines that connected through a worm and ring gear to the nacelle yaw ring would rotate the turbine to constantly face the wind (Christensen, 2008).

Figure 4-XXII: Front and back halves of the FLS Aeromotor 2-bladed machine from Ullerslev, Denmark now kept at the D.V.S. archives. The yaw worm and ring gear with the hub for the wind rose propellers are in the left corner of the right-hand photo.

Figure 4-XXIII: 3-bladed Aeromotor drivetrains at the Nordic Folkecenter in Thy, Denmark. Left: full drivetrain of the 3-bladed Gedser FLS Aeromotor. Right: Partial drivetrain of one of the 3-bladed FLS Aeromotor machines with the gearing exposed.

Even from inspection, one can tell that the FLS Aeromotors were very massive machines. The overall rotor-nacelle-assembly (RNA) weight was 8600 kg (Westh, 1974)\(^56\). The power to weight ratio for the

\(^{56}\) The weight is not given for a particular blade design. The initial designs used plywood while later blades had a metal skin. The plywood designs involved a mass of approximately 388 kg (Hilsen, 1942) for the 3-bladed system for a total of about 1200 kg for the rotor that would make the nacelle and hub mass about 7400 kg.
machine was then 70000 W / 8600 kg or 8 W / kg of RNA weight. Later machines of the 1970s from Denmark had power to weight ratios of over 11 W / kg and modern large-scale machines may have ratios in excess of 20 W / kg (Airmond, 2012). From the sheer sizing of the machine, we can see that the machine design would withstand very strong loads. As it turns out, the design loads used to dimension the blades and other components were based on extreme conditions involving operating at rated speed (57.7 rpm for the 3-bladed machine) in an environment with wind speeds of 50 m/s or wind speeds of 40 m/s with a misalignment of the rotor to the wind direction of up to 30 degrees (Hilsen, 1942; Westh, 1974). For perspective, machines today shut down for wind speeds in excess of 25 m/s and feather their blades to avoid operation in such extreme conditions. These conservative design conditions led to a drivetrain (including mechanical and electrical components) with an estimated life of 30 years according to Westh (Westh, 1974). The two cases above represent the most extreme design cases considered, but two other design cases were considered as well including loads at stand-still in winds of 50 m/s and operating at rated speed in winds of 0 m/s (a fictitious case to explore the balancing of centrifugal loads with the blade bending moments) (Hilsen, 1942).

Engineers also used these design cases for dimensioning the blade structure. Zeuthen performed the rotor design – including the aerodynamics of the rotor and the structure of both the blades and the hub – potentially with help from colleagues at Skandinavsk Aero Industri A/S. As mentioned earlier, Zeuthen, educated at the Technical University of Denmark, would have been exposed to the latest theory and design practices in aerodynamics – in particular given the close association of Denmark and Germany where Prandtl’s laboratory was pushing forward theories in aerodynamics including Betz’ work specific to wind turbine design. Zeuthen was also familiar with work in aerodynamics across the ocean and in fact, just as von Karman for the Smith-Putnam turbine; he used NACA airfoils in the design of the rotor. Also similar to the Smith-Putnam turbine, the design involved a relatively simple construction most likely to ease manufacturing. The twist of the blade was constant, but due to the smaller size of the machine and the use of glued plywood for the blade construction, there was a possibility to vary the chord and airfoil design along the blade span. For the actual design of the 3-bladed 24 meter diameter machine design in 1942, the general airfoil design was fixed using NACA Airfoil 23012 whose design and properties were published just a few years before in 1936 (Jacobs and Pinkerton, 1936; Jacobs and Clay, 1936; Hilsen, 1942). The airfoil was designed and tested using the variable density wind tunnel as part of a general class of airfoils for medium thickness and moderate camber (arch) similar and showed improved characteristics compared to earlier airfoils of the same class (such as NACA 2212) since it has a similar lift/drag profile but significantly lower pitching coefficients (Jacobs and Clay 1936: Jacobs and Pinkerton 1936). The low pitching moment coefficients could have been helpful if torsion were a concern for the slender 24 m diameter FLS machine blades. The airfoil had smaller thickness than the NACA 4418 used on the Smith-Putnam turbine (12 versus 18%) and a smaller camber (2% versus 4%). See a comparison of the two airfoil shapes below.
The chord did in fact vary along the length of the blade and similar to a modern turbine, the chord increased from the blade root to a maximum at about 25 to 30% span and then decreased moving towards the tip (Hilsen, 1942). The original design used a wooden structure made from glued Oregon pine and oak (5 cm thick) for the blade root and inboard sections of the blade while lighter plywood was used for the outboard section (Aeromotor, 1942; Christensen, 2008). In order to design the blades from the structural side, the same design cases were used for operating at rated speed in extreme conditions of 40 and 50 m/s wind speeds (in the former case with a misalignment of the machine yaw angle with the incoming wind direction). This again, led to a blade structure that was quite strong and the rotor was structurally reinforced in both the two and three-bladed cases by braces attached from the shaft to a point about mid-way along the span of the blade. Engineers later estimated the lifetime for the blades at about 10 years (Westh, 1974) and in fact, the blades were the only substantial part of the FLS Aeromotors that needed replacement about 10 years after the start of operation. Rather than replace them with new wooden blades, the original structure of Oregon pine and oak was preserved but with a new stainless steel canvas covering to create the aerodynamic design of the blade. These new metal-covered blades were used until decommissioning of the turbines in the late 1950s (Christensen, 2008; Westh, 1974).
Ultimately, all of the loads produced by the rotor sized not just the drivetrain but also the tower (also affected by the weight of the rotor-nacelle assembly). The early prototype turbines were placed on lattice-towers, but due to the lack of available steel or perhaps also due to the company’s interests in cement production, the towers for the production units were all of concrete (Christensen, 2008). The concrete towers have been a particular focus of discussion for the FLS Aeromotors because they triggered the only significant design change after the program started development and also because they were very strong structures (Christensen, 2008, Westh, 1974). Even today, a constraining factor on tower design is the resonance of the tower natural frequencies with the frequency with which the blades pass by the tower. These rotor frequencies depend on the rotor speed and the number of blades of the machine and for each of the turbine types (the 2 and 3 bladed machines) approached 3 Hz which in many cases was higher than the natural frequency of the tower (especially on where soft soil conditions were present) (Christensen, 2008). These created resonance with the tower during operation that caused vibration in the tower leading to the formation of small cracks. To address the issue, reinforcement ribs attached to each of the 4-sides of the tower in order to provide additional stiffness and increase the natural frequency to higher values over 3 Hz so that even at rated speed, the natural frequency of the tower was above the frequencies of the rotor (Christensen, 2008; Thornildahl, 2009). Later estimates showed that, after reinforcement, the towers were likely to have lifetimes of 100 years or more for the FLS Aeromotor applications (Westh, 1974; Christensen, 2008). Thus, the drivetrain and tower for the machines had levels of reliability well-beyond those of modern machines.
All of these physical design features indicate that the FLS Aeromotors were built to last. The decision to use extreme design conditions of operation in extreme wind speeds with direction changes indicated that the design process was conservative. It is unclear who made the decisions about which design cases to use for load estimation. Zeuthen, who came from the burgeoning aerospace industry and who would have been concerned with safety, may have chosen a worst-case scenario for loads estimation. Alternatively, Westh and his team at FLS Aeromotors may have had concerns about the reputation and performance of the new machines so that they would not break down. Either way, both the structural design and even the operation of the machine embodied a risk-averse approach. In the second case, risk-aversion is visible in the controls used for operation of the machines. An instructions document that provides detailed operation instructions for the machine was translated into English in the 1970s as part of the NASA wind turbine research program (F.L. Smidth & Co. A/S, 1975). The instructions describe mechanisms for speed control and braking, and in addition to electronic actuation of these elements, a windlass at the base of the tower that could manually activate the flaps and mechanical brakes. Similar to earlier machines, the machine also had a control system of relays to connect and disconnect the machine from the generator depending on the machine rotational speed and voltage levels in the system; this included a set of overvoltage controls as well that may surface when strong gusts would induce high voltage transients in the generator. There was also significant concern about winds that “come from behind” (when the wind direction is misaligned more than 90 degrees with the machine) and a specially braking system to avoid rotation of the machine in the opposite direction from that to which it was designed (F.L. Smidth & Co. A/S, 1975).
The company built and deployed the FLS Aeromotors were in 1941 through 1944. In total, the company built 19 Aeromotors in addition to the prototype machine and 7 of those were the 3-bladed configuration. Their operation reflected the reliability built into the machine in most cases. The prototype machine itself suffered a catastrophic blade failure similar to the Smith-Putnam turbine and threw the blade nearly 1 km, and two other machines caught fire possibly due to lightning events but potentially due to electrical failures as well (Christensen, 2008). Most of the machines, however, continued to operate for many years. However, 1944 would be the last year of production for the FLS Aeromotors for several reasons. Firstly, the end of the war meant the end of German occupation and F.L. Schmidt would again be able to participate in its more lucrative and primary export businesses. Secondly, there was a push in Denmark after the war to build out a national AC-based electric power grid network and DC systems changed over to AC-systems; utilities increasingly put DC power generation out of service and decommissioned it (Westh, 1974). Finally, following the war, fuel prices also dropped substantially so there would have been less demand by the remaining DC power stations in the country for wind turbine systems to complement or supplant diesel-based generation equipment (Westh, 1974). Several FLS Aeromotors were thus decommissioned and by 1947, only 13 of the original 27 were in operation (Christensen, 2008). By the mid-1950’s, only 2 machines were still operating – the 2-bladed Aeromotor at Ullerslev and the 3-bladed Aeromotor at Gedser – and these were provided with the metal-clad blades at that time. Both then remained in operation until 1959 and 1958 for 19 and 16 years of operation respectively and the Gedser turbine was still standing into the mid-1970s.

Figure 4-XXVIII: The 2-bladed FLS Aeromotor at Ullerslev and the 3-bladed FLS Aeromotor at Gedser both with the upgraded metal-clad blade designs (Christensen, 2008; Thorndahl, 2009).
The FLS Aeromotors demonstrated that utility-scale wind turbines could be designed, developed, commercialized and even integrated into utility systems (albeit DC systems with the exception of their prototype machine). Zeuthen used new aerodynamic methods to design the rotor and conservative design principles to dimension all the machine components so that they would have high levels of reliability and long expected lifetimes. The origin of decisions surrounding these design principles are unknown but the theme of conservative design is what that would surface again in later Danish wind turbine designs, as we will see in the next section.

4.2.2.2 Johannes Juul and the Gedser 200 kW Modern Wind Turbine

The FLS Aeromotors were an early success in utility-integrated wind energy systems. However, interest in these DC machines waned after the war ended—even by the F.L. Schmidt Company itself. The FLS Aeromotors represented the last surge of effort for DC-based wind plants coupled with battery storage systems or DC power plants. The Smith-Putnam project had focused on compatibility with large AC electric power systems with a grid-compatible synchronous generator where the variable speed of the rotor was isolated from the constant speed of the generator by a hydraulic coupling. Such synchronous systems exist today though they are typically decoupled from the rotor through electronic power conversion systems. Another approach, one that would dominate the wind energy technology for a few decades, was to use an asynchronous generator. Discussion around asynchronous generators for grid-connected wind turbines had taken place in Germany in the 1920s and was part of the Agricco wind turbine design in Denmark even earlier. The Russian 100 kW that inspired Putnam in his own design also used an asynchronous generator. The Russian design, however, did not have a significant direct impact on modern machines. On the other hand, the 200 kW Gedser wind turbine with asynchronous generator would become the most famous and influential wind turbine on the 1970’s oil-crisis era of wind development. One of Poul la Cour’s “Boys of Askov,” Johannes Juul, together with the Zealand Power Company, Sydsjællands Elektricitets Aktieselskab (SEAS), realized the idea through the development of a utility-scale grid-interconnected wind turbine with an asynchronous generator in a series of three wind turbines—the last being the 200 kW Gedser wind turbine.57

4.2.2.2.1 From Poul la Cour to Johannes Juul

Johannes Juul was already in his 60’s when he started designing the SEAS wind turbine series. But, his knowledge of and experience with wind machines began when he was just 17 years old and had the opportunity to attend Poul la Cour’s school at Askov. Juul was born to an established farming family and was brought up on the farm first by his own father and then by his uncle—who he had come to live with and work for since his uncle had no children of his own (Thorndahl, 2005a). It was on the farm, similar to other early wind pioneers, that he began to tinker with and experiment with electrical devices. According to Thorndahl, Juul officially set himself on a path a career as an electrical engineer when he read a book about Thomas Edison’s invention for the phonograph and the electric light in 1902-3. The book was likely Edison, hans liv og hans opfindelser (Edison, his life and his inventions) which was

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57 Jytte Thorndahl of the Danish Energy Museum (Energi Museet) and historian of the Gedser wind turbine has written several good works on project, mostly in Danish, (Thorndahl 2005a, 2005b, 2009, and 2010) and a good amount of the account below draws from her collected body of work on the subject.
published in Denmark in 1897 and chronicled not just the inventions themselves but Edison’s invention process along with many anecdotes (Dahl, 1897). The work was a translated version of American and British book on the same subject: *The life and inventions of Thomas Alva Edison* (Dickson and Dickson, 1894). The book apparently so inspired Juul that he was forever “lost for agriculture” (Thorndahl, 2005a). To pursue this interest, Juul sought to attend a high school where he could study physics and electricity and was most interested in the Aarhus Katedralskole (Arhus Cathedral School) which was an old and prestigious school of Aarhus that had existed for centuries—in close association with the Catholic Church. However, similar to Poul la Cour, Juul’s family was involved in the frikirke (Free Church) inspired by Grundtvig’s teaching so, the family insisted he attend the Askov Højskole (Askov People’s School) instead of the Catholic School in Askov (Thorndahl, 2005a). Had he not attended that school in 1904, it is hard to say if some 40 plus years later, he would have embarked on the path for developing the SEAS wind turbines.

![Figure 4-XXIX: Johannes Juul (left) and the 1904 Askov School class with la Cour and Juul both present (right) (Thorndahl, 2009).](image)

At Askov, Juul learned la Cour’s teachings and the general coursework surrounding DC-based electricity systems and wind power plants. By 1905, he was an apprentice of a rural electrician, Gudmund Bentsen, and was able to participate in the installation of a wind electric power plant on a farm in Otterup on the island of Funen (Thorndahl, 2005a). Bentsen soon recommended him for his diploma that the Askov School then granted him, and he then went on like many “Boys of Askov” to install power plants at small Danish utilities, factories and residences in Denmark. He continued to work in the field of electrical engineering and during WWI, he was able to study for the recently created state electrical engineering exam (Thorndahl, 2005a). He continued to work as an independent installer but also established his own factory for electrical equipment and even took out patents on some of the technology (Thorndahl, 2005a). Finally, in 1926 he was hired on to SEAS where he continued to work as
an electrical engineer and even his own independent research according to a special clause in his hiring contract; this independent research allowed him to invent new electric appliances including a very popular low-voltage electric stove that he patented in 1934 (Thorndahl, 2005a).

By 1940, Juul had had a long and successful career as an engineer and inventor. Then came the German occupation in WWII. Just like F.L. Schmidt, the fuel shortages affected SEAS, and Juul worked on issues associated with using the domestic resource of peat for electricity production (Thorndahl, 2005a). With the scarceness of peat supplies, Juul was apparently inspired to look at wind power as a potential option. Thus, Juul was able to bridge from the days of la Cour and early wind power plants in Denmark to a new modern era of wind energy. However, it was not until after the war ended in 1947 that Juul was able to get the support of SEAS to design and build a prototype wind turbine.

### 4.2.2.2.2 The SEAS Wind Turbines

Through SEAS and subsequently government grants, Juul was the lead designer on three wind turbines. SEAS built the first, an experimental wind turbine, at Vester Egesborg and included an 8 m diameter rotor and a two-generator system at 3 kW and 10 kW so that the overall system was 13 kW. Juul designed a two-bladed machine and adapted the rotor configuration over time during the experimental campaign. The SEAS acquired the second machine, the Bogø mill, from F.L. Schmidt — one of the FLS Aeromotor 2-blade machines rated for 45 kW. Juul replaced the generator and rotor to create a 3-bladed 17.5 m diameter 65 kW machine AC-machine. However, the gearing for the FLS Aeromotor could not sustain the thermal heating operating at the higher speed and the machine was derated to 45 kW (Thorndahl, 2005b). The final machine was the Gedser mill. The machine, installed in Gedser, was a 3-bladed 24 m diameter and rated at 200 kW. Gedser was a location that had already supported the installation of an FLS Aeromotor that would operate into the late 1950s as discussed earlier. The three machines had very similar design features for the design of major components as well as overall operation. The key design features embodied a new standard in wind energy technology—one which would have great influence on the modern era.
By 1947, Juul had secured the support of SEAS management to pursue the development of wind turbine technology. In that same year, he published an article in the Elektroteknikeren (Electrical Engineering Journal) which touted the idea for a wind turbine with an asynchronous generator that for use on AC power systems (Thorndahl, 2005a). An AC wind turbine could complement coal as a power source on an AC electric system—especially with the shortages of coal during and after WWII. Such a machine, he presented, could provide power at 50 Hz at 6 m/s with a tip speed ratio of 6.5 so that the overall machine tip speed would be on the order of 39 m/s (a relatively slow machine by today's standards). The design of the Gedser machine did indeed have a maximum tip speed of 39 m/s (Thorndahl, 2005a; Juul, 1961a). Juul also suggested that such a modern wind turbine design should leverage the advancements in aviation and aerodynamics and his article highlighted the ability to use aerodynamics to design an "ideal blade of streamlined shape and in compliance with aerodynamics" (Thorndahl, 2005a).

However, Juul did not dive in directly to the design of the machines. Instead, in an "Edisonian" tradition, Juul used the support from SEAS to embark on an experimental campaign of measurement of wind speeds and force as well as an extensive set of experiments on airfoil designs (Thorndahl, 2005a). He even had his own wind tunnel made to help test designs of small wind machines—a 2 m diameter propeller powered by a motor would produce about 7 m/s winds in the 5.5 m long wind tunnel. Small wind turbine blades attached to a little dynamo and Juul tested some 30 different blade designs (Thorndahl, 2005a; Juul, 1961a). Through this testing campaign, Juul was able to learn a lot the subtleties of aerodynamic design of wind turbine blades and these experimental campaigns directly influenced the design of SEAS blades beginning with the first test machine 1950 (Thorndahl, 2005a; Juul, 1961a). In particular, the wind tunnel experiments impressed upon Juul how small variations in the
design could have large impacts on the overall aerodynamic efficiency. The initial pilot mill built at Vester Egesborg embodied the key design principles of the overall wind turbine.

First, there is the aerodynamic design of the wind turbine blades. The wind tunnel experiments tested the designs but modern aerodynamic theory – particularly from Germany – influenced the design of the rotor. Juul carefully selected airfoils and made the overall blade design conform to aerodynamic principles. Juul would have been able to take advantage, as did von Karman and likely Zeuthen, the comprehensive blade-element momentum theory for propeller and wind turbine design. The final blade design arose from testing in the wind tunnel and remained the same for the pilot turbine, the Bogø and Gedser wind turbines. The design used an airfoil quite similar to that used by the FLS Aeromotors of moderate thickness and small camber. Retroactively, a study at Risø classified the airfoil as a “Clark Y” type of airfoil that was a popular airfoil used in aviation during the period (Lundsager, 1980). The airfoil design does indeed very nearly match that of the “Clark Y” design as can be seen through inspection of the below drawings. Zeuthen used an airfoil, the NACA 23012, for the FLS Aeromotor rotor design that was slightly newer and had properties that are more consistent over a larger range of Reynold’s numbers according to wind tunnel tests that compared the two airfoil types (Jacobs and Pinkerton, 1936). However, as already mentioned, the wind tunnel tests themselves most heavily influenced the ultimate design though the use of modern aerodynamic theory underlay the process.

![Figure 4-XXXI: Aerodynamic efficiency of the SEAS blade design for different tip speed ratios. The design tip speed ratio ~ 6 m/s. On the right is the airfoil profile of the blade design with the different the thickness to chord ratios marked along the profile (Juul, 1961a).](image-url)
The FLS Aeromotor design had allowed the chord to vary along the length of the blade and so did the early rotor design for the first SEAS test turbine. However, unlike the FLS Aeromotor, Juul also allowed the blade to have twist along the span of the blade. The level of twist varied from 14 degrees at the blade root to 3 degrees at the blade tip; this level of twist having been determined through the wind tunnel experiments as the “minimum level of twist for making the mill start automatically at 5 m/s wind velocity” (Juul, 1961a). Thus, unlike the Zeuthen FLS design, Juul’s SEAS turbines were self-starting and did not need a motor as the FLS machines did in order to start their operation once wind speeds were high enough.

Self-starting capability was not a new feature – twist existed on many small wind charger machines and the Smith-Putnam turbine in order to enable this design feature. A more novel aspect of Juul’s designs was the use of the principle of stall in regulating the speed above rated power. No other turbine known before that time regulated speed in that manner. The small wind chargers in the United States and elsewhere used a variety of mechanisms for controlling the speed above rated power. The Jacobs wind charger allowed the rotor speed to increase until wind speeds reached 22 mph (~10 m/s) and then a governor system would turn the blades to increase the angle of attack and stall the turbine to slow it. The Wincharger machine, as mentioned, used air brakes to counteract the tendency of the rotor speed to increase above certain speeds. Other systems included the “slip the wind” concept where the rotor increased its tilt as wind speeds increased until eventually the rotor would be facing vertically. Similarly, other systems turned the rotor horizontally out of the wind. Palmer Putnam reviewed all these various methods before settling on pitch control for the Smith-Putnam turbine in which the blade pitch adjusted along the entire blade above rated power in order to keep the speed and power output constant. Finally, the FLS Aeromotors, many of which were still operating at the time, used the flaps on their blades to control speed. In contrast, Juul used the principle of stall in order to keep the wind turbine speed relatively constant above a certain level. This “stall-regulation” as opposed to “pitch-regulation” would become an industry standard for machine design after the 1970s. Essentially, as the speed of the wind turbine increases so does the angle-of-attack for the relative wind speed seen by the wind turbine rotor as the wind speed and rotor speed increase. Beyond a certain level, the flow on the trailing edge of the blade becomes detached introducing stall. This stall effect reduces lift and counteracts the tendency of the rotor speed to increase further. As the wind speed continues to increase, the separation increases as does the impact of stall and the overall rotor speed is thus limited.
Figure 4-XXXIII: Graphic illustrates how flow becomes detached/separated as the angle of attack increases. This increase in angle of attack for a wind turbine rotor is caused by the increasing wind speed and rotor speed so that the relative angle of the wind flow increases.

Not only is stall-regulation an effective means of controlling the wind turbine speed above its rated value, it also simplifies the design drastically since the complex pitch actuator, flaps, air-brakes, and other speed control mechanisms are not needed. Still, in very high winds, it would be dangerous to allow the machine to continue to operate and some braking mechanism is still necessary. With a pitch-regulated machine, such as the Smith-Putnam turbine, the same mechanism used for speed control could “feather” the blades out of the wind. With the stall-regulated machine, some other mechanism for braking was necessary. Similar to other machines, Juul did design the SEAS turbines with mechanical brakes on the high-speed generator shaft would serve to help lock the turbine. However, more importantly, he created a special type of aerodynamic braking system to serve as the primary braking system by allowing just the tips of the turbine (where most of the power and force are produced) to feather in high winds or when the machine was shutdown. Juul’s patented tip-brake system complemented the stall-regulation as a relatively simple aerodynamic braking mechanism on the SEAS turbines (Thorndahl, 2005a; Juul, 1961a). Rods that extended from the tips through the blade and connected to a pole on the main shaft controlled the mechanism. The tip default position (without power) was feathered. For operation, a motor would pull the rods that would pull the brake flaps in line with the rest of the blade; the opposite motion would apply the brake flaps to stop the turbine either below the wind turbine cut-in speed or at dangerously high wind speeds.

Finally, there was the design of the rotor for fixed-speed operation. In designing a wind turbine rotor from an aerodynamic perspective, the power coefficient is a function of the tip-speed ratio that is a function of the rotor tip speed over the wind speed. For maximum power extraction, typically modern machines are designed to operate at variable speed – that is, there rotor speed varies as wind speed varies in order to maintain an optimum tip-speed ratio and the maximum power coefficient for a given wind condition. However, designing a rotor for variable speed operation also means that the speed input to the generator would vary beyond an acceptable range so Juul smartly designed the SEAS turbine rotors to operate at fixed speeds. During the experimental campaign at Vester Egesborg, several wind operational wind speeds from 35 to 60 m/s were tested (Juul, 1954). The plot above shows how from Juul’s 1961 article shows how the tip-speed ratio varied with wind speed in order to keep the rotor speed at the constant design tip velocity of 38 m/s (Juul, 1961a).

The tip brakes, fixed-speed and stall-regulation of the rotor design emphasized simplicity and reliability. The rest of the system design also emphasized these traits – from the blade structure to the drivetrain. One key embodiment of this simplicity and reliability was in the decision to keep the designs relatively consistent. The SEAS turbines scaled from the Vester Egesborg test unit of 13 kW (using a combination
of a 3 kW and 10 kW generator starting at 5 m/s and 8 m/s speeds respectively), to the Bogø Mill at 65 kW (reduced to 45 kW in operation), then finally to the Gedser Mill at 200 kW (Nielsen, 1962; Thorndahl, 2005b). The overall design of the machine was as similar as possible including the aerodynamic design above as well as the blade structure and drivetrain design. The only major deviation in design from the test machine to the Gedser machine was the design to move from two to three blades. The original design of the SEAS experimental turbine used two blades without any support structure in a downwind configuration; however, it was determined early on that the asymmetric loading of the 2-blade design was a concern and needed to be addressed (Thorndahl, 2005b). This led to the addition of a set of stays to provide support and absorb the loads and the blade root, but even this was not enough, and soon after, two small support arms were added to further reduce the asymmetric loads of the machine (Thorndahl, 2005b). For the next machine installed as Bogø, Juul used a 3-bladed configuration. Many tout 2-blade designs for the potential reduction in mass and cost of the rotor and potential for reduced loads on the rest of the system, but, as mentioned before, the asymmetry of gyroscopic loads with 2-blade machines imposes additional design constraints on the wind turbine that can cause instability in particular when the turbine yaws (Lundsager, 1980). The decision to move to a 3-bladed design for the Bogø and subsequently the Gedser mill derived from these stability criteria (Nielsen, 1962; Juul, 1954). The only major rotor design feature aside from the rotor configuration that changed between the three designs was the activation of the tip-brakes. The Bogø machine used spring-loaded tip brakes aligned with the rotor with a servomotor while the Gedser mill used the above described hydraulic actuation system with rods that moved the brakes into and out of alignment (Juul, 1961a).

![Figure 4-XXXIV: Diagram of the Gedser wind turbine blade with tip brake actuation.](image)

The actual aerodynamic and structural design of the blades remained consistent across the three machines – based on the early work from the wind tunnel tests. In the first two machines the blade cover extended down the full length of the blade to the root while in the Gedser machine, the blade spar was uncovered in the root region of the blade. In all cases, spars secured the blades in place and absorbed a significant proportion of the aerodynamic loads that the blades would experience (Juul,
Because of the fixed pitch of the blades, the construction of the blades with guys and struts was relatively straightforward and cheap – another benefit of the design simplicity (Juul, 1954). Initially, the experimental turbine did not have any supporting stays and operated as a downwind machine; however, after three months of operation, the last sections of the blades broke off while operating in winds of 6-7 m/s (Juul, 1954). The cause of the failure was likely the smaller size of the spar in the last section of the blade that broke adjacent to the welding at the interconnection point with the previous spar section (Juul, 1954). The remedy was to increase the size of the latter spar section and to flatten the end of the tube to preserve the aerodynamic profile of the blade at the tips. In addition, the orientation of the rotor was moved from a downwind to an upwind configuration. For such a small size machine as the experimental wind turbine, the operating speed was quite low at about 91 rpm and the centrifugal forces created at that speed were not strong enough to counter the thrust force on the blades—this was likely the main source of loads leading to the tower failure (Juul, 1954). The shift to an upwind configuration and the stronger blades with supporting stays should have avoided such a failure but after another 3 months, a crack began to develop in one of the blade roots; in this case, the suspected cause was the periodic gravitational forces on the blades (Juul, 1954). Juul reconstructed the blades once again with additional stays leading to the final construction pictured above. The overall loading of the blades shifted to the supporting stays and the machine began continual operation in April of 1951 for several years. Juul applied the use of stays in the design of the Bogø and Gedser machines from the hub to each blade as well as between each of the blades.

The blade design itself included a welded steel rectangular spar covered by aerodynamically shaped wooden ribs and ultimately covered by thin aluminum sheets for final framing of the aerodynamic shape and protection of the blade exterior from the elements (Juul, 1961a). Juul himself acknowledged that the machines were designed and manufactured in a “craft tradition” and for commercial production, other methods for blade structural design and manufacture might be more suitable – even the use of fiber glass in blade design (Juul, 1961a). The dimensioning of the blades in terms of the spar design for the Bogø and Gedser mills stemmed primarily from measurements taken from the Vester Egesborg turbine for the thrust at different wind speeds and the rated torque of the machine (Juul, 1961a). The rated torque for the Gedser machine was calculated as 5300 kg-m (52000 Nm) and the maximum thrust load was calculated as 35 kg / m² (340 N / m²) normalized to the swept area of the Vester Egesborg wind turbine (Juul, 1961a). While the Zeuthen for FLS Aeromotor turbines used calculations at extreme conditions of 40 m/s and 50 m/s to dimension the machine, Juul for the SEAS turbines used a measurement based approach from the smaller test turbine and extrapolated to the Gedser 200 kW machine.
The calculations based on the thrust and torque values showed that designing a rotor of steel blades without support stays would lead to a weak design and the necessity of the stays to address the shortcomings of the steel-blade design (Juul, 1961a). Juul measured the actual forces and moments for the Gedser mill through an experimental campaign with a measurement cylinder attached between the tower and the nacelle. He measured both the thrust force on the machine and the moment around the vertical axis. The maximum thrust force was around 6000 kg (59000 N) at wind speeds in the range of 15 to 20 m/s (Askegaard, 1961). At a swept area of 450 m² for the Gedser mill this would be only about 13 kg/m² — well below the design criteria shown in the figure above of 35 kg/m². The design of the machine (for the tower and other components) used a maximum thrust value of 15000 kg (or 33 kg/m² dividing by the Gedser swept area). That value is similar to the value reported on the chart above that was likely an extrapolated curve fit from the Vester Egesborg experimental data — it is likely that machine never operated at wind speeds nearing 30 m/s. Thus, even though the Gedser mill was not using extreme conditions like the FLS Aeromotors of 40 m/s and 50 m/s operating conditions, the extrapolation of load data from the experimental turbine led to a significantly overdesigned machine from the perspective of maximum operating thrust loads. The overall machine design can be seen below.
Engineers used these loads in the design of the blade structure as well as the drivetrain system. For both the experimental turbine and the Gedser mill, Juul used a chain driven gearbox system and the existing FLS Aeromotor gearbox for the Bogø mill. Similar to other machines up to that time, the machine had a 4-point mounted drivetrain with two main bearings along the main shaft; the primary main bearing absorbed most of the thrust loads of the machine and transferred them to the bedplate, yaw bearing and tower (Juul, 1961a). The chain driven gearbox system used a single stage system where the speed was stepped up once from the rotor speed to the generator speed by a system of chains and sprockets. Unlike the FLS Aeromotors that used a more traditional mechanical yaw system, the SEAS turbine used an electronic motor to power the yaw system with a large bull gear that supported the moment around the vertical axis. The loads seen by the Gedser machine were higher than anticipated for the yaw system (around 6000-kg m versus the 5000 kg-m used in the tower design) but were still well below the design limit of the component (Askegaard, 1961). Generally, the overall drivetrain had a significant margin of safety and no major component failures occurred in any of the three machines during their operation. The only major issues with the machine drivetrain design included the de-rating of the Bogø Mill to avoid overheating of the FLS gear system and a general issue with oil leakage from the machine (Thorndahl, 2005b).

The reliability extended to the generator and electronic control systems that employed the induction generator technology. The machines, as discussed before, used induction generators to produce power at variable speeds using the property of “slip” associated with such machines which allowed the machine speed and grid frequency to be out of synch by a small margin (from 5% for the experimental turbine to 1% for the Gedser mill) (Juul, 1961b). The machine operated at a fixed rotational speed of 38
m/s with a diameter of 24 m for a rotor speed of ~30 rpm stepped up by a gear ratio of 25 to 750 rpm (Juul, 1961a). An anemometer measured wind speed and linked to a control system to allow the turbine to begin operation when measured wind speeds reached 5 m/s, and a series of relays controlled the interconnection of the rotor to the generator and the grid system as well as provided safety safeguards for operation (Juul, 1961a). The performance of the machines from an electrical perspective were adequate except for the presence of pulsations in the power output which led to several investigations during the development of the experimental turbine, during the years of operation of the Gedser mill in the 1960s and even a follow-up analysis in the 1970s (Juul, 1961b; Lundsager, Frandsen and Christensen, 1980). Engineers never determined the root cause of the pulsations but a primary causes was supposedly the periodicity of rotor power. This was caused by wind shear on the rotor both due to the coning of the rotor, the difference in wind speed vertically, other harmonics of the structure. In addition, the grid frequency itself potentially caused some pulsation since the inertia of the rotor would keep the rotor speed in check while the grid frequency could vary which would mean a constant change in the value of generator slip (Juul, 1961b, Lundsager, 1980). The pulsations, however, were not strong enough to cause problems for grid interconnection, but Juul suggested that future machines of the induction type should use a larger value of slip in order to have more flexibility in damping out such pulsating behavior (Juul, 1961b).

Finally, the tower designs for each of the three turbines differed substantially. The experimental turbine had a lattice tower supported by guy-wires and Juul’s own later designs featured lattice tower with guy-wire systems (Juul, 1961b). However, the Bogø mill used the FLS tower that was already present and the Gedser mill used a similar tower configuration of pre-stressed concrete with reinforcements on each of the four corners (Juul, 1961a). The tower was the only piece of the Gedser mill system that was not heavily influenced in the design by Juul himself as he says in his 1961 report that “the tower was conceived and calculated by B. Højlund Rasmussen, Copenhagen” which was the predecessor of engineering consulting firm Rambøll, Hannemann & Højlund A/S (Juul, 1961a). This was likely because the Gedser turbine was not solely a SEAS / Juul project. The Gedser mill was a project supported by the Danske Elvaerker Forening (DEF) or the Association of Danish Electricity works; stemming from a SEAS proposal to DEF, a wind power committee was appointed to investigate wind generated electric power (Juul, 1961; Nielsen, 1962).

4.2.2.2.3 The 200 kW Gedser Turbine and its Legacy

The efforts of SEAS and Juul in the creation of experimental and Bogø wind turbines received no public-funding support. Even as the first experimental turbine went into operation in 1950, there was growing interest across Europe regarding the potential of grid-connected wind energy systems. The fuel shortages during the war affected a large number of countries and utilities, industries and even the public were still conscious of the hardship brought by those shortages. Still, energy was just one of the many serious concerns of European nations in the aftermath of the war – widespread destruction of communities, economies had taken place, and the continent was just beginning a long road to recovery. One important part of the recovery process was the “European Recovery Program” better known as the Marshall Plan that involved $13 billion USD in aid to European nations in order to support economic development and recovery and to ward off the spread of Soviet Communism. The Marshall Plan was
signed in 1948 and provided $5 billion of funding as a first installment. The Organization for European Economic Co-operation\(^\text{58}\) (OEEC) formed to help manage the allocation of those funds. In 1950, a Wind-Power Working Group formed as part of the OEEC with the intent to assess the state-of-the-art and to support wind energy research across the Europe. A first meeting convened in April of that year with Johannes Juul in attendance (Thorndahl, 2005b). The committee operated through 1954, provided a forum for international collaboration in the area of wind energy, and advocated for the use of Marshall Plan funds for the wind energy research and development. Perhaps the most prominent figure of the group was Edward William Golding who was the head of the Rural Electrification and Wind Power Department of the Electricity Research Association of Great Britain (New 1957). He was appointed the head of the new department in 1947 after many years already focused on the topic of rural electrification. He worked on wind energy in Great Britain and was a great supporter of Juul and the two had significant correspondence over the period (Thorndahl, 2005b). After Juul spoke on the experimental turbine in April, Golding invited him to participate in a second meeting in November in London as an official delegate from the country of Denmark—his trip paid for by the Ministry of Foreign Affairs (Thorndahl, 2005b). In September of that same year, likely by suggestion from the OEEC and Danish government, the DEF approved the formation of Danish wind power committee that included several wind energy experts including Johannes Juul and a SEAS civil engineer S.M. Buhl as the chairman (Nielsen, 1962; Thorndahl, 2005b). There were also representatives from FL Smidt & Co. A/S as well as the Lykkegaard manufacturer of the la Cour style turbines for DC system which were still being manufactured and sold throughout Denmark during the 1940s (Nielsen, 1962).

The committee formed even as the experimental test turbine at Vester Egesborg was going through its first series of tests. While the presence of other wind turbine designers may have influenced the committee’s activities, it does appear that Juul’s influence was dominant from early on in the decisions. Juul communicated the results of the experimental activities with the committee as the campaign went on and the group followed the Bogø wind turbine project as well. The committee went so far as to claim that the “experimental windmill... was put at the disposal of the committee” which indicates that the committee had some input into the design and testing of the machine (Nielsen, 1962). The group followed the experiments on both the Vester Egesborg and Bogø turbines from 1950-1952. The question, then, was what to pursue as a next phase of development. Juul already had been creating paper designs of larger size turbines for utility use. However, rather than upscaling the Bogø design to a larger size rotor and generator, Juul was more interested in the development of multi-rotor machines – similar to those proposed by Honnef of Germany and Thomas of the United States. The multi-rotor machines attached to a guyed-lattice tower and he proposed two rotors of 75 kW to form an overall wind turbine generation capacity of 150 kW (Thorndahl, 2005b; Juul, 1961a).

\(^{58}\) The OEEC was the predecessor organization to the Organization of for Economic Co-operation and Development (OECD) that now includes 34 countries including the United States, Canada, Mexico, Japan, South Korea, New Zealand and Australia in addition to the European nations.
In 1952, they held several meetings to decide on a direction for a proposal for a new wind turbine. Chairman Buhl, along with Juul, recommended upscaling to a design of approximately 100 kW but the rest of the committee apparently wanted to continue with development of more smaller turbines for testing – for instance, reconstructing two DC turbines that were recently out of service (Thorndahl, 2005b). Several additional proposals were made during the next few years regarding design options. However, the committee finally agreed with Chairman Buhl and Juul to build a larger turbine and to solicit funds from the state to support the larger turbine project (Thorndahl, 2005b). On May 8, 1952, the committee, with the broader support of SEAS and DEF, requested 300,000 Danish Kr for the construction of a 200 kW AC generator wind turbine to the Ministry of Public Works and specifically Marshall Plan funds for technological and scientific research (Nielsen, 1962). It took another two years for the committee to make the funds available, and as part of the agreement, the Academy of Engineering Sciences was to be included on the committee including Professor B.J. Rambøll of the Rambøll & Hannemann. Along with Buhl and Juul, Professor A. Meldahl, Rambøll and Civil Engineer B. Vester of FL Schmidt all joined together as the working committee on construction of the new turbine (Nielsen, 1962). It is notable that his designs featured the use of lattice tower while the actual Gedser machine had a concrete tower – the only sub-system not designed by Juul himself. A study compared steel and concrete towers before the committee ultimately selected the concrete tower design. It appears that the tower was likely the only aspect of the design where Juul did not have significant influence. It was designed by a third party consulting firm but carries a very similar appearance, as can
be seen in photographs, to the FLS Aeromotor tower designs with the pre-stressed sections of concrete reinforced by 4 ribs on each corner. The tower was likely influenced by the three other committee members.

In 1956, the Gedser turbine with the dominant features of Juul’s design was erected. As described earlier, the wind turbine featured a 24 m diameter rotor and a 200 kW generator on top of a 25 m tower. The aerodynamic profile of the design followed the Bogø and Vester Egesborg mill, as did the stall regulation control scheme and the aerodynamic tip brakes. The only key difference in the design, as already mentioned, was the decision to use a concrete tower. The machine, after an initial period of breaking in, operated very well without any significant failures. It began operation in 1957 but the operators had to stop it for a period in 1958 to have the chain casings disconnected. An oil leak from a sprocket wheel left the generator axel running for a period without oil and eventually it cracked (“Power Output from the Gedser Mill”, 1959). The main source of issues with the machine had to do with leaking oil that earned the machine the nickname “the oil mill” by the surrounding community (Thorndahl, 2005b). Juul and his team requested additional funds of 225,000 in the inaugural year of 1957 to pay for some of the turbine costs and installation as well as to add meteorological and structural measurement equipment (Nielsen, 1962). In addition, Golding of Great Britain was able to secure some funds to support a measurement campaign at the site as well. The first few years of operation involved extensive campaigns of measurement for both the wind resource as well as the machine performance including both power and structural performance. A special device in the tower top measured the main turbine loads and strain on the tower. The estimates of turbine loads mentioned earlier were the result of these investigations. From 1958 on, the turbine was then operating continuously without major failures.

Already in that year of 1957, however, support for the project and wind power began to wane. The committed evaluated the request for funds with a good amount of scrutiny and pointed out that nuclear research was showing great promise for a future secure supply of electricity (Thorndahl, 2005b). Total funds for the wind energy research from the state totaled 525,000 Danish Kroner (of which 390,000 was used for the Gedser turbine while the rest went to measurement, travel and miscellaneous expenses) and mainly relied on Marshall Plan funds. At the same time, nuclear energy in the single year of 1955 had received 150,000,000 Danish Kroner for research at the Risø laboratory (Thorndahl, 2005b). In the years following the war, the main impetus for wind energy research was the fuel shortages experienced during the war, but the promise of nuclear energy for large-scale electricity production displaced this need. Not only this, there was expectation of submarine cable interconnections to the hydro-rich electric grids of Norway and Sweden which would provide another very secure electricity supply to Denmark; the first such line was established in 1965 (Thorndahl, 2010). These two factors compounded along with cheap fuel prices following the war meant that the economic prospects of wind energy no longer looked as strong. The DEF commissioned the mill finally on July 26, 1957. On that day, the president of DEF made a speech in which he said, “the test plant here does not represent a sensational new form of exploitation of a novel source of power... wind power plants can only be used to supplement other power sources that are independent of the weather” (translated from Thorndahl, 2005b).
The Gedser turbine would continue to operate for the next 10 years until it the company that maintained it, SEAS, decided not to repair it after a minor mechanical failure in the gearbox – it was too costly to continue to maintain at that point (Thorndahl, 2005b). In her comprehensive work on the topic, Thorndahl provides a chart of expenses versus profits (in terms of fuel savings) for each year of operation of the Gedser turbine from 1961 to 1966; the result is a net loss of 23000 Kroner with most of the expenses occurring in the last two years of operation (Thorndahl, 2005b). Already in 1954, the OEEC Wind-Power Working Group had completed its work and disbanded. In 1962, the DEF Wind Energy Committee followed suit and published a final report on the Gedser wind turbine project. Juul himself retired in 1957 after seeing the Gedser wind turbine put into continuous operation. Those champions of wind energy in Denmark from Lykkegaard to Fl Schmidt to SEAS were slowly moving on – mostly through retirement – and, as mentioned, the new generation appeared to favor large power generation plants and nuclear power in particular. The final report from the committee suggested that in order for wind power to be profitable, fuel prices would need to be greater than 17-19 Kr/Gcal while fuel prices at the time were only 8-9 Kr/Gcal with a 10-year average price of 13.5 Kr/Gcal (Nielsen, 1962). The analysis assumed a wind turbine price of a minimum of 240,000 Kroner (less than the 320,000 for the Gedser turbine due to assumptions about economies of scale). At that price, the wind turbine itself would cost 1200 DKK/kW or approximately 168 USD/kW using an exchange rate at the time was 0.14 USD/DKK (Juul, 1954). Adjusting for inflation the turbine cost today would be about 1400-1500 USD/DKK which would be considered expensive for a land-based turbine. The capacity assumed was 400,000 kWh which was slightly higher than the Gedser output which averages about 350,000 kWh/year during its operation, but even at this higher assumed rate, the capacity factor was only 23% which is low by today’s standards (Nielsen, 1962). The combined effect of low energy output with high installed cost made wind energy look very unattractive from an economic perspective.

Juul himself abstained from signing the final report due to his disagreement with the general conclusions surrounding the economics of wind energy – but having already retired from the committee and with Buhl no longer the chairman, little could be done to counter the committee’s final recommendations to DEF that wind energy would not be worth investment in the foreseeable future. In Juul’s own economic analysis which he presented at the UN conference in 1961, he used a cost of steam power at the average rate or higher as well as provided for a capacity payment to be made to the wind energy generator for 100% of its rated capacity (or 200 kW) (Juul, 1961c). The committee’s study had assumed that 100% of wind energy would need to be backed up for reserve and thus penalized the technology two-fold by firstly not providing the wind generator with any capacity payment at all and also charging the wind turbine generator the fee for the back-up power (Nielsen, 1962). While Juul’s analysis was likely optimistic and the committee’s analysis was slightly pessimistic for the time period, Juul’s study did emphasize that while fuel costs were now low as the committee suggested, they had been decreasing steadily over the last 10 years and that situation was not likely to continue (Juul, 1961c). In his final conclusions, Juul advocated for wind energy investment for up to 20% of the country’s electricity by siting its potential profitability based on his analysis, the great wind resource in the country, the ability to create local industry and jobs through the production of wind turbines, and the need to “ward off a state of catastrophe in case the fuel supply from abroad fails or prices rise materially” (Juul, 1961c). In addition, Thorndahl notes that Juul saw potential compatibility between
wind energy and hydropower through interconnection to Norwegian and Swedish hydro systems that had complementary seasonal behavior (Thorndahl, 2005b). From today's vantage point, these comments are prophetic and all of these factors have been a part of the development of the modern Danish wind industry. However, after 1962, the committee's activities did cease and made no further investment into wind energy. SEAS took on the role of managing the turbines from that point forward as part of its general portfolio of energy activities but also did not invest further in the technology's development.

Figure 4-XXXVIII: The Gedser 200 kW wind turbine (Thorndahl, 2009)

The SEAS machines including the Gedser turbine continued to operate until 1967 when they shut down due to growing maintenance costs and dwindling power output. They were still capable of operation and the Gedser mill was put back into operation in the late 1970s in order to gather information on its performance and machine properties (Thorndahl, 2005b). The legacy of the Gedser turbine would remain long after Juul designed the machine in the 1950s. Already in 1961, wind energy enthusiasts around the world were celebrating Juul's work. Even though the DEF committee disagreed with the potential for wind power, an international consortium consisting of E W Golding and others continued to investigate the potential. Juul was invited on two important occasions to speak on his work. In 1954, Juul spoke at a Wind and Solar energy symposium held by the United Nations Organization for Education, Science and Culture (UNESCO) where he presented the results of activities with the
experimental turbine in detail and discussed the Bogø wind turbine. In 1961, at a UN conference New Sources of Energy, even though the new chairperson of the DEF wind energy committee was the official delegate, Juul was invited by the organizers to give several talks. Apparently, Juul received a standing ovation upon taking the stage for his first presentation (Thorndahl, 2005b). Even without the benefit of our current understanding of the impact of the Gedser turbine on modern wind technology, there was an appreciation in the early 1960s for Juul’s technology and its success at providing electricity reliably to a large AC electric grid—a feat no other large turbine had done up to that time despite several attempts.

When the oil crisis occurred in 1973, both the Gedser turbine and the FLS Aeromotor in Gedser were still standing. A state-funded effort jointly managed by NASA in the US and Risø laboratory in Denmark worked to repair the Gedser turbine and put it back into operation for a new measurement campaign from 1977 to 1979. The effort was successful and Risø wrote several reports on the operation to study various aspects of the machine including power performance, electrical interconnection, and wind turbine loads (Lundsager, 1980). Engineers placed some 90 sensors for measuring all aspects of the wind and machine performance on the turbine and a newly constructed taller meteorological mast. The results helped to build understanding of wind turbine physics and even to support development of simple physical models for wind turbine performance.

Figure 4-XXXIX: Measurement equipment on the Gedser turbine and the meteorological tower (Lundsager, 1980).
Figure 4-XL: Gedser turbine next to a measurement tower during the 1970s campaign (Lundsager, 1980).

The Gedser also had a significant role in influencing general wind turbine design in Denmark in the 1970s. As will be seen, the basic elements of the machine including the design tip speed, fixed speed and stall regulation principles as well as the tip brakes and many other aspects of the machine design directly influenced modern wind energy. The overarching principles of reliability in the design and use of significant safety margins also surfaced in the 1970s Danish machines. The design drivers for the Juul turbine design are below and emphasize in particular the grid interconnection, similar to the Smith-Putnam turbine, but also a greater emphasis on reliability.
Figure 4-XLI: Design criteria as seen from Palmer Putnam - replacing adequate means for energy storage with grid interconnection stability and site / function design variance with maximizing power extraction.

While not the only source, the Gedser turbine certainly was the largest single influence on the modern machine design. We will discuss this in much more detail in the following chapter. Even after the decommission of the Gedser turbine following the testing campaign in the late 1970s, its importance was recognized and the machine has been preserved as part of a collection of wind turbine technology at the Danish Energy Museum.
4.2.3 Utility-Scale Turbine Development in Germany: Ulrich Hütter

Fuel shortages in Germany were a continual source of interest in wind energy in the years leading up to, during, and after World War II (Heymann, 1995). Heymann’s work provides a detailed account of the various German wind energy activities during that period with particular emphasis on the prominent character of Hermann Honnef. Honnef would continue to seek out support for his grand multi-rotor tall-tower wind turbines throughout the entire period of the 1930s, 1940s and even into the 1950s (Heymann, 1995). He constantly sought support from various state agencies through various petitions, grant applications, etc. The Nazi party came to power in Germany beginning in 1933 and associated with it a Reich Association of Wind Power (RAW) was formed in 1933 with the goal of investigating electricity from wind energy as an answer to the threat of exhaustion of coal resources – particularly coal resources within Germany’s borders and control (Heymann, 1995). The RAW was a central organization for the evaluation of various wind energy proposals including those of Hermann Honnef that featured a 520 m tall tower with two counter-rotating rotors of 120 m and 160 m respectively and powering ring generators (Heymann, 1995). Honnef did succeed in raising funds to perform some small-scale tests in the AVA wind tunnels using a model that had rotor diameters of 3.3 m in diameter and
there were severe vibrations any time there was an alignment of the two counter-rotating rotors (Heymann, 1995).

Eventually, Honnef was able to collect enough funds to establish a wind turbine test field at Boetzow located to the Northwest of Berlin with capacity for testing of four wind turbines at a time. The test station tested several wind turbines including: 1) a 15 kW DC machine with two 9 m rotor diameter counter-rotating blades on a 36 m tower, 2) a 1 kW 2 500 W generator DC system with twin rotors placed side by side on a 24 m tower, 3) a 2-6 kW AC wind turbine with two counter-rotating rotors of 3 and 4 blades of 3.4 m rotor diameter on a 10 m high steel mast, 4) a 14 kW 2 7 kW DC generator turbine system with side-by-side rotors on a 24 m tower, and 5) a 17 kW AC wind turbine with 2 6-bladed counter-rotating rotors of 8 m in diameter (Heymann, 1995). Towards the end of the war, damage occurred to much of the field and Honnef had trouble securing funding to support maintaining the test field and turbines; eventually the test site was shut down and the turbines were at some point removed. Honnef continued to give lectures and lobby for funding for his large wind turbines for many years after but without success. Leading academics and engineers increasingly criticized his work and funding agencies were wary of his grandiose notions of wind turbines on a scale 10 or more times the state-of-the-art of the time (Heymann, 1995). Even in the 1950s, Honnef still sought to secure funds for wind turbine projects and was given a general award for his work in wind energy shortly before his death in 1961 (Heymann, 1995).
There were others as well who attempted to address fuel shortages with wind power. One was mining and engineering company Gutehoffnungshütte Sterkade (GHH) that collaborated with engineer Wilhelm Teubert. This led to the development first of a 6 kW 4-bladed wind turbine with an 8 m rotor diameter on a 33 m tower and then in 1940 and then a 10 kW 3-bladed downwind turbine with a 15 m diameter on a 15 m tower (Heymann, 1995; Hütter, 1954a). The latter machine was quite successful and received a lot of attention from the RAW and other groups; however, a disconnect between GHH and Teubert as well as overloading of GHH with wartime production needs prohibited further development of their wind energy efforts (Heymann, 1995). Efforts by other groups continued to work on proposals for large-scale turbines as well as smaller turbine for rural applications. The Hein, Lehmann & Company in Berlin from the mid-1930s and after produced an 8 kW machine with rotor diameters of 5 to 7 m designed by the German engineers Koenig and Ringer and had the key design feature of centrifugally governed pitch control of the blades (Heymann, 1995; Hütter, 1954a).

The famous automotive manufacturer Porsche also developed a wind turbine with a 3-bladed 10 kW 9.2 m rotor diameter machine in 1944 but the company did continue its efforts after the war end.
Finally, in 1945, a company by the name of Nordwind GmbH founded by a D. Stein built and successfully sold many 3-bladed wind turbines of 15 m in diameter on a 20 m lattice tower. Similar to Juul's design on the Bogø mill, these turbines used a centrifugally governed tip-deflection system that in that case used for speed control and not aerodynamic braking (Hütter, 1954b). The turbines could supply either electricity generation or pumping. Most of the designs discussed featured steel blades at least for the aerodynamic shape of the blade if not the structural components as well. Such rotor blades were extremely heavy and led one wind turbine pioneer from the 1920s, R. Bauer, to transition to a one-bladed system in order to reduce rotor weight and loads on the rest of the turbine (Hütter, 1954a). The machine had very high tip-speed-ratios of 12.6 to 20 and used a counterweight to balance the weight of the rotor (Hütter, 1954a). The firm Winkelstraater built and sold the machines in the late 1940s and early 1950s by of sizes of 3 kW and an 8.6 m rotor diameter (Hütter, 1954a).

Finally, the windmill company, Ventimotor GmbH, in Weimar contracted Kurt Bilau as a consultant for the design of wind turbines for electricity generations (Hütter, 1954a). However, Bilau passed away in 1941 and the overall leader of the effort sought design talent by traveling both inside of Germany and in nearby countries (Heymann, 1995). Ulrich Hütter, who like Juul would become another key influence on modern wind technology, joined the company around 1940 and participated in the design of new Ventimotor wind turbines (Heymann, 1995). The early machines included a 10 kW with a 10 m rotor diameter and a 50 kW with an 18 m rotor diameter for operation with DC grid systems and small end-use facilities (Hütter, 1954b). The smaller three-bladed system used a tail-vane for passive yaw control while the larger machine had a mechanically controlled active-yaw system (Hütter, 1954b). These new Ventimotor machines were more aerodynamic than his previous designs and achieved much higher operating efficiencies (Hütter, 1954b). Much of the improved aerodynamics was due in particular to the influence of Hütter on the Ventimotor designs. Hütter was active as an advisor and worked for both Ventimotor and another German wind turbine company Allgaier-Werke during the 1940s and 1950s (Hütter, 1974). During the early 1940s, he built on the work of Prandtl and Betz to advance the fundamental science of wind energy related to the aerodynamic design in particular.

4.2.3.1 The Wind Research of Ulrich Hütter

Ulrich Hütter was born in 1910 in Plzeň (Pilsen) in the modern day Czech Republic but was then part of Austro-Hungarian Empire. There is little information about his family but at some point they moved to Austria where Ulrich attended high school and then went on to study mechanical engineering at the Vienna Technical University from 1930 to 1936 (Heymann, 1995). His brother Wolfgang introduced him to the sport of hang-gliding which after which Hütter turned his attention towards aerodynamics. Hütter was so taken with the sport of hang-gliding that he joined the aeronautical engineering department at the Technical University of Stuttgart and graduated with a second bachelor's degree in 1938 (Heymann, 1995). At some point soon after graduation, he went to work with Ventimotor. His sense of adventure from gliding and appreciation for modern aerodynamics began to affect Ventimotor’s activities in development of modern wind turbine electric generators. His activities and research at Ventimotor would be the start of his activities in wind energy that would lead to the foundation of modern wind turbine aerodynamics.
While working for Ventimotor, Hütter became familiar in particular with the past work of Betz and Bilau in wind turbine design and theory. Similar to Juul, Hütter’s wind turbine work and theory development stemmed from certain fundamental design principles. While Juul’s decisions emphasized the reliability and simplicity of the system, Hütter targeted cost as the highest priority. Hütter recognized that the energy capture was a function of the rotor diameter squared while the weight of the rotor and many other components were a cubic function of the rotor diameter (Hütter, 1954b). Thus, as wind turbines grew, simply scaling the turbine and keeping all wind conditions the same would lead to a penalty in turbine energy produced per unit. In addition, through design practice over the years, Hütter estimated that the rotor blades themselves were about 25 to 35 % of the overall wind turbine cost (Hütter, 1974). The rotor design also had a considerable impact on the rest of the turbine design. As turbines grew larger, gearing system costs, another key cost contributor to the turbine, would also grow and methods to avoid the increased gearing costs for larger size turbines was pinpointed by Hütter as a key enabler for moving to larger machines (Hütter, 1954b).

So how did Hütter propose to address the cost issues of moving to large-size wind turbines? Essentially, he honed in on a principle still today recognized as a potential mechanism for improving wind turbine energy output to cost ratio: high tip-speed wind turbines. Hütter extended the work of Betz and Prandtl in a variety of ways through a thesis done while at Ventimotor in conjunction with the University of Vienna which he finished in 1942 (Hütter, 1954b). In the work, he developed a series of graphical methods to design blade profiles according to the Blade-element momentum theory earlier developed by several individuals and summarized in Glauert’s 1934 work (Hütter, 1954b). The key aspect of the work was the rotor solidity that is the integration of the local solidity (the chord length multiplied by the number of blades over the swept area at that chord location) along the rotor diameter. More generally, the rotor solidity is the total area of the rotor blades over the total swept area of the rotor. For an optimally designed blade (or “Betz optimum blade“), the local solidity at each location is inversely proportional to lift coefficient and the tip-speed ratio:

\[
\frac{zc}{2\pi r} = \frac{4}{3} \frac{\sin(\theta)}{C_l \lambda}
\]

Where \( z \) is the number of blades, \( c \) is the chord length at a certain span-wise location \( r \) along the blade, \( \theta \) is the relative wind velocity at that location accounting for the twist of the blade along its axis and the angle of attack, \( C_l \) is the lift coefficient for the airfoil, and \( \lambda \) is the tip-speed-ratio at that location. A Betz optimum blade can then be designed given by setting certain parameters (i.e. the tip-speed and rotor diameter) and then determining others (i.e. the chord). At a given diameter, there is an inverse relationship between the solidity and tip-speed-ratio that Hütter understood as a key design principle (Hütter, 1954a, 1954b). To address this, as tip-speed increases, the designer can reduce the overall rotor solidity by either removing a rotor blade or decreasing the chord along the blade as in two graphics from Hütter’s work below. In the first case, the reduced number of rotor blades corresponds with a higher optimal operating tip-speed and in the later, for a fixed three-blade design, the chord along the blade decreases with increased optimal operating tip-speed.
Figure 4-XLV: Image of how optimal tip-speed increases as the blade number decreases from a multi-rotor design (A) to 4-blades (C) to 3-blades (D) to 4-blades (E) (Hütter, 1954a).

Figure 4-XLVI: Decreasing solidity with increases optimal tip-speed-ratios (or as Hütter has put it here the relationship between the aspect ratio factor for chord over the diameter in comparison to the ideal rotor velocity) (Hütter, 1954b).

By moving to a higher tip-speed design, Hütter saw the potential for reducing the solidity and thus overall weight of the rotor – which had the potential to substantially reduce cost of the rotor by having
fewer blades, smaller blades, or both. In addition, from a simple computation, it can be seen that for a
given generator with a known operating speed, the sizing of the gearing system is a function then of the
operating speed of the rotor. The gearbox ratio is equal to generator speed divided by the rotor speed
and this ratio then decreases as the rotor speed increases. Correspondingly, total torque into the
drivetrain components decrease. This has the potential for reducing the costs of those components
impacted heavily by torque – mainly the gearbox but also potentially the main shaft. By going to very
high speeds, it would even be possible to eliminate the gearbox.

In 1946, Hütter sought to do just that. Following on the work of Bauer, Hütter created a single-blade
wind turbine counterbalanced by the generator driven directly, separated only by a short main shaft
and bearing (Hütter, 1954a). Likely, due to the stress of World War II, the activities of Ventimotor in
wind energy came to a halt and it does not appear that those activities revived after the war. The
military drafted Hütter himself in 1943, but he was still able to work on the design of wind turbines as
part of a wartime effort for development of the technology (Heymann, 1995). In 1946, the firm
Schempp-Kirth sponsored Hütter to work on wind energy and he designed and built a small one-bladed
turbine with a rotor diameter of 6 m and a rated power output of 600 W (Hütter, 1954a). The firm did
not continue to support the work after the initial effort but Hütter went on to work for a larger firm,
Allgaierwerke GmbH, which has still today produces transportation related components and at the time
manufactured components for both aircrafts (Hütter, 1954a). Wolfgang Hütter also worked for the
company and has a few US patents at the firm related to agricultural transportation systems (Hütter,
and Kaspar, 1957a, 1957b, 1958). By 1948, Hütter was head of design for the creation of a commercial
DC wind charger system that Allgaierwerke marketed for rural locations as a complementary system for
Diesel-generators or stand-alone with a battery system back-up. Hütter’s work over the next several
years focused on the design of these wind charger systems for independent power stations (Hütter,
1954b). The initial test turbine had an 8 m diameter, 3-bladed rotor and produced 1.3 kW – with an
optimal tip-speed-ratio of eight (Hütter, 1954a). While less controversial than the 1-bladed design, the
higher tip-speed-ratio and lower solidity aerodynamically designed rotor incorporated Hütter’s theory
and novel design approach.
The company commercialized 25 or more of the machines across Germany and other countries throughout the world. The ultimate design kept the tip-speed-ratio of eight but increased the rotor diameter to 10 m and decreased the rated power to 7.2 kW in order to improve energy capture at lower wind speeds (Hütter, 1954a). The design originally used plastic coated wooden blades but later on used steel blades made by a novel manufacturing process with a special welding technique that allowed manufacturing of them to the necessary specifications of the aerodynamic shapes (Hütter, 1954a). The controls for the turbine were mechanic in nature; Hütter suggested that mechanical controls – especially for braking – needed to be “mechanical and direct” in order to meet a certain level of safety standards (Hütter, 1954b). The early designs used the Old Dutch “side-wheel” for yaw controls, as it was a proven concept “used for the past 200 years” (Hütter, 1954b). Control of the voltage to the generator relied on a sophisticated circuit set-up to monitor the system and prevent over-voltages.

For speed control, Hütter was aware of the principles of fixed-speed design. He described the basis for such operation in his 1961 where the inertia of the load (whether feeding machinery and pumps or a large electric grid system) kept the speed either constant for synchronous machines or near constant for asynchronous machines (Hütter, 1961). The design of the machine and the optimal wind speeds at which it operates are intertwined with the characterization of the distribution of wind speeds for a specific site and ends the designer towards site-specific design. This was a topic that was part of Juul’s efforts for the SEAS turbines and Hütter wrote about the subject in a paper as early as 1948 (Hütter, 1954b). Through a series of studies, Hütter and others showed that fixed speed operation was ~94% as efficient as variable speed operation when properly design for a particular wind site (Hütter, 1961). Hütter was also aware of the principle of stall-regulation and showed how for higher tip speed machines, there was a natural tendency for the turbines to stall as the incident wind speed increased significantly above the rated value (Hütter, 1961). Rather than operating continuously at the optimal tip-speed-ratio, such machines operated at a constantly changing tip-speed ratio and at some point as the wind speed became higher and higher, the tip-speed-ratio would be quite different from the optimal design ratio that would lead to flow separation and stall.

![Figure 4-XLVIII: Example turbine design and operating power curves for stall-control machines with different operating rotor speeds (Hütter, 1961).](image-url)
However, for his own machines he preferred pitch control once the wind turbine reached rated speeds and he designed the Allgaierwerke 8 kW machine initially with a centrifugally governed pitch control mechanism mounted on the main shaft of the turbine. He patented the approach in the US in 1953 with Hütter as the inventor and Allgaier as the assignor (Hütter, 1953). However, the mechanical centrifugal device did not have the response time necessary to address certain extreme gusts especially in areas with a significant danger of storms (i.e. hurricane prone regions). He introduced a hydraulic system in order to address the dangers of strong gusts as well as to provide faster response times in general for pitch control operation (Hütter, 1954a). Hütter with Allgaier again as the assignor (Hütter, 1958) filed a second patent on the hydraulic pitch control mechanism in the US in 1956. Hütter noted that with high-speed machines, the aspects of control became more important since such machines were particularly sensitive to wind conditions and fast response times of control systems for such machines were necessary.

Figure 4-XLIX: Images from Hütter’s US wind turbine control patents; (left) the centrifugal-governed pitch-control mechanism (Hütter, 1953) and (right) the hydraulically controlled pitch-control mechanism (Hütter, 1958).

In addition to supplying DC power for farms, Allgaier also sponsored the development of asynchronous grid connected machines in the late 1940s. This was timely as the formation of the OEEC was underway and the emphasis of the group was on creating larger machines (of approximately 100 kW in size) that could be fed into the grid (Christaller, 1951). In addition, a wind energy research group formed in Stuttgart – the Deusch Studiengesellschaft Windkraft e. V. (StGW) (Hütter, 1954a, Christaller, 1951, Heymann, 1995). By 1953, Allgaier had adapted one of their DC machines for grid interconnection to study the interaction of a wind machine with the grid and an electro-hydraulic control system provided the pitch-control in order to keep the power constant above the rated value (Hütter, 1954b). However,
there were apparently serious issues with operation of the plant and one of the early sponsors withdrew financial support from the test plant (Heymann, 1995).

4.2.3.2 Hütter’s 100 kW Test Turbine
The StGW became involved with the activities of the OEEC and the emphasis soon led to the development of a 100 kW wind plant. After the issues with the test plant, the support from Allgaier began to falter but a community wind energy grant stepped in to support wind energy development and a competition was held for different 100 kW concepts (Hütter, 1954a; Heymann, 1995). Similar to the Gedser turbine, the government provided funds to support the project along with funds from several large German companies – overall about 40% of the funds came from the government, 29% from utilities and the rest from other private companies (Heymann, 1995). Hütter’s design ultimately won the competition and it deviated substantially from the small-scale 3-bladed DC wind chargers that he had designed for the Allgaierwerke Company. The design was ambitious by most standards of the day. To start, the blades “were designed without compromise according to aerodynamic optimum requirements” (Armbrust, 1961). Hütter used his theories and design techniques for high-speed rotors to develop a two-bladed machine with a rotor diameter of 34 m, a maximum operating speed of 42 rpm for 100 kW of output and a tip-speed-ratio that varied between 6.7 and 22 for the fixed speed machine (Heymann, 1995). The initial design was selected in 1953 out of four possible designs and by 1954; the main aspects of the wind turbine configuration were completed. The machine would be an upwind machine with a 34 m rotor diameter machine and an asynchronous 100 kW that would deliver power to the grid (Hütter, 1964). In 1955, Hütter ran wind tunnel tests on various airfoils. An experimental field was set up in Stotten, Germany to test small wind plants.

However, it took another year for the larger turbine development to get underway. Part of the intent of the project was to involve utilities and major manufacturers, and the project contracted with several companies to provide system components including Mannesmann for the tower, Voith for the gear system, AEG for the generator and electronics, Escher-Wyss for the yaw system and Porsche for the main frames (Heymann, 1995). Allgaierwerke manufacture red the blades themselves according to novel manufacturing processes for fiberglass blades that Hütter had developed. The steel and aluminum plated blades were used on several of the previous large wind turbine designs. The original FLS blades were wood, but steel sheets eventually replaced the plywood outer aerodynamic area since wood (even wood coated in plastic) was highly susceptible to environmental degradation. Juul had mentioned fiberglass blades as a potential solution for blade design but the materials were relatively new and manufacturing methods did not exist for the construction of the blades to the specific aerodynamic and structural specifications necessary. Hütter describes his manufacturing process in detail in US Patent for a “Process for Producing a Structure of Fiber Reinforced Plastic Material” (Hütter, 1962). The technique included methods for orienting layers of fibers in different directions of stress along the blade to create targeted reinforcement of the blade. The patent also provided a description of the famous “Hütter blade root” which is characterized by wrapping the fibers in a several loops at the blade root so that the root can be attached to the hub. This design would become an important aspect of post oil-crisis Danish wind turbines.
Figure 4-L: Bottom and top view of the Hütter style blade root with wound fiberglass around bolt-holes.

Figure 4-L: Hütter patent for fiberglass blade manufacturer including the novel root design technique (Hütter, 1973).
The manufacturing process described above could be seen as an enabling technology for the overall machine design which hinged upon Hütter fully employing his high-speed rotor design techniques. The ability to carefully construct and integrate the different airfoil shapes along the blade and to build in the structural support as well through layers of fiber of different orientations allowed the use of a very advanced aerodynamic blade design. Rather than using a single airfoil design for the entire span of the blades, as was characteristic of previous designs, Hütter used five different airfoil shapes. The design used relatively thick profiles inboard and typical NACA profiles outboard. This had the effect of limiting the propagation of separation of flow inward from the tip and improved overall energy efficiency in particular at higher tip-speed-ratios (Hütter, 1964). This way, Hütter was able to demonstrate the importance of designing the entire blade aerodynamically – from the tip to the blade root.

Table 4-3: Airfoils used in the Allgaierwerke/StGW/Hütter 100 kW machine design (Hütter, 1964).

<table>
<thead>
<tr>
<th>Span Location of Transition to Next Airfoil (m)</th>
<th>Profile Thickness as a percentage of chord</th>
<th>Profile Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>100%</td>
<td>Circle</td>
</tr>
<tr>
<td>3.0</td>
<td>32%</td>
<td>Gottingen 643</td>
</tr>
<tr>
<td>6.0</td>
<td>21%</td>
<td>NACA 64 (4) 621</td>
</tr>
<tr>
<td>11.0</td>
<td>18%</td>
<td>NACA 64 (3) 618</td>
</tr>
<tr>
<td>17.0</td>
<td>18%</td>
<td>NACA 64 (2) 618</td>
</tr>
</tbody>
</table>

In order to estimate the loads to the system, Hütter again used blade-element momentum theory and his own analytical techniques and corrections to estimate the loads on the blades and the overall aerodynamic loads of the system. Similar to Zeuthen for the FLS systems, Hütter defined a set of extreme and operational load cases in order to calculate loads for the structural design loads of the blades and the rest of the wind turbine components (Hütter, 1964). The method of “load-cases” that Hütter chose were informed by practice in the aircraft design sector which specified standard sets of load-cases that an aircraft should be able to meet (Hütter, 1964). His differed substantially, however, to those of Zeuthen and embodied a higher degree of complexity. This may have been because Hütter carried over 10 years of design experience with wind turbines by the time he designed the 100 kW machine. The key design cases identified by Hütter were: 1) extreme load cases during storms where wind speeds were excessive, i.e. 60 m/s, 2) blades feather suddenly during operation and experience loads of ~2.5 times the rated, 3) operating a rated power with a sudden gust of twice the rated wind speed or in a second case, where the wind speed suddenly drops to 0 and a negative lift is experienced on the blade, 4) fatigue cases with a 10% over speed condition and loads and a gust of ~5 times rated value is experienced as well as the opposite case where the wind speed drops to 0, and 5) a 40% over speed condition with the loads as in case 3 (Hütter, 1964). In all of these cases, an additional safety factor of 1.35 applied to all the load estimates.
Not surprisingly, conditions of extreme gusts in load-cases 3, 4 and 5 were the designing load cases for the blades. This was similar to what Zeuthen found in designing the FLS blades where the machine operating at extreme wind speeds produced the extreme loads. Based on these load estimates, the design of the structure of the blade included the layup of the fiber material and resin. The internal structure itself, as can be seen in the patent drawing, was made of a “rubber-like” foam core material (Hütter, 1964). Even using these extreme loads estimates, however, the overall blade weight ended up being quite light. The total weight for the two blades was 1360 kg or 680 kg per blade. The overall rotor-nacelle-assembly weight was 8520 kg for an overall power to weight ratio of 12 W / kg that was only slightly higher than that of the FLS Aeromotor. However, the specific power of the 100 kW machine (the ratio of power over swept area) was 115 W / m^2 while that for the FLS Aeromotor 70 kW machine was over 150 W / m^2 which means that for the power produced (Hütter, 1964). The rotor was significantly larger for the Hütter machine that would have affected the loads produced and the impact those loads carried through the rest of the system design. The low specific power was another key design principle for Hütter since a larger power to area ratio meant that machines would operate more and have improved energy capture at lower wind speeds (Hütter 1954, Hütter, 1961). Today manufacturers design machines for low-wind-speed sites have these characteristics and such a design principle is a relatively novel design trait of modern machines.

The different industrial participants in the process influenced the rest of the design. The generator was a 100 kW rated, 1500 rpm asynchronous generator which was connected to the rotor through a main shaft with one main bearing and 3-stage parallel Voith gearbox with an overall maximum gear ratio of 35.8 (Hütter, 1964). On the main shaft was the hydraulic pitch system; if the pitch system stopped working, the blades would automatically feather (similar to the tip-brake system of Juul) in order to protect the system from failure (Hütter, 1964). The circuits were similar in design and complexity to those of Juul and other turbines and included features for power regulation, over voltages and over speed protection as well as traditional functionality for controlling machine start-up and shutdown. An electric motor and worm gear as well as a back-up mechanical side-wheel mechanism provided yaw control. It is uncertain why there were redundant yaw systems – the complexity of the integration of the two mechanisms certainly would have added to the overall cost of the design. The tower was a monopole with guy-wires for additional support.
Hütter finally assembled his machine in late 1957 but already by early 1958, it ran into operational problems. A heavy storm came through the region in early January and after two full-days of weathering the conditions, there was a failure of the shaft interconnection to the hub and the rotor was left hanging on part of the shaft with the blades tossed by the extreme weather periodically into the tower guy wires (Heymann, 1995). The damage to the blades was so extensive with the tips frayed and split that they had to be removed for repair and it was not until late fall that the blades were ready to fly again (Heymann, 1995). In the spring of 1959, the experimental campaign began anew but there were quickly issues with vibration that were evident in the system design (Heymann, 1995). There is a general trade-off in aerodynamic refinement of a wind turbine blade and the potential for stability issues such as flutter and general vibrational issues in the system. We saw already that such issues had a significant impact on the Smith-Putnam design. Given the lack of understanding of wind turbine aerodynamics and aeroelastic behavior of a wind turbine, it is not surprising that such design problems surfaced with the advanced aerodynamic design of Hütter at the larger 100 kW scale. A major overhaul of the system addressed the issues of the design, and the maximum speed reduced to 34 rpm while Hütter downsized the generator to a 20 kW machine (Heymann, 1995). The experiments went on only to again experience a major issue with a hairline crack in the blade spar which had been damaged back in the storm of 1958 but was only noticed in 1961 (Hütter, 1961). After more repair, the system was operational in 1962 and continued to operate until 1966 (Hütter, 1974).

However, even as early as 1958 after the first failure, support for the project had begun to wane. In 1964, the sponsors decided to produce a final report on the project and to transfer ownership of the machine to the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), in Stuttgart where Hütter was now a vice-president (Heymann, 1995). The facility was completely dismantled in 1968. However, the end of the experimental campaign and the activities of StGW did not mean the end for Hütter's career in wind energy. Now as head of the DLR and part of an instructor at the University of Stuttgart, he would go on to have a major influence in wind energy research and design in the era of the oil crisis. In particular, his design principles would resonate with future generations of
wind turbine designers. The emphasis on high-speed designs for lower cost as well as the guidance in
design from aircraft principles and the use of aerodynamic theory would become much more prevalent
in the decades to come.

![Diagram](image)

**Figure 4-1111: Design criteria as seen from Palmer Putnam - replacing adequate means for energy storage with grid interconnection stability and site / function design variance with maximizing power extraction**

### 4.2.4 Other European Wind Turbine Efforts from the 1940s through the 1960s

There are many important points of comparisons across the different large-scale wind turbines designed
in the 1940s and 1950s; before that, however, it is worthwhile to look at other European efforts that
deserve mention. We already mentioned the Soviet and French efforts of the 1930s. In particular, the
Soviet Union had looked seriously at wind power for rural applications as part of their national energy
plan (Heymann, 1995). This is not surprising given the sheer size of the country and the overall
population density that was far less than that of European nations. In France, additional efforts to
develop wind energy were underway in the 1950s. First, there was an effort by the Electricite de France
(EdF) to develop the Best-Romani 30.1 m diameter 800 kW wind turbine (Schmid and Palz, 1986, Hau,
2013). It was built in 1958 and taken down in 1963 after some blade damage. EdF also sponsored via
Louis Vadot the design and development of two additional large turbines – first of 132 kW at 21.1 m
diameter and then a 100 kW at 35 m diameter (Hau, 2013). They were built around the same time as
the Best-Romani plants and dismantled in 1964 and 1966 respectively when EdF moved away from wind
energy development; however, the plants apparently performed rather well while they were operating
(Hau, 2013).
The last country where wind energy activity was significant in the 1950s in particular was in Great Britain. Two large-scale machines were also built in the country. The first was a 100 kW 3-bladed downwind machine built in 1952 in Scotland in the Orkney Islands (Schmid and Palz, 1986). The machine however only operated for a few years and had serious issues with vibration and flutter throughout the entire period of operation (Heymann, 1995). A second, somewhat odd, machine was built in 1949 by the British Electricity Authority using a concept by the French engineer Andreau in which the turbine spins and centrifugal forces pull air out of the wing tips which are hollow. The turbine pulls the air up through the tower into the nacelle through the tips and a turbine fits at the base of the tower (Heymann, 1995; Schmid and Palz, 1986). The turbine had the advantage of not needing a sophisticated transmission tower in the nacelle but had a very low efficiency - the plant only operated for 180 hours before damage to a wing brought the project to a halt and they did not attempt to repair it (Heymann, 1995). However, perhaps the most important contribution from Great Britain to wind energy during the 1940s and 1950s was the leadership in the international community of E.W. Golding. Golding was critical in catalyzing the OEEC wind energy efforts. His presence is notable in the 1954 New Delhi conference where he gave talks and provided comments on nearly every single wind energy presentation given (Golding, 1954). In 1955, he published a detailed book on wind energy that gained widespread publication (Golding, 1955a) and wrote various articles on wind energy and its potential uses in particular for rural electrification (Golding, 1949, 1955b, 1961a, 1961). He also interacted to a great extent with Hütter and Juul and others throughout the period of development of the large wind turbines. The activities of the OEEC brought the major wind turbine personalities together – in particular Hütter and Juul – so that each was well aware by the late 1950s of the work of the other. Still, similar to those of France, the wind turbines of the UK arguably did not have a lasting impact on the wind turbine design community.
4.2.5 Comparison of Large Scale Wind Turbine Developments from the 1930s through the 1960s

Several of the turbines developed in the mid-20th century would go on to influence the designs that emerged in the wake of the 1970s oil crisis. Before moving to that topic, a comparison across the different turbines and design philosophies is helpful to understand since those characteristics will resurface again looking at modern wind technology. The designs that were of focus in this chapter are those that had the most significant influence on wind energy designs in the 1970s: the Smith-Putnam turbine, the FLS Aeromotors, Juul’s Gedser turbine, and Hütter’s StGW turbine. The latter turbine, Hütter’s, was much less of an influence than Hütter himself as he was actively engaged in the wind energy community in the mid to late 1970s. The FLS Aeromotors also had less of a direct impact on wind energy activity in the 1970s but they were an important development in wind energy in the 1940s as the first successfully deployment of grid-connected wind turbines that used modern aerodynamics in the design process. The key features of each of these turbines are summarized in the below table and
several key similarities and differences can be seen between them. They embody fundamental aspects of the different design approaches.
<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Smith-Putnam</th>
<th>FLS Aeromotor (2-bladed)</th>
<th>FLS Aeromotor (3-bladed)</th>
<th>SEAS / Juul Giedt</th>
<th>StGW / Allgaier / Hutter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>Target Site</td>
<td>Hill - Mountain-tops</td>
<td>Danish plains / near shorelines</td>
<td>Danish plains / near shorelines</td>
<td>Danish plains</td>
<td>Low wind-speed sites</td>
</tr>
<tr>
<td></td>
<td>Orientation</td>
<td>Downwind</td>
<td>Upwind</td>
<td>Upwind</td>
<td>Upwind</td>
<td>Upwind</td>
</tr>
<tr>
<td></td>
<td>Rated power (kW)</td>
<td>1250</td>
<td>70</td>
<td>200</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Rotor Diameter (m)</td>
<td>53</td>
<td>70</td>
<td>24</td>
<td>25</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Hub Height</td>
<td>36.5</td>
<td>34</td>
<td>24</td>
<td>24</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Coning angle (degrees)</td>
<td>6</td>
<td>negligible</td>
<td>negligible</td>
<td>negligible</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Tilt (degrees)</td>
<td>12.5</td>
<td>12</td>
<td>~9</td>
<td>~9</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>°Swept Area (m²)</td>
<td>2200</td>
<td>241</td>
<td>452</td>
<td>450</td>
<td>908</td>
</tr>
<tr>
<td></td>
<td>Specific Power (W / m²)</td>
<td>567</td>
<td>208</td>
<td>155</td>
<td>444</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Airfoils</td>
<td>NACA 4418</td>
<td>NACA 23012 (+ circular root)</td>
<td>NACA 23012 (+ circular root)</td>
<td>Clark Y</td>
<td>Circle / Göttingen 643 / NACA 64 (4) 621 / NACA 64 (3) 618 / NACA 64 (2) 618</td>
</tr>
<tr>
<td></td>
<td>Twist Profile</td>
<td>Variable (5 degrees over 3 sections)</td>
<td>Constant</td>
<td>Constant</td>
<td>Variable (14 degrees at root to 3 degrees at tip)</td>
<td>Variable (14 degrees at root to 3 degrees at tip)</td>
</tr>
<tr>
<td></td>
<td>Chord Profile</td>
<td>Constant (3.45 m)</td>
<td>Variable (Max at 25-30% span)</td>
<td>Variable (Max at 25-30% span)</td>
<td>Constant (1.5 m)</td>
<td>Variable (14 degrees at root to 3 degrees at tip)</td>
</tr>
<tr>
<td></td>
<td>Rated Wind Speed (m/s)</td>
<td>13.4</td>
<td>10</td>
<td>8.5</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Rated Rotor Speed (rpm)</td>
<td>28.7</td>
<td>65 (max 90)</td>
<td>57.7</td>
<td>30</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Design TSR</td>
<td>6</td>
<td>~8</td>
<td>~9</td>
<td>~9</td>
<td>~8</td>
</tr>
<tr>
<td></td>
<td>Rated Tip Speed (m/s)</td>
<td>80</td>
<td>82</td>
<td>73</td>
<td>38</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Blade Construction</td>
<td>Steel spar / steel skins</td>
<td>Oregon pine spar / plywood then steel skins</td>
<td>Oregon pine spar / plywood then steel skins</td>
<td>Steel spar / aluminum skin</td>
<td>Foam core fiberglass-reinforced blades / fiberglass skins</td>
</tr>
<tr>
<td>Tower</td>
<td>Tower Configuration</td>
<td>Lattice Tower</td>
<td>Tapered Concrete PP 1:15</td>
<td>Tapered Concrete PP 1:25</td>
<td>Tapered Concrete 2 Chain drives 1:25</td>
<td>Monopole + Guy wires PP 1:35.8 (Variable transmission) 1500 rpm Synchronous Generator Fixed Pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>Gearbox (Overall speed ratio)</td>
<td>Unknown 1:21</td>
<td>600 rpm Synchronous generator</td>
<td>975 rpm DC generator</td>
<td>1440 rpm DC generator</td>
<td>750 rpm Asynchronous Generator Fixed Pitch</td>
</tr>
<tr>
<td>Controls</td>
<td>Generator</td>
<td>600 rpm</td>
<td>975 rpm DC generator</td>
<td>1440 rpm DC generator</td>
<td>750 rpm Asynchronous Generator Fixed Pitch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixed/Variable Speed</td>
<td>Variable</td>
<td>Variable Flaps</td>
<td>Variable Flaps</td>
<td>Variable Flaps</td>
<td>Variable Flaps</td>
</tr>
<tr>
<td></td>
<td>Stall/Pitch Regulation</td>
<td>Variable</td>
<td>Flaps + High-Speed Shaft Brakes</td>
<td>Flaps + High-Speed Shaft Brakes</td>
<td>Flaps + High-Speed Shaft Brakes</td>
<td>Flaps + High-Speed Shaft Brakes</td>
</tr>
<tr>
<td></td>
<td>Braking Mechanisms</td>
<td>Pitch + High-Speed Shaft Brakes</td>
<td>Relays</td>
<td>Relays</td>
<td>Relays</td>
<td>Relays</td>
</tr>
<tr>
<td></td>
<td>Power Regulation</td>
<td>Hydraulic Coupling + Relays</td>
<td>-</td>
<td>388</td>
<td>1600</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td>Weight</td>
<td>7250</td>
<td>-</td>
<td>8600</td>
<td>-</td>
<td>8520</td>
</tr>
<tr>
<td>Weights</td>
<td>Blade Power Density</td>
<td>172</td>
<td>-</td>
<td>180</td>
<td>125</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>RNA Weight (kg)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>RNA Power Density (W/kg)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Operation</td>
<td>Operating Years</td>
<td>1941 - 1945</td>
<td>Longest of 2-blade machines: 1941-1959</td>
<td>Longest of 3-blade machines: 1943-1958</td>
<td>No major failures over operating period; only made enhancements to gearbox to avoid oil spills</td>
<td>Shaft suspension breaks (1958) / Vibration issues require overhaul (1959) / Hairline blade crack (1961)</td>
</tr>
<tr>
<td></td>
<td>Failure Events</td>
<td>General vibration issues required yaw system retrofit (1941) / blade cracks require root reinforcement (1942) / main bearing shifted position (1943) / loss of blade accident (1945)</td>
<td>Prototype had a catastrophic blade failure, two machines caught fire potentially due to lightning (of total set of 13 2-bladed and 7 3-bladed machines)</td>
<td>Prototype had a catastrophic blade failure, two machines caught fire potentially due to lightning (of total set of 13 2-bladed and 7 3-bladed machines)</td>
<td>No major failures over operating period; only made enhancements to gearbox to avoid oil spills</td>
<td>Shaft suspension breaks (1958) / Vibration issues require overhaul (1959) / Hairline blade crack (1961)</td>
</tr>
</tbody>
</table>
Firstly, the designs are very different in terms of their overall configurations. On the one end, you have a very large-scale 1250 kW downwind machine with two blades and on the other end you have three 50 kW upwind 2-bladed machine and a 70 kW upwind 3-bladed machine. The sizes of the Smith-Putnam turbine as well as its downwind orientation stand out as a huge anomaly among the major large-scale wind turbine design efforts of the mid-20th century. Not only that, looking across the designs, the Smith-Putnam turbine had the largest approximate specific power\(^{59}\) (power output over swept area) which was in direct contrast to the Hütter approach of trying to minimize specific power in order to capture more wind at lower wind speeds (thus enhancing the overall capacity factor of the machine). The capacity factor is the percentage of power generated relative to what would be generated if the machine were running at its rated value every hour during the year:

\[
 CF = \frac{AEP}{8760 \times RP}
\]

Where \(CF\) is the capacity factor, \(AEP\) is the actual annual energy production of the machine, and \(RP\) is the rated power of the machine. Hütter’s design philosophy likely stemmed from his background working with DC wind chargers for rural locations. For those locations in particular, lulls were a very critical factor in designing a system. A battery set-up was necessary to weather the lulls where the winds were not present for hours and days. By having a lower specific power, wind turbine power curves shift to the left so to speak and are not only able to capture more power at lower wind speeds, they will operate more frequently and as a combined result, the capacity factor will be lower. Low-wind-speed technology has been used by wind turbine designers in the latter part of the 2000s to improve profitability of wind plants in regions where wind speeds are not as strong (the southeast of the United States for example versus the higher wind speed regions of the Great Plains) (Schreck, 2005). Of all the machines, Hütter’s design had the lowest approximate specific power at 110 W/\(m^2\) while the Smith-Putnam had the highest at 567 W/\(m^2\). Unlike Hütter, Putnam and his colleagues focused on aggressively maximizing power output from the turbine. While Hütter emphasizes several times in his works the importance of low specific power, Putnam emphasizes several times in his work the need for maximizing energy production. Indeed, these two diverging perspectives are core to the design philosophies of each machine. The drive to maximizing energy production pushed Putnam and his colleagues to make a very large machine for a particular site with very high wind speeds—a mountain top where the speed up of winds over the hill would further increase the overall wind through the machine and power production. Versus maximizing annual efficiency, Putnam sought to have a machine capable of producing large amounts of instantaneous power based on its size and location.

The FLS Aeromotors designed by Westh and Zeuthen had specific powers somewhere between these two extremes, as did Juul’s Gedser turbine. For FLS, the specific power was closer to Hütter while the Gedser specific power was closer to the Smith-Putnam. We cannot say much about the design choices for the FLS Aeromotor specific power without more information. However, for the Gedser turbine, we

\(^{59}\) Approximate specific power because the coning values to calculate exact swept area was not available for all turbines.
know that the specific power was the result of a decision process that intertwined several aspects of the machine design. Juul combined the generator speed and operating conditions with the choice of tip speed and machine rotational speed to determine the overall rotor size, operating speed and generator size in a highly integrated way. This led to a machine with a relatively high specific power, but more importantly, this led to a design where the tip speed of the machine was very low at only 38 m/s. The other machines all had tip speeds nearing 80 m/s. 80 m/s tip speed is a typical target even for machine designs today since the tip speed directly influences the amount of noise a machine produces. The sizing of the FLS Aeromotor 3-bladed machine kept the tip speed relatively consistent which moving from the 2-bladed design (Christensen, 2008). Juul did not select a 38 m/s tip speed because of noise concerns; instead, for his rotor designs, it appeared that 38 m/s was the most efficient for the design wind speeds of interest (Juul, 1961a). His target design tip-speed-ratio (the design tip-speed divided by the design wind speed) was “four. His overall machine had a relatively high solidity which a chord of 1.5 m which translated to a solidity of roughly 0.119 (assuming the blades are roughly rectangles). In contrast, Hütter’s machine had a solidity of 0.0291 (Hütter, 1964). The Gedser turbine, by inspection, had the highest solidity of all the large machines. As Hütter’s research work showed, the optimal design tip-speed-ratio for a machine inversely correlates with machine solidity (even accounting for constant number of rotor blades between designs). Thus, as the highest solidity machine, the Gedser turbines optimal design tip-speed-ratio was the lowest and resulted in a lower overall tip speed. The low tip speed of the Gedser machine would have a direct impact on future Danish designs as will be discussed in the next chapter.

All of these design aspects mentioned above influence the aerodynamic design of the machine. The aerodynamic design varied considerably between the machines as well. Similar to specific power, there is a grouping of the Smith-Putnam and Gedser turbines on the one hand and the FLS and StGW turbines on the other. The FLS and StGW turbines embodied very sophisticated aerodynamic design approaches with tapering of the chord along the blade and selection of advanced airfoils. These machines also had low solidity and high design tip-speed-ratios. It is not surprising that the aerodynamic designs for both FLS and StGW were done by engineers with strong aerodynamic backgrounds—Zeuthen and Hütter respectively. The Smith-Putnam aerodynamic design was also done by an expert aerodynamicist, von Karman, but the constraints imposed by manufacturing steel blades of the specified size for a 1250 kW machine drastically limited the ability to design the rotor using state-of-the-art propeller or air-screw theory. Von Karman’s design, however, did involve twist along the blade since that was an easier manufacturing process than building in variation in chord or airfoil design. Hütter’s design used a significant amount of variability all of the airfoils, twist and chord at different sections along the blade while the FLS turbine used constant airfoil and twist but allowed the chord to vary and Juul used a constant airfoil and chord but allowed for a significant amount of twist along the blade. From his wind tunnel tests, Juul did not believe that chord variation had a significant impact on rotor performance but this intertwined with his emphasis on higher solidity machines (Juul, 1961a). As Hütter would show, the solidity and thus the chord did have a very significant impact on machine design and maximum

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60 Exact solidity is hard to find for the different machines, but just looking at the photo it is easy to see that the solidity of the Gedser machine is the highest.
efficiency. For the high solidity design of Juul, however, small variations in chord did not affect the aerodynamic performance of the machine. What did have a significant impact, on the other hand, was the use of twist in the blade; the twist of the blades was what allowed the machines to be self-starting and all of the machines were except for the FLS turbines that did not employ any twist along the blades. It is somewhat surprising that Zeuthen did not incorporate twist into his designs; this is perhaps an artifact of the use of plywood layers for the design of the blade skins that may have made incorporating twist more difficult. The plywood skins of the FLS blades were eventually replaced in the 1950s, but the steel skins that replaced them had the same aerodynamic shape. The machines already used a motor for starting the blades and shifting to a self-starting design would have required substantial changes to other parts of the system.

The discussion on materials for the blades brings us to another important design feature of the system: the design of both the blade skins as well as the internal structural support. Again, the strategies used by the different designers varied quite a bit. On the one hand, again we have the Smith-Putnam machine with its all steel blades including different types of steel for the skin and the spar. The use of steel for the blade construction again related to manufacturing for such a large-scale machine. The Smith-Putnam team did not consider using lighter material aluminum skins for the blades specifically because of manufacturing considerations (Wilcox, 1973). However, the all steel blades resulted in a very heavy blade of 7250 kg. However, because the specific power of the machine was so high the actual blade power density (power output of the machine per unit blade weight) was one of the highest across the machines. This illustrates the influence that fundamental aspects of the machine design have on its performance attributes. Low-wind-speed machines with low specific power will typically have a lower power density than machines with a higher specific power. Cost relates directly to mass, so a high specific power machine like the Smith-Putnam will have lower costs per unit of rated power. However, the machine may have higher costs per unit of power produced due to the capacity factor impacts discussed before. Thus, assessing the designs based on cost would really require a full cost of energy analysis including plant costs for installation and maintenance. This would be particularly challenging for these designs given the large differences between the different designs and the prototype nature of the Smith-Putnam and Hütter machines in particular.

Returning to the blade design, the next designs from FLS focused on the use of wood for the blade spar as well as the skins and then steel skins were introduced approximately 10 years into operation. The use of wood made the overall blades much lighter than they would have been for a steel configuration but because of the lower specific power of the machine, the power density of the machine relative to blade weight was not much higher than that of the Smith-Putnam machine. These machines were relatively small which made manufacturing wooden blades much more feasible than in the case of the Smith-Putnam turbine and the oak used for the blade spar proved so durable that for the two machines that operated the longest, the original blade spars were still in use 16 and 19 years into operation. Next were Juul’s blades that used steel spars with aluminum skin. The weight of the steel spar combined with the lower specific power of the Gedser turbine compared to the Smith-Putnam turbine meant that the overall blade power density was the lowest of all the designs. The second lowest was surprisingly from the Hütter machine that employed new lightweight fiberglass materials for both the blade structure and
Hütter’s own invention of a novel manufacturing process for fiberglass blades enabled him to use this material—Juul had been interested in the material himself but did not have the manufacturing capability to do so for the Gedser turbine (Juul, 1961a). The low power density is of course a byproduct of the fact that the Hütter machine had the lowest specific power of all the designs.

Because of the different design philosophies, it is hard to compare the weights and power density of the machines. It is thus even more difficult to compare the designs on an overall basis of cost since not enough information about the annual energy production, installation and operational costs is available. A one-to-one comparison of the overall system designs is thus very difficult. Compounding this is the fact that the drivetrains of the machines were quite different—ranging from DC generation for small-grid systems for the FLS motors, to asynchronous generation for the Gedser turbine, to synchronous generation for the Smith-Putnam and StGW machines. While all the machines were grid-connected, they were very different in their approaches to designing a machine for grid interconnection. In the Smith-Putnam case, the desire was to mimic as closely as possible traditional generation units on a large-scale AC electric grid. This resulted in a design that used a traditional synchronous generator and a relatively complex system of controls including pitch control for the blades and a hydraulic coupling link between the variable speed machine and the synchronous generator. Hütter’s StGW design very closely matched this approach. For the FLS machines, such design constraints were not as critical, since the machines integrated into a DC grid network where the variability of the wind turbine was a much less significant issue. Thus, the designs used no pitch control system and aerodynamic braking was accomplished using a system of flaps on the outboard portion of the blades. Juul’s design for the Gedser turbine introduced a revolutionary approach to design of a grid-connected machine on a large AC electric grid. He employed the technique of stall on the blades to have the machine automatically passively regulate its own speed and power output as wind speed increased. The use of stall control drastically simplified the design of the machine and eliminated the need for pitch control. Instead, the novel use of tip brakes provided aerodynamic braking with either mechanical or hydraulic activation. As we will see in the next chapter, the overall decisions about control of the machine is a key decision in the design process of a wind turbine and the designs of Hütter, Smith-Putnam and Juul would all influence the control schemes of turbines in the 1970s.

Since comparing the turbines performance on overall cost would involve too much speculation, what we can do is to compare the turbines in terms of their overall performance and reliability. Comparing annual energy production is hard since many of the machines were test machines that did not operate over long periods and, again, the machines were designed for different sites and the site characteristics where the turbines were installed varied greatly. Even reliability is a difficult metric to provide a comparative assessment of the turbines since each operated in such different site conditions. Still, it is useful to look at the different levels of reliability of the machines as this too had an impact on later machine designs. The longest operating of all the machines had arguably the least influence on modern machines—these were the FLS Aeromotors. 20 FLS Aeromotors were built which operated over varied lengths of time. By the late 1940s, the interest in DC wind turbines had waned due to the multitude of factors discussed earlier. Thus, many of the machines were taken down even though they had not had significant reliability issues. Two of the machines, however, one 2-blade and one 3-blade machine,
continued to operate well into the late 1950s for a total of 19 and 16 years respectively. In that time, there were likely many maintenance issues but the only major design overall was the installation of the metal skins to replace the plywood skins on the blades in the 1950s. Two of the FLS Aeromotors did catch fire (possibly due to lightning) and the prototype did toss a blade during an early experimental campaign. For catastrophic events, however, none is as fantastic as that of the Smith-Putnam turbine. The machine operated off and on from 1941 to 1945 as a test machine with over a year locked down from the need to replace the main bearing of the machine. The loads on the rotor during the time when it was not operating induced significant fatigue damage that likely caused the ultimate blade failure when it began operation again in early 1945. The Smith-Putnam turbine almost from the beginning of operation experienced one reliability issue or failure after another. The location on top of a mountain where the wind flow was likely very complex and the downwind configuration where the tower and nacelle would further disrupt inflow to the rotor likely did not help either. The fundamental decision for a two-bladed machine introduced vibrational issues that were a perennial reliability problem. Similarly, the StGW turbine, which operated periodically from 1957 to 1966, also had a series of reliability issue including a broken suspension, frayed blade tips, vibrational issues and eventually a hairline crack in the blade. However, since it was a much smaller machine, it was much more economically feasible to overhaul the machine and replace components and it supposedly operated quite well during the early 1960s before it was decommissioned in 1966. No machine, however, operated as reliably as the Gedser turbine. The early test turbine at Vester Egesborg had issues with vibration and loads on the blade and had to go through several designing changes including moving from a downwind to upwind machine and the addition of struts to support the blade. However, due to the progressive nature of development of the SEAS turbines, Juul was able to improve the design so that by the time he built the Gedser turbine, the reliability issues were all but absent. Reliability and simplicity were a key focus of design for Juul, perhaps due to his background working with electric appliances and power systems technologies. In the utility industry, reliability is a key design feature – almost superseding emphasis on low cost. Electric grid networks designs have two basic principles: guaranteed reliability delivery of electricity for the lowest cost possible. The Gedser emphasized the first of these two principles but was a relatively high cost machine as even Juul himself admitted (1961a, b).

Thus, in each of these major designs we can see the embodiment of different design philosophies of Putnam, Juul and Hütter. We know less about the FLS Aeromotor design process and the machines had less impact on modern technology, so we will exclude the design philosophies of Zeuthen and Westh here. Putnam’s main philosophy involved creating a technology that mimicked as closely as possible a traditional fossil-fuel generation unit. On top of this, there was a certain amount of hubris in his design approach noted by several authors. He wanted to create a very large-scale machine that produced the maximum amount of power. Rather than building any test machines, Putnam and his colleagues went straight to a 1250 kW machine that was 10 times the size of any other machine previously constructed. These two foci of seamless grid integration and maximum power production led to a huge machine with massive heavy steel blades that ultimately had significant stability issues. The desire to keep the costs low of the overall project led to the two-bladed design that introduced reliability problems. The size of the machine meant that the reliability problems could not economically addressed and patches were made (i.e. the blade root reinforcement) that did not adequately address the design issues. Once a
significant failure occurred, the blade shearing off, the economics of fixing the issue by designing and installing a more robust blade was prohibitive. In hindsight, the aggressive nature of the project given the uncertainty around the physics of wind turbines and the complexities and inexperience of actually developing such large machines meant that the likelihood of success for the project was very small. Ultimately, several historians of wind energy technology have judged the Smith-Putnam as a failure—a bad omen of what would come from similarly aggressive projects in the 1970s.

In stark contrast to the Smith-Putnam turbine stands the Gedser turbine and the underlying design philosophies of Juul in comparison to Putnam. Like Putnam, Juul also emphasized the importance of seamless grid integration. However, perhaps due to his background in the power industry, Juul focused on the integration from the ends perspective rather than the means. Juul understood that wind turbines were a fundamentally different technology than traditional power generation technologies and rather than try to make a wind turbine mirror a traditional technology, he focused on designing a wind turbine that would deliver the key attributes to a grid that the utility ultimately cared about—constant power generation from a reliable resource. This viewpoint influenced the two key aspects of Juul’s design philosophy: seamless grid integration with stall regulation and an asynchronous generator and a very reliable machine that would not break down. Underlying both of these design goals of grid integration and reliability was design simplicity—as simple a design as possible in order to allow easier grid integration (through stall regulation) and limited complexity of design (tip brakes rather than pitch control, passive controls in the aerodynamics for stall and start-up, etc.).

Lastly, there is Hütter whose guiding principle is as overall system cost and energy production. Hütter’s design principles are very similar to the guiding principles for machines today. By overall system cost, Hütter focused on high-speed machines with low rotor solidity. He felt it was necessary to use high-speed machines with low solidity in order to build larger machines economically. On top of this, he emphasized the low specific power that ultimately would improve the overall energy production value proposition. Rather than focusing on just the turbine cost per unit rated power, he focused on the cost of the machine per unit energy produced. This again is similar to today’s perspective where manufacturers design the machine in the context of cost of energy rather than cost of power. Hütter’s design principles needed state-of-the-art aerodynamics and his own new development in design methodologies for wind turbines. However, the uncertainty of the science and complexity of wind systems again challenged the success of the design and only because the machine was relatively small was he able to fund significant repairs to the machines that were necessary due to a series of failures—failures resulting largely from the machine complexity.

Finally, there is the wind turbine itself and the underlying nature of wind energy flows interacting with fabricated structures. What role did the wind turbine have in mediating the success of the different efforts? The science of wind flow, the aerodynamics of a wind turbine rotor, the aero-elasticity of the rotor and interaction with the rest of the machine, these were all very young areas of scientific investigation at the time of building these large-scale machines. The uncertainty surrounding the physics of wind energy made it difficult a priori to understand how such machines would behave. Thus, the cautious approach of Juul in building up experience moving from smaller to larger machines appears advantageous to the approach of Putnam moving to an extremely large-scale machine without any
previous experience. In addition, the simplicity of the design of Juul's machine appears advantageous in comparison to the aggressive aerodynamic design of Hütter. The FLS Aeromotor also had a relatively aggressive aerodynamic design but it performed better, arguably, than the Hütter system. The answer is perhaps in how the respective efforts addressed the uncertainty in the physics and the environments. Juul addressed uncertainty through simply adding bulk to the machine components from the rotor to the drivetrain to the tower. On the other hand, employing aerodynamic theory, Zeuthen addressed uncertainty by choosing design load cases that were well beyond what the machines would experience in practice (i.e. the turbine operating at 50 m/s with a direction change). Hütter also used aerodynamic theory and an extensive set of load cases, but he was dealing with uncertainty in other forms due to the very low solidity of his machine. More advanced aerodynamic designs have the trade-off discussed earlier of being more susceptible to aerodynamic instabilities and it was ultimately these issues that plagued Hütter's machine during operation.

Not just the uncertainty of the wind itself but also the uncertainty in the complexity of how the machine components would interact with one another was difficult to know a priori. Again, by making bulky components, Juul, as well as Westh, were able to create machines that did not have significant vibration issues and drivetrain failures. There massive drivetrains proved reliable over many years of operation. On the other, soon in operation, the drivetrains of the StGW and Smith-Putnam issues experienced major failures due to complexities and lack of foresight into how the aerodynamic loads of the rotor transferred to the drivetrain components. The underlying nature of the wind and the physics of the aerodynamics and structural dynamics of the system had a significant influence in the success of these machines and even today, play the uncertainty in these areas plays a crucial role in the success of different wind turbine technologies. How designers address that uncertainty, however, is a matter of agency and the technology here mediates the intent of the designer in ways that cannot be fully controlled or anticipated. We will see how the wind energy technology and underlying science itself continues to affect the different machine development efforts in the 1970s and after.

4.3 Interlude: the 1960s lead-up to the OPEC Oil Crisis

Despite the attention to large-scale WECS during WWII and after, the integration of regional electricity networks into nationally and internationally connected grid systems in both in Europe and the US dominated the electricity generation markets during the 1950s and 1960s (Righter, 1996; Van Est 1999). Development of decentralized electricity production technologies, such as small-independent oil, gas and other combustion plants, as well as solar and wind were not openly encouraged and may have even been internally or overtly discouraged by some utilities (Hamrin, 2008; Roe 1984; Righter, 1996). Oil-fired plants made up a significant percentage of electricity generation facilities in both US and Europe and the relative stability of the oil price since the early 1900s meant that the search for alternative technological solutions was limited. Electricity was viewed as a commodity: the public was not concerned with its particulars, only its presence and its price. Thus, it was not until the Oil Crisis of 1973, as will be seen in the next chapter, when the public paid serious attention to non-fossil fuel based generation such as solar and wind. The efforts of the 1950s following World War II energy shortages began to dwindle and the 1960s represented a growth in the use of conventional resources combining a
baseload generation source of coal, or the developing nuclear power, with peak loads serviced largely by oil-fired generation plants.

Oil is probably the most famous, or notorious, of all nonrenewable resources. Before jumping into the model, a short history of how OPEC came to be helps elucidate the critical supply-side issues in the oil market. OPEC, the Organization of Petroleum Exporting Countries, has a propensity to impose seemingly “random” cuts in crude oil production in order to shore up oligopoly-rents from an imperfect market. The story of OPEC starts not in the Middle East, the geographic region it is most commonly associated with today, but in Latin America. To understand the history of OPEC, we must start with the political climate and oil markets of Latin America in the 1930s. Mexico nationalized its oil industry as far back as 1938 but other countries, such as Venezuela or Middle-Eastern nations, did not possess an adequately stable political climate for such action (Terzian, 1985). It was not until 1947 in the advent of Venezuela's first democratic presidential election that a country aside from Mexico was able to confront the various international companies who extracted the country's oil resources without conferring a substantial share of the profits to their own government (Terzian, 1985). In that year, Venezuela, the third largest producer of oil at the time behind Russia and the US, was able to pass a 50 percent tax on profits from oil extraction within her borders. Also in that year, the US began importing oil for the first time from the Middle-East and as transport costs fell so did prices of oil from the Middle-East and consequently, Venezuela's bargaining position and its tax revenue diminished (Terzian, 1985).

The taxes extracted by weaker Middle Eastern governments were low and fixed in the late 1940s. Thus, as production from the regions rose, the income to those states per barrel fell (Terzian, 1985). As these countries detached themselves from their former colonial status, they began to impose larger taxes similar to the 50-50 split in Venezuela (Terzian, 1985). Iran even attempted nationalization of its oil sector that only resulted in an overthrow of its government largely due to economic pressures led by a joint British-American boycott and seizure of its oil exports (Terzian, 1985). During the 1950's, despite the higher share of revenues being directed to the exporting countries, the international oil producing companies continued to adjust prices and production output without considering the effects that such volatility had on the economically underdeveloped oil exporting nations (Terzian, 1985). By 1960, the large and relatively poor oil producing nations decided to react to what they saw as a history of exploitation by the European and American oil 'majors'. Venezuela pioneered the way for collusion. Under the leadership of Pierre Alfonzo, who noted that the “decline in oil prices [imposed by the international ‘majors’] mostly affects the countries that are in need of development,” OPEC was conceived and eventually born (Terzian, 1985). In September of 1960, a meeting between the leaders of the various Arab nations, Iran and Venezuela led to the formation of OPEC and the beginning of the long end to cheap oil imports for the US and other developed countries. Tangentially, the formation of OPEC also put an end to the innocuous role of geography in determining the imperfect structure of oil markets since the power of price and output determination was essentially transferred from the oil ‘majors’ to OPEC.

OPEC's control of the market strengthened due to the growth during the same period of independent oil companies, outside of the “oil majors”, who were more willing to negotiate fixed-term contracts favorable to the host countries (Rauscher, 1989). Libya was the first country to successfully negotiate
contractual terms favorable to it; this occurred in 1969-1970 and the other OPEC nations quickly followed suit (Rauscher, 1989). Thus, the market climate of the early 1970s was just right for OPEC to initiate the production cuts following the 1973 Yom Kippur war that led to the first oil crisis (Rauscher, 1989). This oil crisis would change the landscape of energy in a way that had not occurred since the development of large-scale electric grid networks in the early 1900s. The PUHCA legislation from 1935 had remained largely intact in the United States and despite the energy shortages in Europe during World War II and after, energy supplies for electricity production had been relatively stable for the better part of the 1950s and 1960s. The shock that the oil crisis would have on the world would destabilize the large utility electric grid networks that had operated comfortably for the last several decades and would open up new opportunities for the reformation of strong wind energy actor-networks seeking to promote an indigenous and clean energy source for electricity generation.

4.4 References


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4.4.1 Patent Citations


The Development of Modern Wind Technology from the Oil Crisis through the 1980's and into the 1990's

5.1 The OPEC Oil Crisis: A World Catalyst for Wind Energy Development

In the early 1970's, there was little concern from the general population around the growing influence of OPEC on world oil markets. In real terms, oil prices had been holding steady or even decreasing over the last several decades; even in nominal terms prices had only increased slightly during the same period (US. Energy Information Administration, 2016). Still, those more central to the industry were increasingly concerned about the ability and willingness of OPEC to exert influence over global oil supplies and prices. As previously mentioned, Libya was the first Arab nation to exercise power over oil price and supply. Discovery of significant oil reserves in 1959 and their subsequent production turned Libya from a relatively poor country into a wealthy nation by the end of the 1960s (Levy, 1971). Resentment over the concentration of that wealth in the hands of the King Idris' monarchy led to a coup d'état and the formation of the Libyan Arab Republic led by Colonel Muammar Gaddafi. Libyan oil had been valuable not just because of the amount but because of its location west of the Suez canal that made it more immediately accessible (in particular to Europe). Following the revolution, the oil majors tried to appease the new leadership by offering higher prices (increases of 6 to 10 cents per barrel) than the pre-revolutionary period but Libya's new government rejected this modest offering. Libya cut back its production and threatened a total cut-off of supply unless the oil majors complied with significant prices increases, and in September of 1970 forced an agreement with the oil majors of a 30 cent per barrel increase with further increases of at least 2 cents per barrel per year for the next 5 years (Levy, 1971). Other countries began to follow suit and what "ensued was a crescendo of demands, backed by threats to withhold production" (Levy, 1971, p. 654). By 1971, the "balance among oil-producing and exporting countries and oil-consuming and importing countries, and among oil companies themselves appears ... to have shifted decisively in favor of the producing countries" (Levy, 1971, p. 653). Oil consumption had grown by a factor of 10 or more in most industrialized countries since 1950 and at the same time, non-OPEC production sources were facing challenges. The US oil production itself peaked in 1970 and imports began to grow in order to accommodate the reduced domestic supply as well as the ever-increasing demand (U.S. Energy Information Administration, 2016).
In the wake of Libya’s actions, OPEC nations began to request substantial price and tax increases and began to bargain collectively with the oil companies over pricing. An agreement in February of 1971 in Tehran laid out a 5 year plan including an immediate price increase of 35 cents per barrel and an additional 11 cents per barrel per year increase through 1975 (Levy, 1971). Still, despite these exercises of power, there was little action to stem the increasing dependence of oil in the major industrial countries during this time. One expert suggested that “within the foreseeable future, to which current planning would reasonably be directed, there thus need be no danger that the United States would become unduly dependent upon insecure sources for its oil supplies” (Levy, 1971 p. 664).

In this environment of inaction despite general concern, another war in the Middle East broke out that led to the OPEC oil crisis and a new era for renewable energy. Egypt and Syria led the 1973 Arab-Israeli War, also known as the Yom Kippur War or Ramadan War, against Israel and began on October 6, 1973. The US along with the Soviet Union and the United Nations sought to mediate a ceasefire formally implemented by October 24 but fighting continued into January 1974. At the same time brokering the ceasefire, the US came to the aid of Israel in the form of military supplies and equipment – including military aircraft, vehicles and missiles – while the Soviet Union provided similar support to the Syrians (Yergin, 2008). The aid to Israel did not go unnoticed. A first authorization of supplies to Israel by President Nixon (Operation Nickel Grass) was followed by a 70% increase in OPEC oil prices. After a second authorization of supplies to Israel on October 19, Libya announced an embargo of oil shipments to the US followed immediately by Saudi Arabia and the other Arab oil-producing nations (Yergin, 2008). In December, the Arab countries of OPEC met again to reaffirm the embargo against the US as well as production cuts that resulted in production levels 15% lower than pre-war levels (El Moudjahid, 1973).
The embargo against the US ended on January 18, 1974 once the US brokered the withdrawal of Israel troops from certain areas of the Sinai Peninsula, but the production cuts that led to high oil prices continued for the next several years. The global community felt these cuts and corresponding increases in oil crises. For the next several years, oil prices in both nominal and real terms remained high — bolstered by OPEC in reaction to US involvement around the Iranian Revolution of 1979.

The sustained high prices of oil over roughly a decade led, for the first time, to a truly global effort to find alternative sources for energy to fossil fuels. One of the key alternative energy technologies pursued during the period was of course wind energy technology. Significant efforts to develop wind energy took place in Europe, the US and elsewhere. Given the emphasis of this work on innovation of wind energy technology, this chapter will focus largely on two countries that had aggressive wind energy development and deployment programs during the era of the oil crisis: Denmark and the United States. Influences of other countries activities will be considered in as much that they influence the general development of the technology and the US and Danish case studies.

5.2 Modern Wind Energy in Denmark and the “Danish Concept”

Scholars and wind industry members frequently use the term the “Danish concept” in discussions of the history of wind energy technology. For some, this may simply mean an upwind turbine — facing into the wind - with three blades turning around a horizontal-axis. Here, we expand the definition to encompass a number of other characteristics of early Danish wind turbines such as stall regulation, a gearbox connected to one (or possibly two) induction generator(s), and may even include the fiberglass material for the blades and a tip-braking system. Beyond the physical characteristics, one may add to the “Danish concept” a set of overall design principles for the technology including: 1) general design conservatives and overdesign for uncertain load conditions, and 2) the use of certain historical precedent from the Gedser wind turbine that was discussed in the previous chapter. Indeed, though the technology has evolved over time, moving from the “55 kW workhorse” turbine of the 1980’s California wind rush (Maegaard, 2010) to the multi-megawatt offshore wind turbines of today, many of the features of the “Danish concept” remain present in state-of-the-art turbine design. Historical
treatments tend to champion the social processes that lead to the creation of the “Danish concept” (Karnoe and Garud, 1999; Heymann, 1998; Garud and Karnoe, 2003; van Est, 1999; Nielsen, 2010). Here, we will highlight the social processes involved but also dig deeper into the technical history of the “Danish concept.” A single organization or entity did not develop it in isolation. Instead, several organizations formed it via a series of steps that built on each other over time from the period just after the oil crisis began in 1973 through the early 1980’s when the California wind-rush took off.

5.2.1 Early Wind Energy Actor-Networks in Denmark (NIVE and Riisager)

Just as with the rest of the industrialized world, Denmark experienced a crisis in response to the OPEC oil embargo of 1973 and again in 1979. However, Denmark, which relied on oil for 92% of its energy consumption (Maegaard, 2009a) and without many indigenous fuel resources, perhaps suffered even more greatly than other nations did. The crisis that began in the fall of 1973 led directly to the formation of a small network of actors in Western Jutland of Denmark who were motivated to find alternative energy sources for electricity and heating. Preben Maegaard, one of the central actors in the Danish wind movement describes how the crisis catalyzed the formation of one such group NIVE, the North-Western Jutland Institute for Renewable Energy:

“That team [NIVE] you see – it was actually founded in January of 1974. This was just when the oil crisis was at its highest. It was the winter and there was a real concern in this country on how we could get through the winter because people were relying on heating their houses by using oil. They had all thrown out their old stoves, and we lived in modern times where oil was available, and it was a complete shock that this supply of oil was suddenly interrupted. And when you live in a cold climate here where we have these cold winters, we really feared to freeze... there were many kinds of disruptions. The minister of trade appeared Saturday evenings in primetime and reported on the supplies of oil and how much was in storage... he would tell people to go to the forest and collect some wood, and he would say you should shut down your various rooms... and only use one room to save energy.” (Maegaard, 2010)

NIVE consisted of a few engineers, blacksmiths, and teachers from a local technical school (Maegaard, 2009a). Referring to the group as an institute was premature at that time Maegaard admits (Maegaard, 2010) but it soon would take on initiatives worthy of such a title. The focus of NIVE was not exclusive to wind energy by any means and in fact, their initial projects focused on other technologies with particular emphasis on biogas and a few projects in solar energy (Maegaard, 2010). They formed in January 12 of 1974 at a meeting at a local Ecumenical college on the “optimal use of local human and technological resources” (Maegaard, 2010). The group had a grant of 50,000 DKr from UNESCO for which it was trying to establish a use for at the meeting. Despite the energy crisis, the college was hoping to focus on spiritual development but Maegaard and others were more concerned about immediate pragmatic and concrete solutions to address the crisis (Maegaard, 2010). There was a farmer, Poul Overgaart, at the meeting that wanted support in developing a biogas plant. He had gone to the technical university and other experts in search for information on how to go about it but could not find anyone who could provide him with the needed practical information for designing and constructing such a facility (Maegaard, 2010). He recommended the group use part of the grant to bring experts to Denmark who might be able to provide the needed information. The outcome was that an organization was needed that could coordinate the access and development of practical information on alternative energy solutions. During the next few years, the NIVE actor-network became involved with a series of projects
to develop small-scale distributed technology including biogas, solar thermal and very soon after, wind energy technology.

As part of the biogas development process, Preben Maegaard had gone to the libraries in Copenhagen to search for any useful information in the literature. The goal of his literature search was to find some contacts and information on experts, 200 or so, in the field of biogas to reach out to for invitations to a meeting based on the earlier discussions at the Ecumenical College. In that process, he came across the proceedings from the UN 1961 conference on new energy sources (Maegaard, 2010). There were several volumes in the set including one on biogas but also one workshop dedicated to wind energy which featured articles and presentations both by Johannes Juul (Juul, 1961) as well as Ulrich Hütter (Hütter, 1961). He went to a local bookstore to buy the set and the wind workshop proceedings would eventually become NIVE’s “bible” on wind energy development (Maegaard, 2010). Maegaard also bought a book on wind turbine design, Vindkraftboken, by a Swedish engineer/scientist referred to by another publication (Maegaard, 2010). He made two early attempts during 1975-1976 to construct a turbine based largely on the Swedish book’s design of a 2-bladed downwind machine with free yaw. However, he found the machine to be a “paper tiger” that would become so powerful and unstable in high winds that he needed a tractor to yaw it out of the wind so that the machine would stop (Maegaard, 2010). After one scary experience with the machine, he decided not to run it again. Instead, a new turbine had 3-blades that had sail wings upon the suggestion of another NIVE actor, Henrik Thisted, who would eventually become an important wind technology developer at Siemens (Maegaard, 2010).

Figure 5-III: Literature that influenced early 1970s experimentation in wind turbine technology

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These early would provide the actor-network at NIVE with the foundation for future work on wind energy development. In late 1976 / early 1977, NIVE actor Bjoern Rossing, a relatively wealthy man from Copenhagen who had decided to retire in Western Jutland, had the idea of purchasing one of the new Riisager turbines (Maegaard, 2010).

The carpenter Christian Riisager had recently become successful selling a 22 kW wind turbine with wooden blades and based largely on the Gedser wind turbine design (Maegaard, 2009). Riisager was the first Danish wind energy pioneer of the 1970s to develop and obtain approval for a grid-connected AC wind turbine (Thorndahl, 2011). Christian Riisager was a carpenter who lived with his wife Boe in the small town of Skærbaek between Holstebro and Herning in Jutland, Denmark. Working as a carpenter in the 1940’s, he had experience with repairs for small wind mills and in the early 1970’s, he developed a water powered electric generation system in a stream by the house to provide power to light his garden (Thorndahl, 2011). In response to the oil crisis, Riisager began to look to wind energy for his home. Riisager was familiar with the work of Johannes Juul and even visited the Gedser turbine prior to embarking on his own wind turbine design. Then, along with his son who was a pilot, Riisager designed wind turbine blades and tested them in a makeshift wind tunnel using a large fan, a bicycle drivetrain, and a small generator and light bulb (Thorndahl, 2011). After some testing, Riisager developed a suitable design and erected a 7.5 kW machine in his garden. The wind turbine technology itself was not as sophisticated as technology we have already discussed from prior wind energy epoques; however, what made this Riisager turbine special was its status as the first AC turbine to be interconnected to the grid in Denmark in the modern wind energy era. The Gedser and FLS turbines had been previously connected to AC and DC electric grid networks respectively, but utilities collaborated on these projects. The Riisager turbine was something new and created the precedent for a grass-roots movement for community wind in Denmark to interconnect with the now dominant large-scale electric utility grids. How this happened was quite innocent. Unconnected to the grid, Riisager’s garden wind turbine was up and running in 1975 and the family decided one day to just connect it up to the grid and to see what would happen. They connected it through the washing machine outlet in the detached garden house basement; Boe watched the electricity meter in the basement run backwards while Christian watched the blades spin around (Thorndahl, 2011). There being no grand catastrophe or interruption to electricity service, Christian went to the local Herning municipal works and talked to the department engineer about his turbine and the engineer suggested he apply for a license from the electricity council. Before the license could even be issued, a local journalist was passing by when the turbine was operating and excitedly reported about the windmill in the Herning local paper (Thorndahl, 2011). By April of 1976, the Herning City Council Committee for Operating Companies officially awarded Riisager a license to operate his windmill. In this climate of the oil crisis, news of the Riisager AC grid-connected turbine spread, and others asked him to build wind turbines for them. He was contracted to provide two turbines for Torgny Møller at Vrinners Hoved near Mols, Denmark and one also for Karsten Fritzner in Boddum, Thy, Denmark (Christiansen, 2009). The blade designs used laminate wood airfoils around a spar, as Riisager’s first design did, and similar to the Gedser turbine, had relatively high rotor solidity and a chord that was relatively large all the way to the tip. Stays were used, just as with the Gedser, to
support the blades outboard. Unlike the Gedser turbine that used electric motors for yaw and tip-brakes to avoid over speed in high-winds, the Riisager machine used an older style mechanical yaw system that would orient used small multi-vane rotors to drive the turbine into the wind for operation and to drive the turbine perpendicular to the wind in high winds (Maegaard, 2013). Over the years, Riisager experimented with several variations on the drivetrain configurations. He also used lattice towers in contracts to the earlier concrete towers of the FLS Aeromotors and Juul’s Gedser machine.

Torgny Møller, one of the first two to buy Riisager machines, also happened to be a journalist with the Danish newspaper Dagbladet Information, a left-leaning publication still in circulation in Denmark today, and he published extensively about his wind turbine and how it provided power for his family (Maegaard, 2013). The turbine cost 55,000 DKK when built in 1976 and apparently, Fritzner paid less than 50,000 DKK for his turbine (Thorndahl, 2011, Maegaard, 2013). Both Møller and Fritzner were able to work out deals with their electric utilities, as Riisager himself had, and they were even compensated for the over production of the mills beyond their own use – Fritzner was able to collect 0.0155 DKK / kWh in 1978 and earned an estimated return of 10% on his wind mill investment (Thorndahl, 2011). Popularity for the Riisager turbines grew and in 1979, of 24 turbines whose statistics were catalogued in the journal “Naturlig Energi,” 18 were Riisager turbines (8 22 kW, 5 30 kW, and 5 45 kW machines) with two more of them clones of the Riisager design (Thorndahl, 2011). The demand for these turbines continued to increase as the oil crisis continued and the movement for renewable energy in Denmark grew.
Unfortunately, Riisager’s success meant that the demand for his turbines quickly outpaced supply and the prices necessarily grew. Bjørn Rosing had wanted to buy a Riisager turbine but discovered that already in 1967 the price for such turbines had grown to 75,000 DKK. He then approached the NIVE group with the idea that they could make such a turbine themselves and even improve upon it (Maegaard, 2010). Two of the NIVE members, Ian Jordan and Preben Maegaard, set forth on the task of designing the blades for the turbine. This activity set in motion important developments for the NIVE group that would play a significant role in the expansion of the overall wind energy actor-network in Denmark. However, the group also would rely on recent developments of a related actor network near Ulfborg, Denmark: the Tvind folk high school windmill.

5.2.2 The anti-nuclear movement, OVE and the Tvind turbine
The unique developments at the Tvind folk high school stand out as inspiration to community activists across the world. The Tvind School has received numerous awards for their grass-roots design, construction and operation of a 2 MW wind turbine. Since the 1950s, Denmark had an ongoing discussion over the potential use of nuclear power as a source of electricity for the country. The government founded the laboratory Risø in Roskilde with a significant focus on research for nuclear power, but the initiative quickly met with community resistance led primarily by the Organization for
Oplysoning ein Atomkraft, OOA (Organization for bringing to light information on nuclear power) (van Est, 1999). The flat-organization of activists had local chapters across the country that would distribute information and lead opposition to nuclear development. Thousands of activists chanted the OOA's slogans such as “Atomkraft? Neg tak!” (“Nuclear power? No thanks!”), and “Veskel vek, Barseback, veskel vek, sol og vind,” (“what shall be gone? Barseback [a Swedish nuclear facility near the border with Denmark], what shall come in? sun and wind!”) (Maegaard, 2010). However, it became clear to the leaders of OOA that the saying no to nuclear was not the same as saying yes to the alternative (Maegaard, 2010). They decided on February 2, 1975 at a nationwide meeting in Bryrup, Jutland to form a new organization and Lars Albertsen, who would be a key figure in the policy-space for wind energy, would set forth a new term “Vedvarende energy” or sustainability energy to describe the goal of the new organization (Windsofchange.dk, 2016). This new organization, OVE (the Organization for Renewable Energy) was initially organized similarly to the OOA – disparate local networks of activists led meetings, called “traef” or sit-in’s, to discuss and share information about renewable energy - primarily wind energy (Maegaard, 2010). Members of both the NIVE and Tvind networks attended and contributed to the various meetings. Maegaard recalls that he went to almost all the OVE meetings across the country which included about four a year from 1975 to 1980 (Maegaard, 2010; Windsofchange.dk, 2016). Beyond activism, the OVE openly promoted technology development and promotion of information sharing (Windsofchange.dk, 2016; Maegaard, 2010). Thus, the earlier network that had brought different actors together around the theme of anti-nuclear power was an important catalyst in the development of the OVE network that would become a critical component of the wind energy development effort in Denmark.

Figure 5-V: OOA and OVE activism in Denmark in the 1970s
One prominent group of soon-to-be OVE members came from the Tvind folk high school of western Jutland. The folk high school, rising out of the early mentioned folk high school tradition in Denmark, at Tvind was actually a hub for distributed activity of so called “travelling high schools” that had begun in 1970 (Jensen, 2010). The schools’ principles involved a few key tenants such as the world as a classroom, the integration of practice and academics, and students as the drivers for teaching and learning (Jensen, 2010). The students in the folk high school were encouraged to “get out in the world and learn from the people who live in it, and that was maybe the most important principle” (Jensen, 2010). The school also emphasized solidarity with those in less-developed communities and part of the studies included world as classroom efforts where students would plan for 2-3 months and then take bus caravans through Europe to Turkey, Iran, Afghanistan and finally Pakistan and India where they could experience first-hand working with community development (Jensen, 2010). Everything at Tvind was a community effort: teachers took responsibility of different project areas but all linked together in a common effort and involved in all aspects of school life. Instead of staff, the students would do the practical work – even supporting the building of the school and running it communally. The site of the Tvind wind turbine today is on the school grounds near where students and teachers first developed a campus in 1972. The teachers in the school also lived communally and shared their time and money in “common savings” (Jensen, 2010). It was from this pool of money that the school was able to kick-start the development of what would become the world’s largest turbine of the time – and likely the longest continuously operating turbine in the world.

Shortly after 1974, the oil crisis would affect the young school and its limited financial resources. The collective teacher community decided that they would need to develop some in-house energy sources and considered both solar and wind as potential options; in the end, the strong wind resource in the area would persuade the group to develop a wind turbine (Jensen, 2010). Indeed, today you can see the trees all over the local area that are permanently sweeping to side by the consistently strong winds in the area.

![Image](image)

Figure 5-VI: Winds are so consistently strong and highly direction in Jutland, Denmark that trees grow to minimize resistance to the strong winds.
In addition to deciding on wind energy, the group also decided that the turbine would have to be big. Given the dependence in western Denmark at the time on oil for heating, this would have provided a much-needed substitute for heating oil. The group at Tvind included some teachers like Amdi Petersen who were strongly against nuclear power (indeed he had been arrested in Germany during protests against nuclear energy in the 1950s) (Jensen, 2010). Nuclear power enthusiasts of the day claimed that wind turbines that were currently under development were so small that they would never have a substantial impact on mitigating Danish dependence on oil, and so the Tvind high school decided to go big in order to show Denmark the potential of wind energy (Jensen, 2010). The original thought was that the windmill should power a system to heat water – enough for the whole facility (Jensen, 2010). However, one of the engineers on the project early on recommended, instead, using the windmill to produce electricity.

Led by the Tvind high school teachers, a group of students, interested community members, engineers and affiliates from universities, institutes and industry came together to build the Tvind 2MW wind turbine. Everything about the turbine was unique for the time: the size of 2M for the generator, a 3-blade downwind configuration, variable speed operation, an asynchronous generator, full pitch control, an active yaw system, and a fully rated converter for grid interconnection - all on top of a concrete cylindrical tower (Tvindkraft.dk, 2016). The uniqueness of the design, compared to the historical Gedser and FLS Aeromotors and the Riisager wind turbines, was a product of how the machine was designed by the community. Some of the people on the team, like Amdi Petersen, had a lot of technical experience and the project had one or two professional engineers on staff throughout the design and development (indeed the salaries of the engineering professionals constituted one of the large expenses for the project) (Jensen, 2010). However, even so, the designs about the machine were made collectively via a process of discussion, debate and consensus building. The team, with an average age of 21, would work with the engineers and present potential solutions for design; not everyone would agree, sometimes the engineers would not even agree with each other, and people would ask questions and debate into the night and sometimes over a long period until everyone agreed unanimously (Jensen, 2010). On some things, everyone accepted the engineers’ recommendations quickly – like the decision to add a generator and produce electricity. However, on other occasions the debate would go on for long periods – one man who lived nearby was convinced that the Tvind turbine should have five wings like the historic windmills of la Cour and others (Jensen, 2010).

The group travelled around the country and visited historical windmills. More than Juul’s Gedser turbine, the work and designs of Ulrich Hütter of the University of Stuttgart inspired Amdi Petersen and the larger team (Maegaard, 2009). The group reached out to Hütter as a consultant and even made a trip to Europe at one point to gather his input on their design. The Tvind group used Hütter’s theory and design principles as the critical source of guidance in the Tvind project development (Maegaard, 2009, Maegaard, 2010). Hütter’s unique blade design allowed the fiberglass strands to wind around the bolt holes so that the entire piece connected easily to the hub without the supporting stays that were required on the Gedser and Riisager turbines (Maegaard, 2009). As discussed, Hütter’s designs were more aggressively aerodynamic than the designs of Juul with respective rotor speeds of 42 to 30 rpm.
The Twind machine operated at a rated speed of 42 rpm—a very high speed for a machine of that size for today's standards. In addition, the 27 m diameter was quite small relative to the design objective of a 2 MW machine. The resulting specific power for the machine with a 27 m rotor diameter was then roughly 3000 W/m^2 which is a factor more than current machine designs. The only significant design flaw was in the combination of sizing of the generator too large relative to the rotor (or vice versa a rotor too small for the generator). Indeed, once in operation, around 28 rpm, harmonic oscillations began to cause significant vibration in the nacelle (felt by one of the millwright's who was in the nacelle when it happened) (Østergaard, 2000). The team then decided to operate the wind turbine from that point on at a lower speed of 21 rpm with a maximum output of 900 kW.

Aside from Hütter and the blade design, the various consultants on the project included a number of future wind industry actors and the project played a key role in influencing the Danish popular imagination about the potential of wind power. The overall design process was truly collective and the Twind design is truly unique. There were a few people that persisted in their involvement throughout the whole project: Amdi Petersen who provided much vision and initiative for the project, Jens Gjerding from Twind's Vestjysk Energikontor collected information and pulled the system design together, Hans Jørgen Lundgaard Laursen was an advisory engineer on the structural dynamics, Lars Svanborg as supervising engineer concerning the machinery, and the chief welder and teacher Henning Jønsson (Maegaard, 2009b). However, many individuals contributed to the overall project design. A team of
students actively worked on the turbine development at all times, and they held regular meetings to discuss and evolve the design and construction of the machine (Jensen, 2010).

The school also relied on minimal funds for the overall project and made the components themselves whenever possible. For the tower, nacelle and foundation, they poured their own concrete after acquiring an elevator and concrete mixer—the economic hardship brought on industrial companies by the oil crisis meant that industry were willing to sell these at heavily discounted prices—this involved both developing the correct concrete mixture as well as performing the complete assembly task (Jensen, 2010). They also made their own blades by first learning from a local carpenter/boat builder how he manufactured fiberglass structures and then applying the techniques they learned to create their own set of blades (Jensen, 2010). The hub, which today would be made of cast-iron, was welded steel and the welds have held through the 30-year operation of the machine (Maegaard, 2009b). They also designed their own active yaw system that included a unique design of two reciprocating 5-toothed arms that would work the turbine around its vertical-axis. The pitch system was equally unique since as a full-bladed pitch system for variable speed operation, the technology was ahead of its time, and also the pitch system provided the entire braking mechanism for the turbine and thus included 3 redundant systems (two collective and one independently able to control the pitch). Finally, the decision to use variable speed technology was due in part to the large size of the turbine and the concern over connecting such a large system to the grid without fully rated conversion power electronics. The team acquired an ASEA generator with a rating of 1725 kW and the ASEA gearbox with an overall ratio of 1:20 from Sweden. The gearbox has previously been used in a copper mine, and the main shaft, acquired from Rotterdam, was originally used by an oil tanker (Maegaard, 2009b). Everything in the design sought to minimize cost at the same time realizing a level of conservatism so that the machine would be successful.

Figure 5-VIII: Overview of the Tvind machine design which can be found on the Tvindkraft informational website: http://www.tvindkraft.dk/en/technical-info/the-individual-parts.html

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Thirty years later, the Tvind turbine, having been designed to be conservative and having been operated even more conservatively (only running at 22 rpm compared to the original 42 rpm design speed), still operates and generates about power for the community (Jensen, 2010). The only major component replacements since the commissioning of the machine in 1976 were the three blades in 1992. The Hütter root, as will be discussed later, had some inherent fatigue challenges since the 180 degree looping of the fiberglass weakened its strength and even with flawless manufacturing, there could be problems. New blades with a design more conventional of today's turbines were put on and the machine is still running, standing high above the tree line in western Denmark. The machine does operate at half of its originally expected rated power that means that parts designed for higher loading are even more conservative than originally designed. However, no wind turbine in the world has been running for as long as the Tvind machine and at such a scale — 900 kW would have been a large-sized wind turbine well into the 1990s. Countless people were involved in the design and manufacture of the successful Tvind turbine and the success of Tvind inspired early wind pioneers all across the country.

5.2.3 From Tvind to NIVE, Oekaer and the Danish wind industry

In 1977, several groups attempted to make a smaller 11 kW version (4.5 m blade) of the Tvind windmill. The Tvind team themselves had made a mold for such a blade, and the mold eventually ended up with the brother of one of the Tvind team members, Erik Grove-Nielsen of Oekaer in Viborg, also in Jutland (Maegaard, 2009). At the same time, NIVE had a design, based on the request for a windmill by Bjoern Rossing, for a 22 kW wind turbine inspired by both the Gedser and Tvind wind turbines (Maegaard, 2010). Just like the Tvind, the design featured a turbine of 3-blades made of fiberglass material winding around the bolt holes at the blade roots for a good connection to the hub (Maegaard, 2009). Preben Maegaard had been somewhat involved with the Tvind wind turbine — he had consulted with them on different aspects of the design and accompanied Amdi Petersen to Sweden to acquire what would be the Tvind drivetrain ASEA generator and gearbox (Jensen, 2010). The Tvind team decided to use a downwind turbine configuration because of the advantage for the use of a more stable yaw system and the coning of the blades away from the tower — both features that would make the turbine more reliable (Jensen, 2010). Maegaard, who had read in detail the 1961 UN report from the conference on new energy sources, had noted in an article on wind testing that the author Morrison had found tower shadow induced cyclic loading on the blades could affect the reliability of downwind turbines (Maegaard, 2010). He shared this with the Tvind team though they had already committed to a downwind design (Maegaard, 2010).

In designing a turbine at NIVE, the team heeded the UN report's advice that an upwind configuration would avoid the problems associated with downwind cyclic loading of the blades. It was from this same report, with its articles by Morrison, Juul and Hütter, that the team at NIVE would use as their main source of guidance for designing their Gedser-inspired 22 kW turbine. The team used many attributes of the Gedser, aside from the fundamental blade design and materials, in the 22 kW design including the upwind 3-blade configuration, asynchronous generator, electrical yawing and automatic control system. To build the turbine locally, Maegaard saw that the critical component would be the blades. Each component was readily available, could be ordered, or could be easily constructed by local companies.
and blacksmiths except for the blade and the control system. He worked with a local controls engineer from Thisted to design the system of relay controls for start-up, shutdown, and grid connection and so on and at the same time, his team began to construct a mold for the 5 m blade (Maegaard, 2010). Before the group at NIVE had a chance to complete the model, the team met Erik Grove-Nielsen of Oekær (Maegaard, 2010). He had realized from early OVE meetings that wind turbine self-builders had problems with creating the blades (Grove-Nielsen, 2009). Erik Grove-Nielsen offered to make the blades for the team himself given his prior experience using the Tvind blade design. From his own experience with Tvind, however, Preben Maegaard knew that those blades were designed to run at a fast tip-speed ratio (when sized down from the Tvind) and thus would be too noisy (Maegaard, 2010). Erik Grove-Nielsen then agreed to produce a modified design from NIVE which featured blade dimensions similar to that of the Gedser turbine but which incorporated Hütter’s modern blade root design compatible with modern fiberglass materials (Maegaard, 2010).

Figure 5-IX: Oekær 5 m blades at the Folkecenter outdoor museum.
The rest of the design was thus inspired by Gedser from the basic configuration, to the sizing of the various components for expected loads (Maegaard, 2010). From the 1961 UN report, various rules of thumbs were incorporated such as a degree of loading on the rotor that the structure would have to withstand, 30 kg/m², or the size of the bearings, 1% of the diameter of the rotor (Maegaard, 2010). Selection of the rest of the components and construction of the first NIVE wind turbine in 1978 involved a highly collaborative process between the group at NIVE under the leadership of Preben Maegaard and various local companies, blacksmiths and engineers. Maegaard became very interested in the component selection process and his team would call up companies across Denmark to order catalogues for selecting the turbines components:

“We took the bearings from the catalogues here” - there are a few large cabinets in the Folkecenter which hold the catalogues with notes used in the early design work – “… and then you needed a yaw ring... this was more difficult to find... you had to think about where you used such a ring, and they were used on cranes and on some vehicles... and then you started calling [the yaw ring manufacturers], these companies, they had never heard of wind power. You called them and they said wind power - what is that? And then you got the catalogues... and it was also a problem, who you talked to about wind power... The company would say wind power? We have heard about that, does it mean that you are some that are against nuclear power? Ah, then they would say, well, we have some policy... we will not deal with that because we don’t believe in this wind power. Now this doesn’t matter for selling some bearings; you sell too many other sectors also. We just want your product, whether it's for wind power it makes no difference... but often you could not get them to send the catalogue once they found it was for wind power... and years later the same company, I would talk to them, and they would say we made a big BIG mistake...” (Maegaard, 2010)

![Dimensioning of the NIVE turbine based on the Gedser wind turbine loads as reported in the UN 1961 proceedings.](image)

In addition, through this process of design work and construction of a set of component suppliers, various industrial actors began to engage with the wind energy technology development. While the local blacksmith community and masons supplied many parts, various parts were outsourced including the yaw ring, gearbox, generator, brake calipers, bearings, and most importantly, the turbine
blades (Maegaard, 2010). This in turn led to the creation of a backbone supply chain for what would become the Danish wind industry – some of whom were already involved in the burgeoning wind industry through supplying parts for Riisager-style turbines, and some of whom were brand new to the industry. The idea of component supply was one of the fundamental aspects of the wind turbine. Maegaard explains the ethos of the local small and medium sized enterprises (SMEs) in Denmark. Unlike the US and much of the rest of Europe that had fully embraced the American system and mass production, Denmark still in the mid twentieth century had a strong local production base including a network of local masons, carpenters, painters and blacksmiths (Christensen, 1983; Maegaard, 2010). The idea in the development of the NIVE turbine was to engage with the local production network to the extent possible for the development of the wind turbine.

Thus, the early windmill development involved local production and engagement from blacksmiths and eventually to the Danish Blacksmiths Association (DS). As mentioned before, local wind turbine manufacturers met regularly at the OVE “vind traef” and other local meetings to discuss best practice for wind turbine design from their field experience (Maegaard, 2010). It was at the fifth of these OVE “vind traef” in Brandbjerg that two men from DS approached the group and were interested in how they could turn wind energy into an economic boon for their members (Maegaard, 2010). This led to the establishment of a formal relationship where NIVE would provide a series of standard design manuals to DS that covered every aspect of the design of a modern wind turbine. Over the years, the design team at NIVE created a design handbook accessible to anyone and based on the “Danish concept” starting with the early 22 kW and 55 kW designs as well as a series of designs including DANmark 8 (13 kW), DANmark 11 (20 kW), DANmark 17 (25 kW), DANmark 19 (95 kW), DANmark 22 (150 kW), and the DANmark 25 (200-270 kW) (Folkecenter, 1990). From this beginning, all of the major Danish wind turbine manufacturers of the 1980s through today can trace their origins to this “Danish concept” established at NIVE and based on the combination of T vind and Gedser turbine design concepts.
The early companies, all working with Oekaer, took advantage of the developing supply chain and leveraged the design basis that established by NIVE. Each new company, however, brought to the table its own area of expertise to improve component design and contribute to the overall Danish wind turbine “supply chain” (Maegaard, 2009a, 2010). For instance, one oversight of the first NIVE turbine designs had to do with the omission of the blade tip brakes that had been present on the Gedser turbine in the 1950s. As Preben noted, for the Tvind tower, they also omitted tip brakes and used parachutes brakes for an emergency stop mechanism — which also made a downwind configuration prohibitive because for a downwind system, the parachutes would hit the tower (Maegaard, 2010). The braking system was one of the more challenging aspects of the first system and in Maegaard’s own words, the tip brakes “in the first [turbines] were not considered. They were neglected. I can tell you they were really neglected... we did not read Juul carefully enough!” (Maegaard, 2010). However, two over speeding situations where the mechanical braking system failed brought the issue back to the fore. The Herborg (later Vestas) turbine introduced by Karl Erik Joergensen and Henrik Stiesdal in 1978 would also use the same basic 22 kW blade design from Oekaer, but only a few months after installation, the prototype ran into an over speed situation and the blade and hub system collapsed to the ground (Grove-Nielsen, 2010). A second failure occurring a few weeks later caused Oekaer to stop production and focus on a braking solution that would be stable — eventually this resulted in the creation of a tip braking system similar to that of the Gedser turbine (Grove-Nielsen, 2010). Another innovation of the Herborg turbine included the use of two differently sized asynchronous generators (at a lower and higher power rating) in order to improve overall turbine performance (Petersen, 1980). This as well became part of the de facto Danish wind turbine standard of the 1980s. The system on the Gedser turbine used hydraulics but Oekaer used a spring-loaded system that would activate whenever the
turbine lost power from the grid (Grove-Nielsen, 2010). In 1979, Jørgensen licensed the Herborg design to Vestas that was at that time a medium sized enterprise that made hydraulic truck cranes and heat exchangers - the company that would later become the largest wind turbine manufacturer in the world (Maegaard, 2009).

The stories of other Danish manufacturers are similar. All of the manufactures were originally focused on agricultural or transportation machinery. Nordtank, originally a tank manufacturer, started as well with the 22 kW turbine and the same blade profile (Maegaard, 2009, Pedersen 1983) but used its expertise in rolling and welding large tank sections in order to produce a “welded tube” tower which eventually replaced the lattice towers of NIVE and Herborg designs to become part of the standard design configuration (Maegaard, 2009). The last major company, Danregn Vindkraft A/S or Bonus Energy A/S, originally tried to license the Nordtank technology but then developed their own design with NIVE serving as consultants to the firm and Maegaard serving on their board for a time in the early years (Maegaard, 2010). From these origins, all linked to NIVE, T vind, OVE and Riisager, the “Danish Concept” became pervasive in early Danish wind manufacturing and eventually obtained its status as the dominant design within the industry. Even Tacke, a German wind turbine manufacturer, later acquired by Enron Wind and then forming the basis of GE’s current day wind turbine operations, has its origins in a jointly-funded program by the EU for the creating a new 400 kW generator (Maegaard, 2010). In 1988, both Nordtank and NIVE submitted proposals but Nordtank won the contract due to their manufacturing base (Maegaard, 2010). However, when Nordtank went bankrupt, the project was turned over to NIVE provided they work with a manufacturing firm, the German company Tacke, with the project cost share of 2/3 and 1/3 respectively (Maegaard, 2010). From this project, Tacke moved into the wind space and eventually became the basis for current day GE wind (Maegaard, 2009).
5.2.4 Industry and the Risø test station: a “mega-network” for Danish wind energy

During the early years of the wind industry development, no formal design or safety standards existed in Denmark. The OVE established a wind turbine safety group at its fourth “Vind Traef”, but this group hardly provided regulation to the industry. However, after 1979, Denmark required certification of wind turbines in order to have access to a subsidy that was essentially an investment grant of 30% (Petersen, 1980). The system was set up to additionally encourage participation by making the certification process free for Danish manufacturers and providing payment to the companies for the time the turbine was at the test station (Petersen, 1980). Risø national laboratory, which had managed the testing and evaluation of the Gedser and NIBE turbines and had consulted on the T vind project along with DTU, had the qualifications to take on this new role as the wind turbine certification center for Denmark. Risø established the test center for small windmills in 1978, and the government gave the institute the licensing task by the government in 1979 (Lundsager and Jensen, 1982). The first certified turbines were the “Gedser-type” machines, or Riisager-inspired designs, that produced 20 or 55 kW of power or they were “second generation types” that included the NIVE-inspired design types with variations for the
different manufacturers (Lundsager and Jensen, 1982). The test station notes that while “design principles exist that ensure mechanical integrity and proper functioning on at least a short-term basis,” longer term performance was still under question which limited the ability of the test station in terms of establishing design requirements (Lundsager and Jensen, 1982). Initially, requirements from the test station allowed for both air brakes as well as braking by yaw, rotating the turbine out of the wind (Petersen, 1980; Pedersen, 1984). However, this was amended in subsequent documentation that required a “fail-safe” braking system that is disengaged with the system is active and in series with each element of critical safety importance for both the electronics as well as vibrations (Lundsager and Jensen, 1982). In addition, two independent braking systems were required to ensure that over speeding, as experienced with the early Herborg and other turbines, was not a problem (Lundsager and Jensen, 1982). Other early guidelines address manually operated breakers for grid disconnection, relay systems for automatic grid disconnection, a designated “operator”, as well as metering and payment rules for electricity generated by small wind turbines owned independently and connected to the grid (Petersen, 1980). These fundamental requirements regarding braking and grid interconnection were then extended under the 1981 subsidy extension act to include a link from the fundamental requirements to the operational status of stopped, normal operation and emergency shutdown, as well as specific requirements regarding system security, static tower and foundation loads, and load tests as performed by the test center (Lundsager and Jensen, 1982).

The Smedemestermoellen, Blacksmith’s turbine – designed by NIVE, was one of the first turbines to be certified by the new test station – having been installed there in September of 1979 (Pedersen, 1981). The same turbine was also used to publish the first set of “standard measurements on windmills at the test station” that would become the evolving Danish test standard throughout the 1980s (Pedersen, 1981). Early operation of the test station identified some design flaws such as varying stall behavior of the NIVE blades or overloading of the drivetrain by the Riisager windmills (Pedersen, 1984). In 1982, the test station was then extended to accommodate a common set of foundations for the new 55 kW series of turbines which were fast coming to market and later a “universal foundation” capable of handling a 300 kW machine was built in 1984 (Pedersen, 1984). It was this very series of 55 kW Danish turbines that would take the California wind market by storm in the mid-1980s and establish Denmark as the top international supplier of wind turbines (van Est, 1999). Up until the end of the decade, Risø served as the single certifying authority for wind turbine manufacturers in Denmark that allowed them to establish themselves as “a centre of knowledge directing itself to the wind turbine industry, public authorities, and to users of the technology” (Petersen and Skrumsager, 1989). This knowledge fed back into the industry reinforcing the development of the technology and the overall Danish mega-actor-network for wind energy technology.
5.2.5 **A note on other actors and large-scale turbine development in Denmark**

There are still important actors within the Danish wind energy mega-network that deserve mentioning. The activity of policy-makers tied intimately to the activity of NIVE, the small and medium sized entrepreneurs, and the Risø test station. Denmark enacted various policies over the years that would buffet the burgeoning wind energy socio-industrial networks. Though this topic deserves attention, such discussion will be left to future work. In addition, the activity of the extended university and scientific networks were also important in the development of wind energy but we will not address them here.

5.2.6 **Danish case summary — a coherent and reinforcing network of networks**

The Danish development of a wind energy industry included a number of small and large actor-networks including the large networks of the OOA and subsequently the OVE, the small local networks formed at NIVE near Thisted and Tvind near Ulfborg, and the extended networks that connected OVE, Tvind, and NIVE with the new wind industry through various meetings and personal relationships. The specific technology of NIVE that would come to be known as the “Danish concept” featured robust, even over-engineered, and relatively simple design based on largely on a previous artifact, the Gedser turbine, whose design and operation had come to be known largely through the UN 1961 conference reports. The reliability of the design helped the technology persist through various trials in the burgeoning markets for wind energy both in the US and Denmark. This reliability was achieved in part through the over design as influenced by the use of the Gedser turbine as a design rule-of-thumb as well as the extensive testing and experience that the design received in the field having been the center of development from NIVE and the vast majority of the companies that entered into the industry. This network of networks was then augmented then by the activity both at universities, such as DTU, and institutions, such as Risø, which provided significant research and development support to the initiatives.
undertaken. Thus, a mega network was formed which included government directed activity at national labs and universities and grass roots development by local enthusiasts and inventors. The traditional story of the “grass-roots” and “bottom-up” approach for wind energy development in Denmark focuses largely on the activity of OVE and the activity of the small-entrepreneurs. However, the significant role of the government run lab at Risø, the university knowledge and research development, the government market support of subsidies and export guarantees, as well as the expertise and clear reliance on the government funded work of both Johannes Juul and Ulrich Hütter should not be discounted. All were important to the eventual success of the Danish wind industry. In the end, the success of the Danish wind industry is not due to only to the bottom-up or to the top-down efforts, but depends on the technology development within a strong regional network of networks all with a coherent and aligned set of objectives for wind energy development.

5.3 Wind Actor-Networks in the US

5.3.1 NASA Lewis Laboratories, NSF and the ’73 Conference

Just as an understanding of the social movement behind the folk high schools played an important role in the later development of the Danish actor-networks at Tvind, the history of government funded research, and in particular the history of the NACA and NASA, are important in the story of wind energy development in the US in the era of the OPEC oil crises. The government formed NACA, the National Advisory committee for Aeronautics, in 1915 largely in response to the perceived threat of European developments in aeronautics technology (Bilstein, 1989). Despite the attempts of the well-known Wright brothers and other enthusiasts to foster domestic development of aviation technology, Europe was well ahead in terms of establishing government support for research and development in aeronautics (Bilstein, 1989). In 1914, the Smithsonian funded a study of the European advances and the report confirmed what experts and enthusiasts feared. This same year, the First World War broke out in Europe and the use of the airplane to provide strategic advantage for long-range bombing and reconnaissance prompted the US government to finally react and establish the NACA within a Navy appropriations bill (Bilstein, 1989). The NACA began serving the US aviation community in supervising wartime research more as a consultant and advisor until construction of the Langley Memorial Aeronautical Laboratory was complete in 1920. The lab began to hire engineers from across the country to come and work on solving practical problems relating to the advancement of aeronautics and aviation and the series of successes in testing engines, blades, and entire airplanes in order to identify and/or problem-solve various issues. The development of the NACA airfoil series and the knowledge gained from the research and development surrounding such blades earned international recognition for the organization (Bilstein, 1989). The second world war ushered in a new level of activity, and the growing interest in engine-specific research led to the establishment in 1941 of the NACA Aircraft Engine Research Laboratory, renamed the Lewis Flight Propulsion Laboratory and eventually to NASA Glenn Research Center (Dawson, 1991). The NACA had fallen behind Europe once again when it came to jet propulsion technology and the end of the second war led to significant research and development in this area in particular at the new Cleveland, Ohio based research facility (Dawson, 1991). When Sputnik launched in 1957, this third “crisis” would again garner significant government and public support for new initiatives in aeronautics and now astronautics (Dawson, 1991). NASA, the National Aeronautics
and Space Administration, formed in response to the fact that despite NACA’s efforts in developing launch vehicles for satellites, it had failed to beat the Soviet’s to space. NASA involved the integration of 3 NACA laboratories, 2 stations, 8000 people and a $400 million per annum budget (Dawson, 1991).

NASA as an organization would be substantially different from NACA and this legacy would be important later for wind energy development. Even prior to the formation of NASA, NACA had begun to move beyond its role of traditional research and development to one of R&D plus management including the full design of complex technical systems such as the X-15 program that began in the mid-1950s (Bilstein, 1989). NACA began with that program to employ a “systems engineering approach” to design. The transition from NACA to NASA and its mandate for space exploration, especially with the Apollo program and the race to the moon, meant that the NASA would take on the additional role of operation in addition to project management, research and development (Bilstein, 1989). Secondly, NASA would become the hub of a large amount of contracted work for the projects that it managed and less work would be done in house as compared to the days of NACA (Bilstein, 1989). The Lewis laboratory similarly engaged with project management in particular with the Centaur and Agena space-related projects in the 1960s, and its budgets grew to match its new role (Dawson, 1991). It’s budget had steadily grown each year from 5 million USD in 1943 to 30 million US in 1958, but during the Apollo years of the mid 1960s, the per annum funding rose to a peak of 393 million USD in 1965 (the whole agency received a budget of 5.2 billion USD that year) (Dawson, 1991). The success of the moon-race coupled to a shift in public priority to earthly matters – poverty and the environment were in the minds of many. Budgets for NASA were slated for significant reductions in the late 1960s and early 1970s. Budgets and staff cuts to all laboratories including Lewis laboratory. At the same time, Lewis engineers began to study environmental problems and extend research into new areas such as an EPA funded project on pollution in Lake Erie (Dawson, 1991). Even today, one can recognize the industrial footprint that left its mark on the entire region surrounding downtown Cleveland and America’s “rustbelt”. However, in the early 1970s, the pollution in Cleveland due to the heavy industrial activity and resulting pollution led to the now infamous burning of Cleveland’s Cuyahoga River. This impressed upon everyone in the region the importance of keeping one’s feet on the ground and turning the gaze from the stars to the city.
In part to address the issue of funding and in part driven by the new environmental concerns of the day and growing public awareness over fossil fuel dependence, the NASA Lewis laboratory began to consider the potential of energy research. Dr. Robert Graham, a staff member at Lewis who would eventually become NASA’s administrator from 1984-1986, wrote a letter to the Lewis Laboratory Director Dr. Lewis Lundin where he championed the unique position of the laboratory to engage in energy research due to its complementary areas of expertise in the propulsion and energy conversion (Dawson, 1991). Dr. Robert English, chief of the Space Power System Division at Lewis, had reached a similar conclusion. In particular, research at NASA involved with solar energy technology for the space station held potential for earthly applications and the cancellation of the space station under the Nixon administration meant
that the technology was newly orphaned and in need of a home (Dawson, 1991). The NSF was the only agency at the time with funding for solar photovoltaics under their Research Applied to National Needs (RANN) program (Eggers, 1973; Thomas, 2008). The NSF, however, did not have a laboratory and with the shortage of funding at NASA, and Lewis was happy to serve as the NSF’s laboratory (Thomas, 2008). Dr. Al Eggers, the assistant director for research applications at NSF, was a former NASA employee, provided a connection to NASA (Thomas, 2008). In 1971, President Nixon urged congress to look at clean energy needs for the country and this led to the creation of 11 panels to look at different potential energy solutions (Morse, 1973). In 1972, NSF and NASA jointly sponsored a “Solar Energy Panel” of forty nation-wide experts whose final report found that wind energy in particular had a large amount of potential for serving US energy needs including the west coast, Great Plains, and off the east cost of the US (Eggers, 1973). Following up on this report, Robert English then commissioned a study on historical wind energy development by Dr. Joseph Savino (Savino, 2008). Work was already underway in the area of solar energy, but NASA had no experience with wind energy technology. Savino recalls his early involvement as a matter of curiosity:

“I guess I was finishing up one project and looking for something else and one day a message came over my desk where Bob English’s division was working on alternative programs. People were already working on the solar; nobody was working on wind, and I volunteered to do that. The interesting thing was that up until that time - I think I’d been working there for 18 years already - I was always one who liked to get library material related to the project. As a rule, I always went to the library when I had a project to work on to learn what others had done, and to my surprise, there were, when you hit the right spot, there was considerable literature around efforts in the 20th century, in the first half of the 20th century to evaluate wind turbines.” (Savino, 2008)

What Savino found through his literature review were the results of efforts during the first half of the 20th century to develop large-scale wind turbines, such as the Gedser wind turbine in Denmark (Savino, 1973). Having presented his findings to NASA and NSF in February of 1973, Savino was then recruited to organize a workshop to bring together domestic and international experts on wind energy (Savino, 1973). This led to the first workshop held jointly by the NSF and NASA on wind energy conversion systems in June of 1973 that included over 30 presentations on wind resource characteristics, turbine design, testing and experiences (Savino, 1973). The workshop invitees featured many veterans of small-wind programs, such as Marcellus Jacobs of the Jacobs wind turbines, as well as a few from the distinguished large-scale turbine projects, such Beauchamp Smith of the Smith-Putnam project and Ulrich Hütter. Hütter played a particularly active role at the workshop. He gave a speech on previous developments of large wind energy plants in Europe where he described his own work as well as referenced the Gedser turbine in Denmark, he made a brief secondary presentation on tower structures and loads, and he played a critical role in the workshop committee side-meetings on rotor characteristics. Hütter’s work truly impressed the participants. Richard Oman of Grumman aerospace who chaired the rotor characteristics committee commented, “Professor Hütter’s hundred kilowatt machine... is truly an engineering achievement of some significance” (Oman, 1973).
The final presentations of the conference unveiled plans by NSF and NASA to proactively pursue a wind energy research program that included a $300,000 USD budget for FY 1973 for the NASA workshop and blade and generator work to be performed Montana State and Oklahoma State universities respectively (Morse, 1973). The government slated another $1.5 Million USD for FY 1974 with an eye on a five-year program, described by NASA Lewis’s Dr. Ronald Thomas, which would design and demonstrate an integrated wind electricity generation and complementary storage system of unspecified size (Thomas, 1973). Thomas, who would eventually become the head of NASA’s wind energy program at Lewis, was interested in the potential of ocean thermal gradients as a heat engine to provide large amounts of base load power (Thomas, 2008). However, the NSF had convinced him and others at NASA to focus their efforts on wind energy. Just as the new program for wind energy was slowly getting underway with its five-year planning, a crisis occurred that would dramatically affect the program going forward. Just months after the workshop, the oil crisis which began October 16, 1973 when OPEC raised its prices for oil by 17% and then continued cuts into November leading President Nixon to sign the Emergency Petroleum Allocation Act (Serchuk, 1996). Also in November of 1973, Thomas and Savino presented their findings on the “Status of Wind-Energy Conversion” to an NSF RANN work symposium. The initial formation of the actor-network involving NASA and NSF personnel had positioned themselves to receive considerable support for its initiatives as the effects of the oil crisis swept across the nation.

5.3.2 The MOD turbine network
As promised, the NASA Lewis laboratory set to work immediately at the end of 1973 to mobilize actors for its work in wind energy that would begin in 1974 under the support of the promised NSF funding. In
1973, energy conversion and power systems were sub-divisions of the space technology and materials division of the Lewis Laboratory, but by 1978, space related aspects of the division were moved to space systems and technology and the division was re-titled as “energy programs” (Dawson, 1991). Similarly, NSF would mobilize around wind energy at the request of the Atomic Energy Commission and the suggestion of a 30 million USD budget for wind energy over the next 5 years (Serchuk, 1996). Dr. Lou Divone, formerly of California Institute of Technology, had come to NSF on temporary leave to direct the FY 1973 activities including the NASA study and workshop (Serchuk, 1996). He stayed on with the program as it continued to develop and was eventually promoted to run all of the newly formed DOE’s solar electric programs (Serchuk, 1996). By the summer of 1974, the NASA wind program was well underway and Savino organized his second workshop this time in Stockholm, Sweden in conjunction with STU/Vattenfall. By the time of the conference, design work on the first turbine at NASA was underway and Dr. David Spera, who would later become the lead engineer of the NASA wind energy program, gave an overview of the design of their first turbine - the MOD 0A (Spera 1974).

Hüttner and Savino were again present at the meeting and gave presentations on the respective historic large wind turbines programs in Germany and the US, but in addition, Neils Meyer, president of the Academy of Technical Sciences in Denmark (ATV) gave a presentation on the historical activity in Denmark as well including the Gedser and earlier turbines (Meyer 1974). Louis Divone also attended and gave an overview of the federal wind program in the US. He and Savino made a trip to visit the Gedser turbine while in Denmark and from that visit initiated a joint effort by the US and Denmark to share the costs of refurbishing and instrumenting the turbine for testing (Savino, 2008; Lundsager, 1978). The Gedser project fit well within the overall program objectives that NASA set forth: “to
advance the technology of wind energy conversion systems – to be cost competitive and capable of rapid commercial expansion for producing significant quantities of energy.” (Divone, 1974) The significant quantities of energy is an important factor – just as with the Danish Tvinde program or the US Apollo program, the federal wind program the NASA component was motivated by a crisis. Moreover, just like the Tvinde program, it was felt that large turbines were necessary to make a significant impact from wind in addressing the current energy crisis (Thomas, 2008; Savino, 2008). There was impetus to go big, at low cost and to do it quickly. The first aspect would influence the size of turbines that the NASA programs encompassed which ranged from 200 kW to 3.2 MW for the last of the series. The second would influence the design choices such as using two blades for a rotor – Hütter designed a 2-blade rotor for his experimental 100 kW turbine that had good aerodynamic efficiency at 2/3 of the weight (Viterna, 2008). The third would come to influence the overall timeline for the program. The original five-year plan to build an integrated wind turbine with storage only a year later became a detailed plan of action with a 100 kW test system deployed in less than a year with 3 to 4 subsequent models in the range of 500 kW to 3 MW systems by the end of the decade (Divone, 1974).

In order to meet these bold tasks, NASA would again assume its role as systems engineer – contracting out design studies and manufacturing to such companies as GE, Boeing, Lockheed and Hamilton Standard (Serchuk, 1996). Still, even with the contracted work, NASA would still play the central role in the projects’ research, design and testing. The governing design for the initial work would be that of Ulrich Hütter who had so impressed Savino, Divone and other during the early workshops. The Hütter design appeared strong because it represented a fairly large size turbine at 100 kW, it used progressive materials and was thus very light weight, and having run for 5 years indicated that even as an experimental turbine it had decent reliability (Savino, 2008). Just as Tvinde had incorporated Hütter’s work and consulting into their design, NASA used his work as a benchmark for their subsequent work. They even brought a set of technical drawings of the Hütter design over to NASA kept now in the Lewis historical archives. The technical drawings were studied in detail and the first model 0-A (MOD 0-A) turbine featured a design very similar to the Hütter design – a 2-bladed, downwind turbine, on a monopole tower. However, just as NIVE left off the tip breaks of the Gedser turbine, the initial MOD turbine did not include a teetered hub – the NASA team was not aware of it (Savino, 2008). The teetered hub that was critical to the 2-bladed design loading under tower shadow was part of the Hütter drawings but somehow the NASA team had missed it. Savino remembers a military visitor who asked about a teetered hub, and none of them had heard of it until that point (Savino, 2008). The MOD programs all featured that similar basic design of a 2-bladed downwind turbine.
5.3.3 Utility Reaction to wind electricity generation

As early as the 1973 workshop, Savino had already completed a major study surveying the nations' utilities regarding their interest in potentially using wind energy for electricity production. The study indicated that utilities did not see much of a reason to look at wind power at all:

"Before the 1973 oil crisis, we went to utilities and we asked them, 'hey do you think you could use large wind turbines as a power source?’, and we had to wait until they stopped laughing. "Wind turbines?” they said. After the 1973 oil crisis, they didn’t laugh anymore.” (Savino, 2008)

NASA, as the center of one actor network of wind technology development in the 1970s, grew to work with the utilities at a very early stage in the game. Working with the utilities as part of the actor-
network was a significant change from NASA's usual mission-oriented programs with the military in the prior decades or with the federal government during the “space race”. Its push into the energy space did not connect with a similarly enthusiastic demand for its research and development projects.

5.3.4 A note on other actors
As with the Danish case, the role of policy-makers have been excluded, as have the important actions of universities and other research institutions such as Sandia Labs, Oregon State University, and SERI laboratory now the National Renewable Energy Laboratory. In addition, the activity of the small wind entrepreneurs is important. Just as in Denmark, the US saw a flurry of activity by small wind entrepreneurs in the mid-1970s and early-1980s. These companies spread across the country, developed a large variety of different designs, but lacked the same openness for testing and sharing of design information – factors that helped solidify the actor-networks in Denmark.

5.3.5 US Case Summary – disparate and incoherent networks
Just like any actor-network, the NASA mod program agents left a trace behind them as they moved. However, the actor-network of the NASA program, like most of the other research and development programs that NASA had run, was temporary. The fall of the oil prices in the 1980s certainly expedited the dissolution of the network, but the technology NASA was creating needed a permanent home, a permanent champion. The cost+ programs with big industry were not likely to continue their efforts with the changing tide of economic conditions. Rather, the small wind entrepreneurs would serve as a more stable and persistent network. Unfortunately, most did not outlast the changing political climate of the 1980s. The lack of strong ties among the actors in the small entrepreneurs’ network and their exclusion from the federal actor-network resulted in an overall weak and incoherent network for wind energy development at the US national level. While both the bottom-up and top-down efforts were prevalent in the US as well, the lack of sustained top-down effort coupled with an incoherent bottom-up network affected the overall future of the US wind energy industry.

5.4 Discussion
Wind energy technology innovation comprises a network – the different designs of Juul, Hütter, and various additions from other inventors have mixed and matched throughout history to form different overall design configurations. These different designs have exerted influence on the human actors around them that seek to control their behavior. The MOD turbines of the NASA program remained elusive in terms of specific design goals of interest – mainly reliability and cost. At the same time, the inherent reliability of the Danish wind turbines helped gain their market acceptance despite their over designed and the impact that would have on the costs. Extending the MOD actor-network to NASA, NSF, the utilities and large industry – the same systems engineering methods utilized by previous actor-networks to send a man to the moon would prove to be effective in certain design goals of building large wind turbines. However, without a key component of the actor-network, a permanent willing sponsor of the technology, the long-term viability of the MOD turbines was not likely. In addition, the MOD network all but excluded the small wind entrepreneurs of the US. The lack of a cohesive and unified mega-network for wind energy in the US hampered the fledgling industry from further development. By contrast, top-down government actions in Denmark supported the organic bottom-up movement of
small wind entrepreneurs for a coherent network of networks that developed into the center of wind energy technology development for several decades.

The lasting presence of a specific configuration or design for a technology is referred to as a “dominant design” (Utterback, 1996). Many interpret this as the resulting “winning technology” from a competitive process. In the early stages, many technologies or technological platforms compete for market share but eventually, one technology or platform captures the bulk of the market. Some may argue that this process is evolutionary in nature by which the intrinsically “superior” technology will ultimately succeed. The factors that establish the superiority of one technology over another may depend on a multitude of performance metrics against which we judge the technology. The technology that satisfies the largest customer base across the broadest or most important set of metrics will be winner. Such an argument is one that discounts the role of history, or path dependency, in technological innovation. Path dependency is a concept that resonates with a variety of academic disciplines. To historians, the idea that history matters and has import for the present is a foregone conclusion. In particular, within the history of technology, regardless of the impact technology has on shaping society (Heilbroner, 1967; Winner, 1980), the social influence on technology innovation and design (Bijker, 1987) or the dual shaping of socio-technical processes actors and networks (Latour, 2005; Callon, 1986), the role of historical events influencing the present and future trajectory of society, technology or both is important.

More recently, the concept of path dependency has become a common term able to bridge the boundaries that traditionally separate academic dialogue between economists, historians, management scientists and even systems engineers. Certain economists have denied the empirical presence of path dependency and technological lock-in altogether. The idea of innovative processes resulting in “sub-optimal” technological configurations was championed through the historic case of the QWERTY keyboard (David, 1985) and led to direct dispute that the DVORAK system, alternative keyboard arrangement, was actually superior (Liebowitz and Margolis, 1994). Economists and innovation theorists have argued for a form of “weak form of path dependency” where sticky social processes inhibit the intrinsically superior technology from obtaining dominance in the short term (Bassani and Dosi, 2001). Going back to the notion of “dominant design”, then, this concept does not arise from intrinsic superiority of a technology, but rather from the path dependent processes that allow it to maintain market dominance “for a time.” At a further extreme, however, there are those such as David who would argue that temporal and social processes could lead to a situation where one technology may achieve long-term dominance regardless of having any sort of “intrinsic” superiority.

When it comes to historical accounts of the development of wind energy technology, a mixture of perspectives is present. Some accounts emphasize the direct “superiority” of the “Danish concept.” At the same time, these historical treatments also tend to champion the social processes that lead to the creation of the “Danish concept.” In these cases, there is an emphasis on how the various actors arranged themselves and interacted with each other. This is especially true in the two often-juxtaposed historical cases of the small Danish wind energy entrepreneurs and the large federal wind energy research programs of the US (Karnoe and Garud, 1999; Heymann, 1998; Serchuk 2006; Garud and Karnoe, 2003; van Est, 1999). One can argue that the “Danish concept” became the dominant design
due to either the strength of its intrinsic value to the users of wind energy technology, the superiority of the social processes that ultimately led to the creation and promotion of the “Danish concept”, or a combination of both. The first view, consistent with a neo-classical economist’s anti-path dependence perspective, would maintain that the social processes were of little importance and that due to its intrinsic superiority, the “Danish concept” would have become dominant regardless. The third perspective, more consistent with a weak path dependence view, would maintain that the technology involved a certain amount of intrinsic superiority according to preferred functionality from a social standpoint but that the social processes involved were also critical in assisting the technology in achieving market dominance. The second perspective, most consistent with a strong path dependence perspective, would argue that there is little to no intrinsic market superiority of the Danish design, but that the social processes involved with the innovation of the “Danish concept” were responsible for its dominance in the market. Historical accounts of the history of wind energy technology development in the 1970s and 1980s are often most in line with the first and the third account. Because of this, the second perspective, that which all but denies the “Danish concept” its intrinsic superiority, becomes more interesting. In general, then, the historical development of wind energy technology becomes an interesting case for which the devil’s advocate may want to test the concept of “strong path dependency”. In the end, the challenges associated with taming the wind for humankind’s use proved to be a much more formidable challenge than expected and the technology was not passive. Its internal forces reacted against attempts to mole it in a powerful and chaotic manner – making its own statement for history.

5.5 Upscaling Turbine Technology and Co-development of Wind Science, Technology and Standards in the Modern Era
Development of wind turbines touches on almost every area of natural science and engineering. From the advanced composite materials used in rotor blades, and the characterization of a turbulent and even chaotic wind resource, to the aerodynamics associated with the rotor, to the design of the electric generator and interface with the electric grid, to the dynamic loads associated with the overall structure, wind turbines have been and still are the subject of a broad set of research and development efforts. Bringing all of these technical innovations together is the overarching system design for a wind turbine that is inherently complex and involves a large amount of uncertainty in terms of the physics of the wind as well as the machine itself. This uncertainty has had a significant impact on the history of wind energy technology and the “Danish Concept” embodies design principles meant to address this uncertainty. Designing the “Danish Concept” and other modern turbines involved many structural considerations—designing towers that would not buckle and collapse, drive shafts that would not crack and fail gearboxes and other components that could handle the applied torque, and loads translated from the rotor through the rest of the system.

5.5.1 Design codes and the science of wind energy
There is much more to say about the specifics of different design concepts, competition among them, and the various actor-networks of the 1970s and 1980s coalescing around the different design concepts. However, the focus of this section is on the intertwining of design methods, the aeroelastic research codes, with the technology development and design standards. Aeroelasticity involves the study or
science of aerodynamic (dynamics of airflow) forces induce load on a structure causing a range of response behavior from the structure. The term and the science inherit from aeronautical engineering and in particular, parallels are often drawn between wind turbine and helicopter technology (Rasmussen, 2003). Aeroelastic codes for wind energy design are so called because they take a technically holistic perspective for design including a meteorological model of the wind field, aerodynamic models characterizing the interaction of the wind field with the blade and the resulting forces, and structural dynamic models which capture the effects of these forces on the entire turbine structure as well as individual components and subsystems (Rasmussen, 2003; Lundsager, Frandsen, and Christensen, 1980). To this, one can add material models that capture how the different material properties of the system components affect the overall structural dynamics (Lundsager, Frandsen, and Christensen, 1980). Today, there exist several commercial and publicly available software packages of codes needed for aeroelastic analysis of horizontal-axis wind turbine configurations (Rasmussen, 2003; Quarton, 1998). However, only pieces of the current analytic suite were available when the Gedser, T vind and NIVE prototype turbines and their descendants were designed and built. In particular, the coupling of meteorological models with the aerodynamics and structural dynamics had not been achieved (Quarton, 1998) and thus characterization of the structural behavior of a turbine under extreme conditions and over its lifetime had not been developed. As Maegaard highlights from the early NIVE design process, “There were many such rules of thumb. They were more on the safe side.” Without well-developed physical models, the NIVE team relied on information in particular from the Gedser project that influenced the design of the NIVE blades then adopted and developed by Oekaer. The UN conference on new energy again became a reliable resource:

“We know from the Gedser windmill that [the turbine] should be induction type – asynchronous type – but you know the size of the rotor, and we had some standards... [From] New Sources of Energy we had all the information from the Gedser windmill. There were some rules of thumb – 30 kg/m^2 – this was the axial pressure on the rotor, and from that one could calculate well the tower – what kind of steel, how the lattice system should be. You could calculate the size of the foundation, and once you have these basic figures, the rest of it is conventional. There will always be some sellers you can go to once you have the loads and you could go to an engineer saying, can you help us to know the size of the steel.”

The measurements taken during the initial operation of Gedser windmill did in fact provide a basis of information over expected loads that may occur both during operation and with the wind turbine stopped (Juul, 1961). Figure 9 of the document shows that measurements from the Gedser windmill indicated that axial pressures, the aerodynamic pressure on the rotor, during operation ranged from around 20 kg/m^2 at 25 m/s wind speeds to nearly 35 kg/m^2 for wind speeds in excess of 30 m/s (Juul, 1961). NIVE used this factor of 30 kg/m2 in dimensioning the rest of the system design. Thus, combining the dimensions of the NIVE turbines with the rules of thumb obtained from the Gedser experiments served as a basis for design when understanding via physical models were not available. Of course, these rules of thumb were known even at the time of the UN conference to be quite conservative. Experiments from the Gedser turbine indicated that “the dimensions of blades, tower and cabin [were] rather on a liberal scale” (Juul, 1961). This “over dimensioning” translated to the NIVE turbine. However, without a better understanding of the physics and dynamic interaction of the structure with the wind field, the over dimensioning was seen as a good design principle“
"[Wind manufacturers] wanted to make a reliable blade. It was the company that wanted to have a reputation for good quality. The uncertainty over how to dimension such a turbine was quite big, so let's make it strong enough. Later it was calculated that the blades had a design life of 70 years when normal design life of such equipment is 20. But, not knowing how to calculate it better, it got a design life that was later proved to be 70 years – which was too much you can say... half would be sufficient. Now [the turbine at the Folkecenter facility] has been here for 25 years, so it's good it was not 20 years... it seems to be of a durability that it can be there for several more years. The gearbox is also over dimensioned, the generator is over dimensioned, etc... the procedure we followed, was if we were uncertain about the loads, then we took the highest value, so it will never down, not break down and so on. Where we could see something critical we took the most cautious solution."

This in part, Maegaard describes, targeted the needs of their client base for the designs – the blacksmiths and small and medium enterprises – were selling directly to the customers, not NIVE:

"These blacksmiths here were selling to their local clients, and if they lose confidence, it could be a disaster of course. So we would rather use too much material, make it too strong, than to lose confidence in the use of it. I think this was an important principle to have, because these wind turbines set the standard of high reliability... they were part of setting the standards for what is wind power in Denmark."

Indeed, during the years, the number of wind turbines manufactured by Danish companies as compared to US companies would climb until the Danish manufacturers all but dominated the entire international market for wind turbines. While the parallels to the aviation sector were important for wind turbine development, especially for blade aerodynamics, when it came to the overall structure and the loads, the analogies began to break down. Many researchers highlight that the aviation-inspired predominantly US technology had a design focus that was less well suited to the wind turbine industry due to the different operational characteristics of the sectors (Heymann, 1998; Garud and Karnoe, 2003; Karnoe and Garud, 1999; Maegaard, 2010). Maegaard notes that while a helicopter undergoes overhaul every 200 hours of operation, “a wind turbine has to run for thousands of hours before having an overhaul” and the principles for over dimensioning and emphasis on reliability were more suited to the wind turbine industry (Maegaard, 2010). One of the earliest employees of NIVE, engineer Jacob Bugge (1978), published Bogem om Vindmoeller (Book of windmills) targeted at wind turbine designers with a number of formulas and equations to calculate, among other things, the design loads for wind turbines of different types. The book’s chapter on “dimensioning” of wind turbine components highlights the design principles utilized by NIVE and the “Danish concept” adopters in its chapter introduction:

"A fairly safe fixing of the dimensioning loads, for example as seen in the different loading standards, requires fairly extensive practical experience. Such experience with wind turbines has not yet been fulfilled. It is therefore important to consider such uncertainty in developing a proposal for design at present. The main three sources for this uncertainty are:

- There is no certain knowledge of the wind loads acting on a windmill.
- In many cases there is a new use of materials and components. The way they behave, and the strength they may be conferred, can be different than expected.
- It can be difficult to predict which strains or strain combinations are really serious. A weak effect which enables harmonics to develop in the mill can thus be devastating.

The design, described below, should be taken with the above reservations. It should only be considered as an interim proposal for the design, until there is a larger body of experience" (Bugge 1978, translated from page 151).
The emphasis from small and medium-sized Danish wind turbine manufacturers was to use a margin of safety commensurate with the understanding of system loads and behavior at the time – that is, a very large margin of safety. The small wind turbines of the early 1980s in Denmark and the 55 kW turbines that were the main Danish export to the California market all stemmed from prior incremental experience dating back to the Gedser turbine (Petersen, 1990). The initial methods of design and invention of NIVE and its contemporaries included the basic information provided by the work of Juul and Hütter coupled with a large amount of trial-and-error development and best-practice transfer across small turbine manufacturers (Maegaard, 2010). Maegaard and others, through the Organization for Renewable Energy (OVE), held regular meetings or “sit-ins” where manufacturers and independent designers/builders could share their experiences and learn from one another (Maegaard, 2010). Contemporaneously, however, a growing body of national and international research on the science and engineering of small and especially large-scale wind turbines was developing, and as turbines increased in size, the science and research of wind energy engineering would increasingly influence industry development. Joergen Thirstup Petersen, one of the first developers of a comprehensive and generally accessible wind turbine design code package, proposes that as the turbines increased in size, the trial-and-error processes of bulk production and collective experimentation were not sustainable since building prototype turbines without a solid understanding of the dynamics loads was cost-prohibitive.

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62 As mentioned previously, several historians have argued that this bottom-up approach to innovation was the reason for the early Danish success (Heymann 1998; Garud and Karnoe 2003; Karnoe and Garud 1999). Again, this argument has to be juxtaposed with similar arguments that the “Danish concept” was a better design than others, or thirdly that the design and the collective innovation were jointly responsible for the Danish success in the wind industry.
At the same time, research efforts had begun in the early 1970s that aimed at understanding wind meteorology, aerodynamics and structural dynamics (Petersen, 1990; Quarton, 1998). Efforts to understand and model the complex dynamics associated with a wind turbine were an important component of the large international research programs in Denmark, the United States and elsewhere. A review of how each of the three main components of aeroelastic codes has evolved is available from Quarton (1998). To summarize, the meteorological models of the mid-1970’s that were used for design assumptions were based on normal and extreme steady, or non-turbulent, winds (Quarton, 1998). However, characterization of turbulent winds are important to wind turbine performance and loading and various research programs developed an understanding of the “spectral” or frequency behavior of turbulent wind so that wind could be modeled to a greater degree of accuracy (Quarton, 1998). The aerodynamics of wind turbines were actually the most well understood aspect of early wind turbine development. The fields of aviation and aeronautics provided the basic theory necessary to understand the interaction of the rotating blades with an incident wind field. The so-called blade element and momentum theory, used in propeller design in the 1930s, involves the combination of two sets of theories in order to be able to determine how the dimensions of the blades will affect aerodynamic performance and loading of the rotor (Quarton, 1998; Hütter, 1961). Such models have been extended to incorporate dynamic wake, or the dynamic movement of the wind field behind the rotor, as well as stall hysteresis, when the wind field is changing rapidly under stall conditions (Quarton, 1998). Finally, the development of structural dynamics models of wind turbines has been ongoing since the 1970’s. As with meteorology and aerodynamics, the research community for wind energy was able to leverage existing knowledge for structural dynamics of other large physical machinery. However, there were significant complications in translating those models to the wind energy space where one the rotor component of the system rotates with respect to the other main components of the system (drivetrain, nacelle and tower) (Quarton, 1998). Thus, the main feature of early code development focused on how to take available models of the meteorology and the aerodynamics and to then appropriately model the structural behavior of a wind turbine.

This early development of aeroelastic codes for wind turbine design was of special interest to research efforts in both Denmark and the United States to build large-scale wind turbines approaching or exceeding a rated capacity of 1 MW. Several historians and other scholars (Serchuk 2006, van Est, 1999, Heymann, 1998, Garud and Karnoe, 2003) have treated the history of the federally funded research program on large-scale wind turbines in the United States. Generally, the focus of such histories has been on the political aspects of the wind energy research programs or the national innovation system including comparative treatments of “market pull” versus “technology push” federal policy strategies (Heymann, 1998; van Est, 1999; Garud and Karnoe, 2003). The development of the aeroelastic wind turbine design codes, originally developed for research and design evaluation, was an area where there was a significant amount of knowledge transfer across international borders. Pressure to address the continuing oil crisis in the mid-1970s led to the formation of the International Energy Agency Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems (IEA Wind) (International Energy Agency, 2003). Initially, two groups formed: the IEA Programme for Research and Development on Wind Energy Conversion Systems (R&D WECS) in 1978 and the IEA Co-operation in the Development of Large-Scale Wind Energy Conversion Systems (LS WECS) in 1977. Each
program involved the four countries with significant research efforts for large size wind turbines including Germany, Denmark, Sweden and the US (International Energy Agency, 2003). Collaboration efforts in terms of knowledge sharing and international workshops had begun as far back as June of 1973 (just before the first OPEC oil embargo) when NASA, on contract from the NSF, held a workshop and invited experts to discuss their knowledge of wind energy technology (Wind 1973). A second workshop, co-organized by NASA and the National Swedish Board for Technical Development, held in Stockholm in 1974 attempted to provide all attendees with an overview of the current state of wind energy technology and research needs (“Wind Energy Conversion Systems”, 1973). Even as early as the 1974 workshop, wind energy veteran Ulrich Hüttner noted in a session on major problem areas that “[t]he number one research problem is the behavior of the whole system, its dynamic behavior, and including the problem of elastic instability even when standing still, which is a problem for very big rotors” (“Wind Energy Conversion Systems”, 1973, p 8-8). Related to that lack of understanding, he noted that safety and security in operation and control of the machines were also an important problem. NASA was soon to find out the difficulties of uncertainty associated with the structural behavior of the overall wind turbine system. Following on the workshop series and the added political support for wind energy development during the oil crisis, NASA was in a unique position to serve as the US center for research and development on large-scale wind turbines. A series of wind turbines were developed beginning in 1975 with the MOD-0 100 kW turbine, followed by the MOD-0A 200 kW turbine in 1978, the MOD-1 2 MW turbine in 1979, the MOD 2 2.5 MW turbine in 1980 and finally the MOD 5 3.2 MW turbine in 1987 (Schefter, 1982). During the early development, NASA became well aware of the limitations Hüttner was referencing in the 1974 workshop. The first MOD-0 turbine had “serious structural problems” and NASA itself has a “lack of confidence in [their] structural dynamics capability” (Robbins, 1978). In addition, NASA, through the newly formed Energy Research and Development Administration of the US government, formed a partnership with the Danish Electricity Supply Undertakings (DEFU). It provided equal funding to put the Gedser turbine back into operation for the purpose measuring the power curve of the windmill, the power quality and in particular the “loads on certain parts of the structure, especially the rotor, and their structural response under various conditions” (Lundsager, 1978). During the years from 1977-1979, the Danish National Laboratory Risø and the Danish Ship Research Laboratory jointly managed the refurbishment of the Gedser turbine and the subsequent tests and analysis (Lundsager, Frandsen, and Christensen, 1980). The development and operation of large-scale wind turbines such as the MOD series in particular, as well as the Gedser turbine and two 630 kW NIBE research turbines in Denmark generated data used in the subsequent development of the design codes (Garrad, 1983). Data from the MOD-0 in particular served as “a workhorse for much experimental testing and validation of computer codes” (Garrad, 1983).

Thus, as part of the development process NASA supported the development of the wind turbine design and analysis codes through data access on their designs and performance but also through specific contracts for code development such as with the wind turbine design code MOSTAS, Modular Stability Analysis system (Schefter 1982). The code development of MOSTAS allowed a redesign of the MOD-0 and the MOD-0A turbines such that they “[met] or [exceeded] all original design requirements (Robbins 1978). Paragon Pacific Corporation, which created MOSTAS over the period of several years, developed a series of codes modified from the helicopter design code MOSTAB including: MOSTAB-WT (modeling a
single blade with one degree of freedom), MOSTAB-WTE (incorporating NASA empirical data), MOSTAB-HFW (modeling a full rotor with four degrees of freedom and a teetering hub), and finally MOSTAS (for complete modeling of the wind turbine generator using both MOD-0 and MOD-2 NASA designs and empirical data) (Spera, 1980). Added to this were a number of initiatives to develop codes for proprietary applications such as REXOR-WT by Lockheed, GETSS by GE Space Division, F-762 by United Technology, and DYLOSAT by the Boeing Aerospace Company (Spera, 1980; Lobitz, 1984). Denmark pursued similar theoretical approaches to design development during the creation of the NIBE 630 kW machines (Petersen, 1990). The Danish Technical University (DTU) carried out the design of the two turbines with support again from Risø national laboratory in both testing and analysis (Jastrup, 1998).

These early efforts did not immediately translate to the commercial development (Petersen, 1990; Schefter, 1982). As previously mentioned, the early Danish designs were more guided by large safety margins than theoretical development and design engineers were focused largely in the early to mid-1980s on satisfying demand for the 55 kW wind turbine systems first in Denmark and then the United
States (Petersen, 1990). Petersen theorizes that in addition to the increasing size of turbines in the 1980s, the need to understand the lifetime structural behavior of the turbine and increasingly, that within the Danish wind companies, the design of turbines was becoming a specialization separate from the production of wind turbines (Petersen, 1990). In addition, many systems were installed in the mid-1980s due to the wind rush induced by strong subsidies in California. Both U.S. and Danish machines were installed, and the majority from the US and some of the larger Danish turbines did not perform well in the field (van Est, 1999).

“When the smoke cleared in Altamont Pass in California and we the engineering community started testing like mad to find out what went wrong, we realized that we had missed the loads terribly, and the fatigue loads. That’s when we started improving the physics models because we now had a better understanding of the physics necessary to derive them, and so the models improved, the testing improved, and more importantly the realization that the testing and the modeling had to go hand in hand” (Butterfield, 2010).

In addition, codes such as MOSTAS or the Danish analogue referred to as “the Code” were both designed in the computer mainframe environment and thus were consuming in both time and monetary resources that limited sharing of information across research environments and designers from industry (Petersen and Skrumsager, 1988). The various codes used today in wind energy design were thus developed with the personal computer in mind for more rapid prototyping of wind turbine designs and evaluation over the expected lifetime. In general, there are currently four such well known aeroelastic design codes for wind turbines including two codes originating out of Denmark, HAWC2 from Risø and FleX5 originally developed by DTU and currently owned by Dong energy, as well as code developed in industry by Garrad, GH Bladed owned by GL Garrad Hassan consulting company, and finally in the United States, FAST/ADAMS developed by the merger of various semi-overlapping design codes and currently managed by the National Renewable Energy Laboratory (NREL). HAWC2, originally HAWC, was developed in the late 1980s as a PhD dissertation specifically to satisfy a nationally funded initiative for developing a PC-based aeroelastic design code for wind turbines (Petersen and Skrumsager, 1988).
The resulting dissertation provided an overview of the different model types beginning with single blade models which look only at the response of each blade considered independently and using the assumptions that the rest of the system, from the hub through the drivetrain to the tower and foundation, are considered to be stiff (Petersen, 1990). For certain small systems of the early 1980s with small rotors on stiff lattice-towers, such assumptions were appropriate. Such single-blade models were developed independently in the early 1980s at NREL in the US and at DTU in Denmark by Thresher and Oeye respectively (Petersen, 1990). Development of the FLAP model in the US involved considerable validation using the MOD program data. FLAP, developed by Bob Thresher on contract with NREL from Oregon State University, was originally a single-blade model but then extended to encompass the full rotor. The code would evolve over the years into several variations that eventually became FAST, NREL's current aeroelastic code suite. The Flex model developed by Oeye would go on to be highly utilized by industry from the late into the 1990s since Vestas, who had early licensed this software, was quickly becoming the world leading manufacturer of wind turbines. A license to Flex included access to the source code allowing for development and customization of the code in house. A similar model served as the first step in the creation of Risø's HAWC code did not develop until the late 1980s and does not reference the earlier models (Petersen, 1990). An additional degree of complexity was taken into account in the mid-1980s for a second generation of models that included a coupled rotor where the hub is not stiff and thus the codes are able to capture additional vibrational responses not captured in the single-blade model suite (Petersen, 1990; Lobitz, 1984). Examples of this software suite included in the US, the Sandia National Laboratories HAWTDYN code, in Denmark, a research model developed in the late 1980s at Risø, and a model, the precursor of Bladed, developed independently by Garrad but very similar to the Lobitz model (Petersen, 1990). Finally, a last set of models distinguished by Petersen begin to approach the earlier MOSTAS and Danish Code and include
the angular velocities at the tower top (Petersen, 1990). In other words, the tower is now flexible for a full aeroelastic treatment of the entire wind turbine system. Both the US, Denmark and Garrad were involved in models for this category including the ASTER5 program from NASA which specifically focused on a teetering hub, a similar model also appropriate for a teetering hub developed by Garrad and later incorporated into Bladed, and a few models developed in Denmark including one at Risø and another at DTU (Petersen, 1990). There have historically been significant differences between the aeroelastic design codes in the representation of the wind fields, the aerodynamics used as well as the structural representation and dynamic calculations. In particular, there has always been an attempt to balance the limitations of computational techniques with the desire for a more refined and detailed representation of the wind turbine system and the equations involved. Whereas the HAWC code was designed based on a finite-element approach, the Bladed code was based on modal expansion of the response (Petersen, 1990). In either case, the goal is to limit the number of degrees of freedom dealt with in discretizing the model for analysis (Petersen, 1990). The decision by the HAWC model to use a finite-element, or multi-body, approach was because it accommodates more complex and more flexible structure designs (Petersen, 1990). As larger turbines have involved the use of more flexible tower and blade structures, the deflection of the blades have become more significant which has induced a stronger interest in multi-body approaches for design codes. The HAWC code was completed in 1990 and was then leased to Bonus for use in their design work while the DTU based Flex code was used by other Danish companies in the design process and eventually Elsam that merged with Dong Energy acquired the code. From 1994 onwards, Flex4 and then Flex5 were available via license from Elsam while Risø licensed HAWC and later HAWC2 for use for commercial use and Garrad Hassan licensed GH Bladed. Only FAST/ADAMS out of the US remained in the public domain as open source code managed by NREL. The use of the code in design as well as design evaluation became pervasive in the wind energy research and industrial community and from the late 1990s onward, became a required component of the newly established international standards for wind turbine design (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1994).

5.5.2 The development of technical standards
During the initial development of technical standards for wind turbine design, testing and certification, the aeroelastic design codes had still not been developed. At the same time, the industry recognized the need for standards to establish safety of wind turbine systems, as mentioned by Hütter during the 1974 international workshop, as well as ensuring quality of the different wind turbine systems in the market. Unlike the research development of the design codes, the initial collaboration on standards for wind turbines were negligible and independent standards sprang up during the 1980s in a number of different places. During the initial phase of wind turbine development in Denmark, Jacob Bugge, who had been involved in the theoretical aspects of the NIVE design process, was asked to develop a set of wind turbine design guidelines on behalf of the Danish Blacksmiths Association and the Energy Ministry of Denmark (Bugge, 1984). In that work published in 1984, he developed a set of calculations for wind turbine loads from basic theory, a set of guidelines for working with different materials, and finally a set of safety classes for wind turbine designs based on location: restricted lands, rural areas, or near-urban areas (Bugge, 1984). However, this set of guidelines was not a mandatory standard and subsequent attempts at forming standards were not visibly influenced by this work, though Bugge did sit on later
committees for development of formal Danish standards for wind turbine design. During the early years of the wind industry development, no formal standards existed in Denmark. However, after 1979, Denmark required certification of wind turbines in order to have access to a subsidy that was essentially an investment grant of 30% (Petersen, 1980). The system was set up to additionally encourage participation by making the certification process free for Danish manufacturers and providing payment to the companies for the time the turbine was at the test station (Petersen, 1980). Risø national laboratory, which had managed the testing and evaluation of the Gedser and NIBE turbines along with DTU, was qualified to take on this new role as the wind turbine certification center for Denmark. The government established the test center for small windmills in 1978 and gave it the licensing task in 1979 (Lundsager and Jensen, 1982). The first certified turbines were the “Gedser-type” machines, or Riisager-inspired designs, that produced 20 or 55 kW of power or they were considered, “second generation types” which included the NIVE-inspired design types with variations for the different manufacturers (Lundsager and Jensen, 1982). The test station notes that while “design principles exist that ensure mechanical integrity and proper functioning on at least a short-term basis,” longer term performance was still under question which limited the ability of the test station in terms of establishing design requirements (Lundsager and Jensen, 1982). Initially, requirements from the test station allowed for both air brakes as well as braking by yaw, rotating the turbine out of the wind (Petersen, 1980; Pedersen, 1984). This was amended in subsequent documentation that required a “fail-safe” braking system that is disengaged with the system is active and is kept in series with each element of critical safety importance for both the electronics as well as vibrations (Lundsager and Jensen, 1982). In addition, two independent braking systems were required to ensure that over speeding, as experienced with the early Herborg and other turbines, was not a problem (Lundsager and Jensen, 1982). Other early guidelines address manually operated breakers for grid disconnection, relay systems for automatic grid disconnection, a designated “operator”, as well as metering and payment rules for electricity generated by small wind turbines owned independently and connected to the grid (Petersen, 1980). These fundamental requirements regarding braking and grid interconnection were then extended under the 1981 subsidy extension act to include a link from the fundamental requirements to the operational status of stopped, normal operation and emergency shutdown, as well as specific requirements regarding system security, static tower and foundation loads, and load tests as performed by the test center (Lundsager and Jensen, 1982). The Smedemestermoellen, Blacksmith’s turbine – designed by NIVE, was one of the first turbines certified by the new test station – having been installed there in September of 1979 (Pedersen, 1981). The same turbine was also used to publish the first set of “standard measurements on windmills at the test station” that would become the evolving Danish test standard throughout the 1980s (Pedersen, 1981). Early operation of the test station identified some design flaws such as varying stall behavior of the NIVE blades or overloading of the drivetrain by the Riisager windmills (Pedersen, 1984). In 1982, the test station was then extended to accommodate a common set of foundations for the new 55 kW series of turbines which were fast coming to market and later a “universal foundation” capable of handling a 300 kW machine was built in 1984 (Pedersen, 1984). This activity of the test station in measuring loads for wind turbine industry designs led to an expertise and development of theoretical knowledge on wind turbine design in-house that Risø then used in subsequent research and development of the aeroelastic design codes (Petersen and Skrumsager, 1988). Certification of a DANWIN 180 kW at the test station was also used to validate the “Danish
Construction Code” which had been completed in 1986 and was awaiting official approval in 1987 from the National Association of (Petersen and Skrumsager, 1988). Up until the end of the decade, Risø served as the single certifying authority for wind turbine manufacturers in Denmark that allowed them to become, “a centre of knowledge directing itself to the wind turbine industry, public authorities, and to users of the technology” (Petersen and Skrumsager, 1989). However, just as Risø was becoming the critical center of the Danish wind industry, movements to decentralize control of the certification process were underway. Firstly, an initiative began in Denmark in 1988 to establish a new certification system that would include “private certification companies and other relevant institutions” (Petersen and Skrumsager, 1989). Secondly, Risø entered into an agreement with other European test stations to harmonize standard test procedures across Europe (Petersen and Skrumsager, 1989). This was part of a larger movement across Europe at the time to harmonize standards in the lead up to the formation of the European Union. It also allowed Denmark, the world leader in wind turbine production at the time, to influence the standard development process (Butterfield, 2010). The test station recommendations continued throughout 1989 while Risø at the same time became involved with another initiative to establish international standards for wind energy. At this time, the International Electrotechnical Commission (IEC) began to establish its TC 88 working group that would become the international working group for current day wind energy design, testing and certification standards (Petersen, 1990). Risø also worked with the International Energy Agency had been engaged in the establishment of standards for wind energy testing as far back as 1982 with a “Power Performance Testing” standard followed by a “Fatigue Loads” standard in 1984 and a “Structural Safety” standard in 1988 (IEA, 2003). As the international harmonization of standards and the commercialization of certification processes continued, Risø became less and less engaged in the actual certification process. In 1991, Denmark, Germany, the UK and the Netherlands began discussions surrounding harmonization of the complete certification process (including both design and test standards) (Petersen and Skrumsager, 1992). Then in 1992, Risø finished collaborative work on the new Danish standards for “The Technical Basis for Type Approval and Certification of Wind Turbines in Denmark” and the “Danish code for loads and safety (DS472)” which together were to serve as a formal certification standard for Denmark (Petersen and Skrumsager, 1993). Then finally, Risø established a cooperation in 1993 with Det Norske Veritas (DNV) in Denmark manage the entire certification process of design, production and installation of wind turbines (Andersen and Skrumsager, 1994). Throughout the rest of the 1990’s, Risø and DNV provided a holistic certification program for wind turbine manufacturers and developers.

At the same time, the initiatives for international standard development were driven by the presence of competition to Risø’s position as the global center for wind turbine testing and certification. Denmark, in some ways, entered into the international standardization process in order to protect its position as a leading exporter of wind turbines (Madsen, 1997). Other countries had developed or were in the process of developing standards for wind turbine design and testing in the mid to late 1980s. While in some countries, the guidelines were not legalized and served only as guidelines, such as in the United States, others were becoming institutionalized, such as in the Netherlands. As early as 1981, the American Wind Energy Association had developed committees to develop standards for the American wind industry (Design Criteria Recommended Practices for Wind Energy Conversion Systems, 1988). A series of standards were developed beginning with the AWEA Standard for “Wind Energy Conversion
Systems Technology" in 1985, the “Design Criteria Recommended Practices: Wind Energy Conversion Systems” in 1988, and the “Recommended Practice for the Installation of Wind Energy Conversion Systems” in 1989 (Design Criteria Recommended Practices for Wind Energy Conversion Systems, 1988). Other AWEA standards included siting and environmental impacts. When the TC88 working group of the IEC formed in 1988, the US became an early member along with the European participants. The first set of standards focused on design and safety (IEC 61400-1 in 1994), the second set on blade testing and performance (IEC 61400-23 and -12 in 1998) and finally certification requirements and structural load testing (IEC 61400-22 and -13) (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 2005). Other important standards included electrical power quality, small wind turbine systems and acoustic measurements. The development of the first edition of the design standard began in 1989 and would take over four years to complete. Robert Sherwin who had been a participant on the formation of the AWEA design criteria standard chaired the committee (Design Criteria Recommended Practices for Wind Energy Conversion Systems, 1988; International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1994). During the time it would take to complete the standard, ECN of the Netherlands also formally published a standard in 1990 for the “type-certification of wind turbines” which was influenced by the earlier IEA testing standards as well as recommendations from Risø on a wind turbine safety standard (Regulation for the Type-Certification of Wind Turbines: Technical Criteria, 1991). Though Denmark had yet to establish a legally binding design and safety standard for wind turbines, the recommendation for the European standard led by Risø with input from ECN and other European countries would come to influence the first generation of the IEC standard (Jensen, 1988). In Germany, Germanischer Lloyd (GL) had worked with the German government to establish a set of standards in place by 1986 and undergoing revision with a certification standard released by GL in 1989 (Preliminary Regulations for the Certification of Wind Energy Conversion Systems, 1989; Jensen, 1988). European countries of Belgium, the Netherlands, Denmark, Germany and the UK completed a collective report in 1986 that showed there had been little formal standards development for testing, safety and design requirements up to that time (Härvooe, 1986). Thus, the groundwork of the ECN document, the Danish standard, and the AWEA design standard would serve as foundational documents upon which the IEC 61400-1 first edition was developed.

Each of ECN, Risø and AWEA standards sought to identify a number of “conditions” that a wind turbine should be designed to for safety assurance and accommodation of system loads. On the one hand, they identified a series of external conditions that would influence the turbines performance in terms of wind (extreme wind speeds, gusts, shear, turbulence and directional changes), temperature and humidity (including icing, hail and lightening), and other extreme events such as earthquakes or corrosive environments (Design Criteria Recommended Practices for Wind Energy Conversion Systems, 1988; Regulation for the Type-Certification of Wind Turbines: Technical Criteria, 1991; Loads and Safety of Wind Turbine Construction, 1992). At the same time, they also specified a set of operational conditions for the turbine including normal operation, extreme operation, fault conditions, emergency shutdown and service. The standards then go on to acknowledge that the combination of the environmental conditions on the operational conditions in order to create a set of design load cases and these are encoded in the ECN document as a matrix of cases and in particular developed a distinction between cases where the fatigue loads were more relevant versus the ultimate loads. The recommendation
made by Risø originally set forth a list of classes for wind turbine types that distinguished between maximum reference speeds on one axis and terrain conditions on the other axis (Jensen, 1988). This recommendation was dropped from the ECN, AWEA and Danish recommendations (which kept only the terrain condition class), but then reappeared in the first release of the IEC 61400-1 with a set of extreme wind speeds and associated normal wind speeds on one axis and the turbulence intensity on the other axis—though only one value was specified for it at the time (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1994). In addition, a table very similar to the ECN table of wind conditions and design situations appears in the first IEC design and safety standard with the same coding for ultimate and fatigue load cases (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1994). Regarding the use of aeroelastic design codes, the first edition released in 1994 does not require their use and explicitly states that “model testing and prototype tests may also be used as a substitute for calculation to verify the structural design” (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1994). While the AWEA standard had specified, “thorough dynamic analysis of the WECS system elements and their interaction should be made using appropriate analytic techniques, dynamic models, and appropriate full-scale testing,” the original recommendation from Risø did not include mention of the use of dynamic models in design (Design Criteria Recommended Practices for Wind Energy Conversion Systems, 1988; Jensen, 1988). However, by the release of the second edition of the IEC 61400-2 in 1998, the use of aeroelastic design codes to predict design loads was now required though verification of load cases could be acquired through testing (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1998). The second edition also increased the number of classes to accommodate multiple terrain conditions similar to the original Risø recommendation but with specific turbulence intensities representing the complexity of the terrain (International Standard: Wind Turbine Generator Systems – Part 1: Safety Requirements, 1998). Along with the second edition of the design and safety standard for large wind turbines, the harmonization of testing and certification standards was made under the IEC in order to create a full suite of international standards that would apply to every aspect of wind turbine design, testing, and installation.
5.5.3 **Interplay of technology, design codes and standards**

Regarding the history of the wind energy industry and associated technology, the development of the two is neither independent nor unidirectional. As many historians and theorists of technology and society have noted, typically there are sources of influence moving both directions from the society to the technology and the technology to the society (Winner 1980, Bijker 1987). A step further, and technology and society are no longer isolated worlds where interactions occur across fixed boundaries. Instead, various material and human agents create actor-networks that may be maintained over considerable lengths of time and morph, grow, decline, split, and interact with each other and other actor-networks (Latour, 2005). This flexibility of analytical perspective is particularly relevant when breaking down certain entrenched narratives regarding the wind industry. Dominant narratives where a social force influenced an innovation process or an innovation process was an intrinsic foregone conclusion might both overlook the complexity of the actual history of interest. In this case, a detailed look at the development of Danish wind energy technology in the 1980s coupled with the history of research codes and standards associated with that technology allow us to tease apart some of the earlier conclusions about the innovation process to expose various layers of detail and complexity. In this case, various actor-networks arose during the development of the wind energy technology from the
1970s to the current day. We only treat a few here. Nonetheless, these few actor-networks can provide an interesting basis for analysis. Firstly, there is the actor-network clustered around the “Danish concept”. Catalyzed by the events of the oil crisis and the fuel shortages in Denmark, this group began to form around the notion of renewable or domestic energy for Denmark (including both wind and biogas). The group began to grow with association of NIVE as its nexus and links tied to various domestic manufacturers and local masons. The participation of the group members in other networks including the Tvind wind turbine group and the Organization for Windmill Owners (OVE) allowed them to expand their own influence over the innovation process. The interaction with Erik Grove-Nielsen and Oekaer led to the establishment of a loosely tied but related network centered on the all-important blade component of the “Danish concept” wind turbine. This interaction was mutually reinforcing in both building the Oekaer-centric wind turbine industry as well as the NIVE influence on the design process – including its formal role as the Blacksmith’s wind turbine designer. This interaction then led to the use of the NIVE design as the basis for standard testing at the newly established Risø test laboratory. The use of the NIVE design in the very first set of formal standards for wind energy, as well as the related Bonus, Vestas and other wind turbines, further established its centrality in the Danish wind turbine industry. At the same time, however, just as NIVE was serving as a center of design for the growing wind turbine industry, the establishment of Risø as a test center was creating a new source of accessible information on the design of wind energy technology. In addition, innovation at a number of other companies complemented the proliferation of the Oekaer blades. Thus, though NIVE continued to serve as a center for design, the development of the theory and science of wind energy began to take on increased importance with Risø as a new nexus for a related and intersecting actor-network. The influence then of Risø was to continue to grow throughout the 1980s with the development of standard test procedures as well as the promotion of the science and engineering behind wind energy design. The development of the aeroelastic codes through the 1980s and their subsequent proliferation of use in the design standards of the 1990s highlight the shift away from the early NIVE design basis. Just as Risø arguably eclipsed NIVE’s centrality in the mid-1980s, Risø eventually lost some of its prominence in the push towards international harmonization and liberalization of the certification process in the early 1990s. Risø’s role in the development of the international wind turbine standards for design and testing was essential to the industry, but the number of players influencing the design and testing process drastically increased from the Danish perspective. Whereas Risø had been the central body with respect to testing, certification and even design support in Denmark during the 1980s (which had then become the largest exporter of wind turbines in the world), a number of organizations served this role going forward with notable influence from Germany (Germanischer Lloyd) as well as the UK (Garrad Hassan) and even the United States (AWEA).

At the same time, the material agents within these actor-networks are frames of reference for analysis of the developing actor-networks. Beginning with the Gedser turbine of the 1950s, the “Danish concept” for wind energy technology began to take shape. The well-documented success of this turbine

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63 A full treatment would look at a myriad of other networks including a detailed account of different federal research programs, domestic entrepreneurial efforts, international agencies and politics, various certification companies, other Danish wind concepts, user groups and other stakeholders.
was a prime motivator for the designs of the late 1970s when information that is more detailed was not available. Aspects of the Gedser turbine surfaced in the Tvind turbine, the NIVE concept, as well as other related concepts such as the Riisager wind turbine that also influenced much of the early Danish wind industry turbine designs. The continued success of the concept coupled with the influence of the Hütter blade allowed it to drive the industry design groups into the mid-1980s California wind rush and afterward. However, subsequent development, in terms of increased size, may have been limited were it not for the introduction of the aeroelastic design codes. Thus, the limitations on the technology in the 1980s, the reverse salient (Hughes, 1983) of the system structural dynamics, willed the design codes into development in order to continue development. The design codes, however, existed prior to the Danish concept in the larger actor-network associated with international research activities on the aeroelastic behavior of wind turbines. Several developments were under way in different sub-groups to develop the codes so that they were increasingly influential in subsequent design of wind turbines. Thus, a feedback occurred where the development of the design codes enabled further analysis and experimentation with the wind turbine technology design and development. The continued dominance of the Danish concept in the current wind industry begs the question of the relative independence of the de facto standard and the design tools. That is to question whether the processes were mutually reinforcing to the point that the code development further enabled dominance of the “Danish concept”. Left over from experimentation with alternative configurations in the late 1970s and early 1980s, the design tools can accommodate a broad range of designs including various rotor configurations, drivetrains, towers and foundations for horizontal-axis configurations. In addition, the voluntary standards for wind energy are careful not to specify particular system requirements (other than general safety requirements) but instead define the load cases based on known environmental and operational criteria. In addition, there has almost been a merging of the codes with the standards where code packages tailor to IEC evaluation and the IEC process uses design code analysis in its certification process. However, the design tools, especially when assessed for offshore wind energy, are not well developed enough to handle the myriad of environmental conditions and technical configurations possible for the relatively new design environment. The introduction of hydrodynamic loads in water of various depths, new foundations and sub-sea structures, introductions of alternative turbine configurations to the “Danish concept” have all been proposed for development in the offshore wind energy space. The standards developed for offshore wind, though, tend to mirror the current onshore design standards. Thus, when looking at the potential for the innovation of offshore wind, the processes of onshore technology, design code and theory, and technical standards development may form an entrenched actor-network, along with the other actor-networks associated with research organizations, existing wind turbine manufacturers, and other wind energy stakeholders.

5.6 References


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5.6.1 Technical Standards


Section 2: A System Dynamics model of Wind Energy Innovation and Diffusion

This section of the thesis takes a quantitative look at the dynamics of technology innovation and diffusion using wind energy as the case study of interest. In particular, as seen in the historical section, the development of the technology has been a global process involving actors from several countries—notably Denmark, the United States and Germany. Here we look at the important feedback between the market development for wind energy in the early 1980's to the present day and the technology dynamics of diffusion and innovation. In addition to simulating the historical development of the technology, the analysis includes scenario analyses of past and future deployment and development of wind energy.
6 Dynamics of Innovation and Diffusion in Large-Scale Complex Technical Systems: the Case of Wind Energy

“The World Market [for new wind plant capacity] is 55 GW and the US market is X.”

CEO of a large wind turbine OEM’s at a recent US Windpower conference

The quote above illustrates the instability in the US market over the years. Inconsistent policy, such as the on-again, off-again production-tax credit scheme in the US, is as a key source for boom and bust cycles in the country’s wind energy industry (U.S. Department of Energy, 2015). Over the last several decades, various incentive systems governments have implemented and removed in a number of nations and states across the globe. The stops and starts of policy supports in key markets (such as the US in the 1980s) have brought about rapid growth and subsequent collapse of the local industry only to be restarted again by new policy incentives in later years (van Est, 1999). The quote above also highlights that regardless of instability in one wind energy market, in this case the US, the industry expects relatively stable global demand. Policies across several nations since the mid-1980s have led to a relatively stable and growing global market for wind energy that has enabled significant innovation in wind energy technology to the present day. This chapter examines the interplay of technology innovation and diffusion dynamics where markets for the technology are local but innovation is global. The author develops a system dynamics model through the combined use of theory and data calibration for wind energy innovation (global) and diffusion (local). The model captures the effects of inconsistent policy for different nations and states while demonstrating that the global aggregation of market demand has enabled continuous technical innovation, which then feeds back to condition local conditions. The result of this turbulent process has enabled wind energy to become a significant component of the global electricity generation portfolio. Finally, the chapter demonstrates through model simulations how short-term bias could have and still may harm the long-term development of the industry by perpetuating boom and bust cycles and hindering further wind energy innovation.

6.1 Introduction

In the last several chapters, we saw several époques of wind energy innovation and development. More than idle curiosity, concerns about resource scarcity and interest in alternatives to coal led to stops and starts of wind energy development for electricity generation. From the mid-1800’s, prominent scientists began to highlight the exhaustibility and non-renewable nature of coal that led Lord Kelvin of England to promote alternatives in the 1880’s. Coincidentally, the first serious approaches to wind energy for electricity generation arise in this period from Charles Buell and Charles Brush in the US and Poul la Cour in Denmark. Coal shortages in World War I lead directly to deployment of La Cour-style windmills by the “Boys of Askov” across Denmark and northern Germany. Lack of coal-based large-scale electricity generation in the rural USA and the leveraging of new aviation science and technology then led to the successful wind charger period. A second round of coal shortages during World War II led to further development of wind energy in Denmark and Germany with the notable development in particular of the FLS Aeromotors and later the Johannes Juul machines. By the time of the 1970’s oil crisis, the world had essentially seen three small boom and bust periods or époques of wind energy development – two of which were a direct result of a fossil fuel shortage. However, by the time that the 1973 oil crisis occurred, large-scale dependency on fossil fuels for electricity generation existed across the world. For
Denmark and the US, the key players for large-scale wind energy deployment in the early 1980s, where there was past concern for coal shortages, the oil-based electricity generation that had replaced coal in each system was now problematic.

Figure 6-1: Electricity Generation by energy source for Denmark and the US from 1971 to 2013 (International Energy Agency, 2016).
As noted above, both the US and Denmark reduced the use of oil for electricity generation from the late 1970s onward because of the oil crisis. Following coal shortages in World War II, Denmark in particular diversified away from coal to the point where about 80% of its electricity generation used oil as a fuel source.

The oil crisis thus directly created a fourth époque of innovation and diffusion of the wind energy technology (the modern era). However, a stable and sustainable wind industry did not blossom immediately. Resistance from established vertically integrated utilities as well as high costs of wind energy was both impediments to growth of the sector. Governments enacted wide variety of national policies and laws to invoke change in the electric utility sectors across Europe and the US in order to allow for the development of wind energy and other non-oil electricity generation technologies. Certain countries, such as the US, sought to create a more competitive electricity market for energy. The Public Utility Regulatory Policies Act of 1978 was the first in a wave of federal legislation seeking to deregulate the electricity market and to incentivize non-oil based forms of electricity production (Gipe, 1995). On the other hand, many European countries with more centralized governmental control over their electric sectors introduced mandates for change. As discussed, Denmark initially promoted nuclear power but found strong resistance from the public. This led them to negotiate a path for reform directly with their utilities and this resulted in investment subsidies and brokered power purchase deals for wind energy (van Est, 1999).

Despite these bold historical initiatives, changing policy landscapes for wind energy have been in general been unstable. In the mid-1980’s, the oil-crisis subsided and the Reagan administration removed the policy support for wind energy that had fueled the “wind rush” (Gipe, 1995). Industry as a result experienced cases of widespread bankruptcy both in the US and Europe. Few companies survived during this period and those that did, predominantly in Denmark, relied on substantial government support for continued operation (van Est, 1999). In the subsequent decade, due once again to renewed policy support for wind energy first in Europe, development rebounded. Eventually in 2000 and after, the US and other global markets adopted policy support for wind energy once again spurring a decade and a half of exponential growth. Below is a chart of global wind installations from 1981 to 2000.
The next graphic shows that despite the smooth growth profile for the industry in terms of installed capacity, the trend in individual countries has been far less consistent. The dramatic rise and crash of the US market in the 1980's was followed by a period in which favorable German then Danish and Spanish subsidies drove the market in the 1990's till the US again adopted favorable (though inconsistent) policy to promote wind after 2000. In addition, after 2000, non-European countries began looking to wind energy for electricity generation. Led by India and then China, the rest of the world became a more prominent adopter of the technology to the point where Europe and the US constitute a little over a third of the global market for wind energy. Thus, the remarks of the CEO reflect the current and historic wind energy climate – sustained growth globally, volatile markets locally.
Figure 6-III: Percent of new global wind energy installed capacity by country (the Wind Power Net 2015, Eco Indicators 2009, and GWEC, 2014)

Figure 6-IV: Capacity Installations for Select Countries by Year.
Some would argue that the industry today with a relatively consistently growing global demand has finally become self-sustaining. The current action of the US government to phase out the main federal policy support for wind, the production tax credit (U.S. Energy Information Administration, 2016), is indicative of this perspective that wind energy is moving towards parity with other energy technologies and should no longer need policy support to remain competitive. At the same time, the wind energy sector, in all countries where it is currently active, relies upon considerable government support. A metric often used to characterize the relative competitiveness of energy technologies is the levelized cost of energy (LCOE), which includes all capital and operating costs normalized to the current year divided by the expected annual energy production. As seen in the graphic, wind energy LCOE for US projects has decreased continuously since the early 1980’s with the exception of the period around year 2010 when supply constraints and high commodity prices led to increasing wind turbine costs and pricing (U.S. Department of Energy, 2015). Current LCOE estimates for a US site with good wind resource are $0.045/kWh and lower versus upwards of $0.50/kWh in the early 1980’s.
Across electricity generation technology, wind energy does indeed compare well on an unsubsidized basis in the US. The Energy Information Administration estimates that for plants installed in the next several years, unsubsidized LCOE for a typical wind plant will be about $0.059/kWh which is higher than the Wind Vision estimate by about $0.015/kWh (U.S. Energy Information Administration, 2016). However, analyses estimated that advanced combined-cycle natural gas plants have an LCOE for the same period of $0.056/kWh – only $0.003/kWh lower than wind energy. Thus, plans to remove subsidies in the US for wind energy by the early 2020’s could still be compatible with continuing growth for wind in that country. On the other hand, discussion of the production tax credit “cliff” is common among industry representatives with many forecasting a rush of installations in the next few years before the federal government removes policy support and an abrupt cessation of development thereafter.

Analysts have made a wide variety of arguments regarding the influence of policy support for wind energy on technology development, adoption trends and firm behavior. This paper presents a system dynamics model that reflects the historic performance of different countries’ wind energy markets. In so doing, we investigate the impact of policy on the respective development of different national markets for wind energy along with the development impacts on the industrial base and the technology innovation. Once we calibrated the model to a set of historic cases, the paper then tests a set of hypothetical policy scenarios on wind energy innovation and diffusion. The results provide insight into the dynamic relationships between policy, technology adoption, and industry development in order to guide national policy-making strategy for future development of the wind energy sector.

6.2 Modeling Wind Energy Diffusion
Before formulating the model, a theoretical understanding of technology diffusion is critical. As discussed, there are two basic types of technology diffusion models. The first is a “threshold model”
that focuses on economic factors as the main determinants for the adoption of a product or technology (Griliches, 1957). The second are “social models” of diffusion relied on social contagion as the main factor influencing adoption (Bass, 1969; Rogers, 1995; Ryan and Gross, 1943; Mahajan and Peterson, 1985; Mahajan, 1990). The basic “Bass model” of diffusion has become especially prominent and well known in marketing and has been used substantially in prior System Dynamics studies (Homer, 1987; Sterman, 2000; Milling and Maier, 2001). In contrast to the aggregated form of the system dynamic/Bass model of diffusion, “network models” of diffusion have also been developed which attempt to capture how complexity within the social networks affect product and technology adoption. Aspects related to network structure, the heterogeneity of network agents and relationships, and sequence or timing have all been shown to influence the adoption process (Valente, 1995). Finally, a last main category of diffusion models brings together the economic aspects of threshold models and the social aspects of the Bass diffusion models. These “mixed-influence models” are particularly well-suited for analysis using system dynamics since the combination of economic and social effects can be well-modeled using additional feedback relationships affecting adoption behavior (Sterman, 2000; Milling and Maier, 2001; Granovetter, 1985; Weil, 1998).

For wind energy adoption, a mixed-influence model is useful to describe both the economic and social aspects affecting diffusion. In fact, a few such models have previously been developed specifically to look at wind energy adoption (Pruyt, 2004; Dyner, 2006). The first model by Pruyt was designed in order to critique a spreadsheet model of diffusion that was created outside of the system dynamics framework and thus ignored key feedback relationships in the system. In particular, he critiques the model for ignoring the development of wind energy sector capacity which is believed to be a critical oversight of the original model. Secondly, he relaxes various assumptions of the original model regarding learning processes for the technology that affect turbine performance and cost overtime. He compares the results of the new model behavior with those projected by the original model in terms of industry performance, installed capacity of WECS and the consequences for greenhouse gas emissions. The model does a good job of identifying the weaknesses associated with lack of feedbacks in the original model and adds critical endogenous relationships. However, the model was designed specifically to be aligned with the GWEC Windforce12 model and thus does not get into the comparative policy evaluation as is proposed in this study. In addition, there are no aspects related to wind resource availability (carrying capacity) and its effects on profitability nor the social dynamics previously discussed including utility and/or public resistance or support.

The second model by Dyner (2006) is a diffusion model for wind energy but takes into account a much more brought set of relationships related to the overall electricity market at the expense of detailed modeling for the wind industry in particular. For instance, the Dyner model does not address aspects related to job creation or industry capacity which are key features of the GWEC Windforce 12 / Pruyt 2004 model. Advantages of the Dyner model are the added endogenous relationships regarding expansion of wind and the overall electricity market supply, demand and price as well as a more detailed financial model of the wind industry including income, cash flow, debt and financial indicators. Thus, the decision to invest is more nuanced in terms of its dependence on the endogenous price of electricity and the influence of financial factors on expected profitability. The importance of the
combination of the industry capacity aspects of the Pruyt 2004 model, the endogenous electricity aspects of the Dyner 2006 model, and the learning curve effects in both models will be discussed in more detail in the model formulation section of this paper.

It is worth noting that there is another model paradigm that has been used to explore the adoption of wind energy: capacity expansion. Capacity expansion models, both using system dynamics or more traditional economic optimization models, reflect the overall development of an entire regional electricity system (Vogstad, 2002). Such models can either focus exclusively on generation or also incorporate aspects of transmission as well. Similarly Dyner 2006, these models incorporate an endogenous relationship between market supply, demand and price of different generation sources. Various applications of capacity expansion models using system dynamics have looked at wind energy development in addition to suite of different electricity generation options (Ozdemeir, 2002; Ford, 1996, 1999; Pruyt, 2004; Vogstad, 2002; Karstad, 2009). Indeed, the diffusion model developed in this paper could be adapted for incorporation into a capacity expansion model. However, two reasons led to the decision to implement a diffusion model for this specific research project. The first reason was desire to isolate wind energy adoption as the unit of analysis for this work and detailed modeling such a focus required. Secondly, the desire to do broad comparison of different national cases in terms of both calibrating and performing model analysis meant that a diffusion model was more appropriate for tractability. Thus, the model discussed in the subsequent sections falls into the category of an aggregate mixed-influence diffusion model for technology adoption.

6.2.1 Integrating Innovation and Diffusion Dynamics
While learning curves are simplistic representations of technology innovation, they do embody the important phenomena that there is interplay between technology innovation and diffusion. While a “market push” model of innovation suggests that innovation is possible in isolation, “demand pull”, “user innovation” and most other theories of the subject rely on adoption of the technology in order to push forward its development. There is an explicit link between the innovation of a technology and its adoption. As a market adopts a technology, there is learning at many levels including the design, manufacturing, deployment, use and operation. This learning leads to innovation that in turn improves the desirability of the technology for one or potentially several metrics such as cost, improved performance, increased functionality, etc. The desirability influences additional adoption and a positive feedback process is established.
Figure 6-VII: Illustration of the basic dynamics of innovation and diffusion.

While seemingly obvious, this basic feedback is critical in particular to technologies of large-scale complex socio-technical systems. Terminology around complex systems can mean many things. Here, we tie the definition to those technologies that, due to their complexity, require a systems engineering approach to their development. There are several definitions of systems engineering, but two prominent ones come from the National Aeronautics and Space Administration (NASA), a leading organization in the development and use of systems engineering techniques since its inception, and the International Council on Systems Engineering (INCOSE). The NASA Systems Engineering Handbook defines core ideas of systems engineering (bold lettering added):

"Systems engineering is the art and science of developing an operable system capable of meeting requirements within often opposed constraints. Systems engineering is a holistic, integrative discipline, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers, and many more disciplines are evaluated and balanced, one against another, to produce a coherent whole that is not dominated by the perspective of a single discipline... Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A 'system' is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce system-level results." (Shishko and Aster, 1995, p. 3)

From this definition, we isolate critical components of a systems engineering approach (Dykes 2011). Systems engineering approaches generally include the following four characteristics: they are (1) holistic, (2) multidisciplinary, (3) integrated and value-driven across stakeholders, and (4) long-term and life cycle oriented. Thus, systems engineering is appropriate for technologies that embody these attributes as well and tend to embody three common characteristics of the actual large-scale complex technical systems themselves are complexity, uncertainty, and heterogeneity. The figure below depicts four systems engineering properties and large-scale complex socio-technical system properties.
Complex systems have many interlinked components and subsystems—they may even involve systems of systems—where the "whole is more than the sum of the parts" and significant physical coupling is present throughout. Secondly, these systems tend to have a large degree of heterogeneity with respect to design conditions. Finally, uncertainty means that these systems face significant sources of uncertainty throughout their design, development and deployment. In order to innovate, it is necessary to develop more understanding of the complexity, heterogeneity and uncertainty that these systems face. Through diffusion, learning takes place around the system complexity in terms of a better understanding of the coupling, reducing the uncertainty and experience with various heterogeneous external conditions. This drives further innovation and the positive feedback loop of innovation and diffusion dynamics. Wind energy is a large-scale complex socio-technical system that embodies all of these attributes (Dykes 2011). Thus, modeling the diffusion of wind energy needs to account for not just the market dynamics, but the dynamics of innovation as well.
"The key characteristics of large-scale, complex technical systems align with key attributes of wind energy systems, including:

- **Complexity:** Wind energy involves nearly every field of engineering and many of the natural and even social sciences. Within engineering, aerospace, mechanical, controls, electrical, materials, and civil engineering are all important to the design and development of wind turbines and plants. The natural sciences, mathematics, physics, chemistry, earth and atmospheric sciences, and even environmental sciences are important to understanding the science of wind energy systems. Within the social sciences, economics, policy, law, and sociology are important to understanding the larger interactions of wind energy technology with the markets and society. The design of a wind turbine and plant interlinks almost all of these distinct disciplines together for a holistic and multidisciplinary design that intrinsically integrates the interests of a wide variety of stakeholders for operation over long time periods.

- **Uncertainty:** The science of wind and wind energy technology is still evolving. Epistemic (or systematic) uncertainty is reflected by the incomplete understanding of both the physical processes and the interaction of the physics with the technology. This leads to an uncertain design environment. There are many sources of epistemic uncertainty affecting wind energy systems from the behavior of the turbulent winds to political and economic developments that can drastically affect the financial viability of wind energy projects. There are also aleatoric (or stochastic) sources of uncertainty such as which particular turbulence events will strike an individual rotor over its lifetime. This implies that some sort of treatment of uncertainty be built into the wind energy design process which may be accomplished either through proactive attempts to quantify the uncertainty within the design process and through the use of design safety margins.

- **Heterogeneity:** Wind turbines and plants must be designed for and operated in a wide array of environments—both from a physical standpoint and from an economic, social and political standpoint. Different wind regimes and terrains will affect wind turbine and plant performance while various factors related to the politics and social aspects of wind energy projects may affect their acceptance and deployment. DOE has separated those factors that limit wind energy development into those that affect the cost of energy and other market barriers that include social, environmental and political factors. Wind energy system design from the turbine to the overall plant must balance the issues involved with particular sites and the overall development of the industry, including the economic benefits of standardized technology and large scale production." (Dykes 2011)
6.3 A System Dynamics Model of Wind Energy Innovation and Diffusion: Model Formulation

Even in 2016, the complex, uncertain and heterogeneous nature of wind energy technology means that innovation depends on deployment. Diffusion drives technical learning that leads to improved system performance and reduced costs which leads to further adoption of the technology. As discussed, the diffusion of wind energy over the last several decades has taken place in one market continuously but instead has been supported by the aggregation of demand across several markets which themselves have each at times been volatile. This system dynamics model for wind deployment and technological innovation depends addresses these interactive global and local dynamics.

6.3.1 Theoretical Derivation – Causal Loop Diagram and Key Assumptions

The basic theoretical framework used in this study is a threshold model of diffusion with additional dynamics for industry development and endogenous technological innovation or learning. In order to reduce the scope of the study and keep the model tractable, we allow a few important simplifying assumptions:

1. Technology evolution / innovation are global phenomena independent of any individual state activity. Wind turbine OEMs have traditionally operated in many national markets with the top global firms competing for market share in every active market. Increasingly, OEM’s tailor their product platforms for different market segments with different needs; however, the technology deployed globally is similar. The main caveat to this is the recent rise of Chinese OEM’s. These OEM’s were initially only active in Chinese and east Asian markets, but they too are now competing in global markets and have similar product offerings to those of other global OEM’s. This also neglects the offshore market where wind turbine innovation has diverged from the land-based markets with turbine sizes much larger than their land-based counterparts do. Future work will need to explore heterogeneity in turbine product lines and their evolution and dynamics over time.

2. The overall wind energy installed capacity and generation is low such that cost impacts to traditional electric grid operation are negligible relative to overall electricity costs. This is important since many studies looking at high levels of renewables on the grid do estimate that there may be additional cost impacts to the overall system in terms of system operation costs and the need for additional new transmission and/or storage (U.S. Department of Energy, 2015). Here, we assume we haven’t reached a critical level of renewables generation to affect any of these costs, or equally, we assume that those issues are resolved through innovation so that the grid itself changes and is able to accommodate increasing levels of wind energy without significant cost increases to operation, transmission or storage. In addition, this means that relative to natural growth of electricity generation and additional capacity, the wind contribution is small and thus unconstrained by “queuing” effects of having to enter into a capacity market pipeline (interview with a wind energy developer 2016). Finally, as levels of wind energy in an electric grid system grow, there can even be concerns over system reliability and stability. While these factor into costs, they are important in and of themselves. In future work, it will be important to address the additional dynamics of grid integration since both
effects of saturation of the forward capacity markets and potentially increased electricity costs are relevant to the current and future wind industry. Several countries do indeed already have levels of wind energy generation above 10% of overall annual generation.

3. Several local factors can limit wind energy development. NIMBY-ism (Not-in-my-backyard-ism) has remained relatively consistent over time such that the percentage of projects fail due to NIMBY issues has not changed over time and we can exclude the dynamics associated with NIMBYism. Similar constraints that limit wind project feasibility are environmental issues, affecting local habitats, species, migration corridors, and national security issues, such as radar interference near military installations. For the purposes of the study, we assume that land that would be affected by NIMBY-ism, environmental or security concerns is already removed from the potential land area available for wind development. Future work will consider dynamics associated with these local factors and NIMBY-ism in particular since in actuality an important feedback between increasing levels of wind energy development and local resistance.

While these assumptions break down for certain cases and under certain conditions, they are generally reasonable for the historical development of the industry with relatively low penetrations of wind energy in the electric grid system. Having defined the scope of the model, we next develop the general dynamics of interest. The core model structure and feedback loops are shown in the below figure.

![Figure 6-IX: Core Causal Loop Diagram for Wind Diffusion](image)
The core of the model is a threshold model where markets adopt wind based on expected profits and low costs. In other words, adoption of wind energy happens when its LCOE is lower than other forms of energy. The initial adoption of the technology, enabled in this case through policy support, kicks off the technology innovation and learning curve dynamics that further reduce the LCOE and create a positive feedback to adoption. The industry capacity limits the speed of adoption. As adoption grows, forecasts for future sales of the technology grow and so does the industry capacity along the value chain. However, the growth of the market in terms of industry build-up and deployment creates a balancing loop where the increased adoption decreases the available good land for projects (i.e. those sites with good wind resource and other criteria to help keep LCOE low) and eventually the market becomes saturated. These are the core dynamics of the model and, as mentioned, the industry and technology dynamics are global while the market dynamics are local: the model disaggregates market dynamics across markets in different countries and states.

As previously mentioned, two key additional sub-models are not included in the core model above. The figure below shows the additional feedbacks.
These include local resistance primarily from NIMBY-ism and grid integration (including cost issues and system stability). These dynamics are important as the market grows. The primary social or Bass dynamics of the model include the population familiarity and population resistance (NIMBY-ism). Before any wind farms exist, there is an intrinsic resistance to the unknown but as industry builds more and more successfully operating wind farms, positive word of mouth concerning the technology's viability spreads. However, there is a secondary social loop around the encroachment of wind farms on nearby population dense areas and NIMBY resistance/negative word of mouth develops. In addition, this larger system diagram includes endogenous relationships between wind energy deployment and electricity price. The more wind capacity on the system, the higher the electricity price due to the system costs associated with the intermittent resource. There is also a build-up of resistance by utilities or system operators who have to manage the system integration issues and from the public if the installed capacity is high enough to affect overall system performance.

While these additional feedback loops are important, especially for high levels of wind in the system, they are much more uncertain and beyond the scope of the current model. In addition to the exclusion of these dynamics associated with local resistance and grid integration, we are also excluding the offshore market essentially adds a duplicate of the original model since the technology, resource and even policy supports can be fundamentally different from for land-based systems. There are even interactive dynamics between local resistance and the move to offshore wind in population dense regions. Future work will add this co-flow structure to the model since offshore wind development is already important in many European countries.

Even in the simplified form, the core model already involves a number of complexities including various nonlinear relationships and feedback delays. The next section describes the formal model and important functional relationships.

6.3.2 Model Formulation
The core model consists of three sub-models: (1) the wind resource, associated land and LCOE for a given project based on the wind resource, (2) technology learning include scaling of the technology, improved performance and reduced cost, and (3) the wind project development pipeline (with co-flows for turbines, capacity and generation) and the industry value chain (turbine suppliers and project developers). We describe each of these model formulations and then in the next section, we demonstrate how we select the cases for analysis including the disaggregation into regional markets that feed the global dynamics of technology development. The model is built in Vensim® DSS for Windows Version 6.4c (x32) from Ventana Systems, Inc. Vensim is a system dynamics modeling software tool that allows a user to visually build up a system dynamics simulation by adding variables to a graphical template and then interlinking them and defining functional relationships.
6.3.2.1 Wind Resource, Cost of Energy and Policy

One of the great sources of heterogeneity and uncertainty for wind energy is the local wind resource. In this model, we aggregate the resource in a certain region into a resource “supply curve” for each state of interest. The model assumes that industry builds projects in the sites with the highest wind resources first and then incrementally less attractive sites and so on. The equation for the marginal wind resource in a given state is:

\[
\text{Marginal install wind speed}[\text{States}] = \text{max wind speed}[\text{States}] + \text{linear term for wind speed by land use}[\text{States}] \times \text{percent land under development}[\text{States}] + \text{quadratic term for wind speed by land use}[\text{States}] \times \text{percent land under development}[\text{States}]^2
\]

Where \text{States} is the index for the current state for analysis (which may be a country or a province). The wind speed for the next best-undeveloped site is determined based on a quadratic supply curve fit to the states’ wind resource data. The percent land under development is land under development or already developed over total available land in a region:\textsuperscript{64}

\[
\text{percent land under development}[\text{States}] = \text{ZIDZ}\left(\frac{\text{total land under development}[\text{States}]}{\text{total potential land}[\text{States}]\text{}}\right)
\]

Other wind deployment studies, such as the US DOE Wind Vision, have used the notion of a supply curve (U.S. Department of Energy, 2015).

\textsuperscript{64} ZIDZ is a function that stands for zero if divide by zero. It is an “if-then” statement which takes the value of the function in parentheses unless the denominator of the function is zero. Rather than use a backslash, the numerator is the first value in the expression followed by a comma and then the denominator.
Figure 6-XI: LCOE supply curve for the entire United States from the wind vision study that takes into account the technology costs, financing and energy production for different sites across the United States (U.S. Department of Energy, 2015). Note that it is essentially a superposition of two supply curves: one for offshore and one for land-based wind energy. This study, as previously mentioned, currently only looks at land-based systems.

In that case, the study translated the supply curves to an LCOE supply curve for each region of interest based on one or more wind turbine technology configurations, the wind resource distribution in the region for all areas that are not excluded. The supply curve excludes many already developed areas, if they are sensitive regions for habitats, migration and other environmental concerns, if they are sensitive due to national security, and if they are too near population dense areas (U.S. Department of Energy, 2015).

LCOE is a project specific value that takes into account all of the upfront capital expenditures and financing costs, financing rates, the lifetime operational expenditures, and the lifetime energy production. To simplify analysis, for instance when assessing a technical innovation, LCOE is a single equation (Fingersh, Hand and Laxon, 2006):

$$LCOE = \frac{F \times CAPEX + OPEX \times (1 - T)}{AEP}$$

Where $F$ is a fixed charge rate that reduces from the complexity of a detailed financial model, $CAPEX$ is the total capital expenditures of the project including insurance, warranties and financing costs, $OPEX$ is the annual operational expenditures for the project, which are reduced by a tax reduction equal to $T$ the tax rate and $AEP$ is the net annual energy production after all losses are taken into account.

For this model, transforming the wind resource, technology costs and financing into LCOE and it is complicated to create LCOE supply curves due to fact that many of the inputs to the LCOE equation change as the dynamics unfold. First, the technology and associated costs change as learning takes
place and this causes the expected energy production for a given resource group to vary as well. Secondly, the policies that a state undertakes to promote adoption of wind technology will change over time and affect the LCOE supply curve. So, instead of an LCOE supply curve, the model takes the technology costs, financing and wind resource and turns them into a breakeven energy production level which is compared to the marginal available expected energy production for the next highest wind resource site in a state that is still undeveloped. Next, we describe this transformation.

First, the expected annual energy for the marginal site is calculated. The model takes the wind resource data for the different states from a global GIS database of wind speed resource estimates at 50 m above ground elevation from the National Aeronautics and Space Administration (NASA) (OpenEI 2016). Since the data is at one hub height, which changes over time, a scaling of the wind speed to the current hub height is necessary. "Wind shear" is the phenomenon that controls this wind speed scaling with height above ground. Various factors can affect wind shear at a given location including where the site is in the world and characteristics of the local atmosphere as well as topography, the surrounding environment, etc. Due to lack of site-specific information at a global level, the wind shear exponent is assumed constant across all sites and is 1/7 or 0.143 (a commonly used value for the shear exponent over flat terrain) (AWS Scientific, 1997). The model then scales wind speed as:

\[
\text{hub height wind speed}[\text{States}] = \frac{\text{marginal install wind speed}[\text{States}]}{\text{hub height/ reference hub height}}^{\text{wind shear exponent}}
\]

This turns the hub height wind speed into a distribution of wind speeds that represent an average year for the location. For real wind project analysis, developers often fit site data to either a Weibull or a Rayleigh distribution. In this case, we use the simpler Rayleigh distribution. The input to the distribution is the mean hub height wind speed of the site as calculated above. For each wind speed, the model calculates a probability of occurrence based on the Rayleigh distribution. The probability density function of the Rayleigh distribution is:

\[
P(x; \sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}
\]

Where \(x\) is the input variable, and \(\sigma \sqrt{\frac{\pi}{2}}\) is the mean of the distribution and \(P\) is the probability of the occurrence of \(x\). The mean in this case is then the calculated hub height wind speed for the site multiplied by \(\sqrt{\frac{\pi}{2}}\) and the probability density function for wind speed becomes:

\[
\text{Rayleigh wind speed probability}[\text{States}, \text{windspeed}] = ZIDZ\left(\frac{\pi \cdot \text{wind speed}[\text{windspeed}]}{2 \cdot \text{hub height wind speed}[\text{States}]^2}\right) e^{-ZIDZ\left(\frac{\pi \cdot \text{wind speed}[\text{windspeed}]^2}{2 \cdot \text{hub height wind speed}[\text{States}]^2}\right)}
\]

Where \(\text{windspeed}\) is the index of wind speeds from 3 m/s to 25 m/s. Most wind turbines will cut-in around 3 m/s when they overcome the force needed to rotate the blades and produce energy. For
safety reasons, most turbines will cut out at 25 m/s. The model then convolves the Rayleigh distribution with the power curve for the turbine to create an estimate of the annual energy at each wind speed, and the model then sums these to get the total annual energy before loss reductions:

Cumulative Energy by Wind Speed [States, windspeed]

\[= \text{Power at wind speed [States, windspeed]} \times \text{Rayleigh wind speed probability [States, windspeed]} \times \text{hours per year}\]

And:

Potential annual energy[States]

\[= \text{SUM(Cumulative Energy by Wind Speed [States, windspeed!])}\]

The wind turbine power curve (the power at each wind speed that the turbine is expected to produce) is determined by the machine size and design. The basic equation of power produced by a wind turbine at a given wind speed is:

Power at wind speed [States, windspeed]

\[= 0.5 \times \text{air density} \times \text{Rotor Swept Area} \times (\text{wind speed [windspeed]}^3) \times \text{power coefficient} \times \text{Watts per kW}\]

And:

Rotor Swept Area \[= \pi\left(\frac{\text{Simulated marginal rotor diameter}}{2}\right)^2\]

This power curve equation is based on simple flow physics where power is proportional to the cubic of the wind speed, the rotor area, the air density at the site (assumed to be 1.225 kg / m^3 at sea level at 15 degrees Celsius (AWS Scientific, 1997)) and the power coefficient (which is based on machine design and has a theoretical limit of 0.59 (Manwell, 2002). Real values are less than the theoretical maximum due to lower than ideal efficiencies for the aerodynamic, mechanical and electrical sub-systems. The model uses a power coefficient that multiplies a reasonable rotor power coefficient of 0.47 by a reasonable drivetrain efficiency of 0.92 for a total of 0.43 (Fingersh, Hand and Laxon, 2006). Most turbines today limit their power output above a "rated level" so the function above is limited to the rated power of the machine and is constant for increasing wind speed once that level has been reached. The Watts per kW factor of 1000 is applied to convert the standard equation for Power from Watts to kW since the rest of the calculations use units of kW.

The expected energy is then the potential annual energy, after losses and turbine availability are accounted for, produced by the convolution of the Rayleigh wind speed distribution above and the wind turbine power curve:

Expected annual energy[States]

\[= \text{Potential annual energy[States]} \times (1 - \text{losses}) \times \text{turbine availability}\]
Once the model calculates the expected annual energy, it compares it to the breakeven annual energy through use of the wind resource distribution and estimates the percent of profitable land out of the total land in the region:

\[
\text{percent profitable land out of total[States]} = ZIDZ\left(\frac{\text{expected annual energy max[States]} - \text{breakeven expected annual energy[States]}}{\text{linear term for wind speed by land use[States]}}\right) + ZIDZ\left(\frac{\text{expected annual energy max[States]} - \text{breakeven expected annual energy[States]}^2}{\text{quadratic term for wind speed by land use[States]}}\right)
\]

From this total, the percent of profitable land still undeveloped, the percent of profitable land under development, and the percent of land already built are determined (for use in project development portion of the model):

\[
\text{percent land under development [States]} = ZIDZ\left(\frac{\text{total land under development [States]}}{\text{total potential land[States]}}\right)
\]

And:

\[
\text{percent land already built[States]} = ZIDZ\left(\frac{\text{Expected land Use from Construction Projects[States]} + \text{Simulated Land Use Installed Base[States]}}{\text{total potential land[States]}}\right)
\]

And:

\[
\text{percent profitable land undeveloped} = \text{percent profitable land out of total[States]} - \text{percent land under development[States]}
\]

The diagram below shows the visual relationships of the above determination of expected annual energy and percentage of profitable sites in region.
To determine breakeven annual energy, the next portion of the model considers technology, its associated costs, financing, revenues and incentives. The sub-model diagram is below and the key equation relating required energy production to revenues and costs is:

$$\text{breakeven annual energy}[\text{States}] = \frac{\text{annual breakeven costs}[\text{States}]}{\text{unit revenue}[\text{States}]}$$
Figure 6-XIII: Model view of the breakeven expected annual energy calculation.

And the constituent equations for breakeven expected annual energy include:

\[
\text{annual breakeven costs} \left[ \text{States} \right] = \text{annual maintenance cost} \left[ \text{States} \right] + (1 - \text{tax rate}) + \text{normalized upfront investments} \left[ \text{States} \right]
\]
annual maintenance cost[States]
    = Simulated OPEX per unit energy * expected annual energy[States]

normalized upfront investments[States]
    = \frac{upfront investment costs[States] \cdot (1 - investment subsidy[States])}{annuity factor}

The basic equations for cost of energy (including the annuity factor and reduced operations and maintenance costs for tax deductions (1 – tax rate)) for a wind plant based on NREL’s wind turbine cost and scaling model (Fingersh, Hand and Laxon, 2006). The model bases the actual costs on the current technology, as we will see in the subsequent sub-section. As shown above, the normalized investment costs account for investment subsidies that are available from the state or national governments. The investment subsidies are determined from a lookup table imported from data for the region(s) of interest. Unit revenue also accounts for any available subsidies:

unit revenue[States]
    = max(electricity price[States] * cost electricity price discount factor[States] + production incentive[States] + rec price[States], feed in tariff rate[States])

Above, either there is the opportunity for the unit revenue to correspond to either a subsidized or unsubsidized price per kWh produced or the opportunity to receive a fixed feed in tariff rate if present. There can be various types of incentives on the production side including direct production incentives, renewable energy certificates (rec) prices that affect the relative value of renewable energy generation to non-renewable sources, and feed in tariffs that provide a direct price for buying electricity that is usually higher than the unsubsidized price would be. The incentives are use lookup tables imported from data for the region(s) of interest.

Lastly, there is a function for the effect of a backlog in turbine inventory on the marginal cost of the turbines that uses a lookup table. We describe the model for the wind industry supply chain in a later sub-section, but here we look at the mark-up of turbine cost due to short supply. There is evidence that the backlog in the wind industry in the late 2000’s rose to 10,000 turbines or more (Kanellos, 2008) and a study found that a portion of the price mark-up during the time could be explained by higher profit margins demanded by the turbine manufacturers in the “seller’s market” in addition to a growth in labor costs, warranty and other factors due to having to ramp up production quickly to meet growing demand (Bolinger and Wiser, 2011). The amount attributed to endogenous factors was roughly a 50% mark-up (Bolinger and Wiser, 2011). Thus, a look-up function applies this mark-up at the 10,000-turbine level similar to that experienced during that period.
6.3.2.2 Technology Innovation and Cost Trends

The major reinforcing feedback loop is the technology innovation and learning loop. There are a many number of areas of innovation in the LCOE equation for wind energy and the associated inverse breakeven annual energy production equations above. Firstly, there are performance side innovations that increase relative energy production for a given wind site. This means improved the Power at wind speed over the various wind speeds. The factors of machine design going into the equation include the power coefficient and the rotor swept area. Thus, one obvious way of generating more electricity with a given wind turbine is to increase the rotor size. Indeed, there has been a continuous increase in rotor diameter (and area) since the early 1980’s and beyond. Enabling this increase in rotor diameter over time is the technological learning from deploying more and more wind turbines. Thus, the model imposes a learning curve on rotor diameter in the model based on the total turbine installations relative to a reference value:

\[
\text{Simulated marginal rotor diameter} = \text{initial rotor size} \times \left( \frac{\text{ratio of total to initial turbine installation experience}}{\text{exponent rotor diameter}} \right)^{\text{exponent rotor diameter}}
\]

Where the model uses a standard learning rate equation to calculate the learning exponent:

\[
\text{exponent rotor diameter} = \frac{\ln(1 + \text{rotor diameter learning rate})}{\ln 2}
\]

Correspondingly, the power rating of the machine has increased over time. Until very recently with a shift to lower specific power machines (power per unit area), the machine rating and rotor diameter had strong functional correlation:
marginal turbine power rating = 
\text{initial turbine power rating} \cdot 2^{ \frac{\text{Simulated marginal rotor diameter}}{\text{initial rotor size}} }^{\text{rotor power exponent}} 

However, what really matters for power produced at wind speeds below rated is the power coefficient or efficiency. The overall machine configuration (rotor diameter and rated power) affect this along with a number of aspects of the aerodynamic, mechanical and electrical design of the machine. Each aspect contributes its own efficiency at a given operating point that rolls up into the power coefficient. The power coefficient is a complex representation of the machine design and thus it is a constant at a reasonable value of 0.47 that is high for older turbines such that the model overestimates the energy production of those machines by a small amount.

Finally, the turbine availability has improved over time such that turbines break less often and the time that they are down due to each break is less. The formulation is the same as for the rotor diameter and is based on turbine installation (and thus operational) experience:

\text{turbine availability} = \frac{\text{initial turbine availability}}{\text{ratio of total to initial turbine installation experience}}^{\text{exponent availability}} 

Where a standard learning rate equation is used to calculate the learning exponent:

\text{exponent availability} = \frac{\ln(1 + \text{availability learning rate})}{\ln 2} 

In addition to the learning on the performance side, there is learning associated with all aspects of the cost side of the turbine and plant. The formulation is the same for each cost element (on a per kW basis) including turbine costs, balance of station costs and operational expenditures and mimics the performance formulations based on the turbine installation and operational experience:

\text{Simulated turbine capital cost per unit power} = \text{initial upfront turbine costs per unit power} \cdot \text{ratio of total to initial turbine installation experience}^{\text{exponent turbine costs}} 

Where:

\text{exponent turbine costs} = \frac{\ln(1 - \text{turbine costs learning rate})}{\ln 2} 

And:

\text{balance of station costs per unit power} = \text{initial balance of station costs per unit power} \cdot (\text{ratio of total to initial turbine installation experience})^{\text{exponent bos costs}} 

Where:
\[
\text{exponent turbine costs} = \frac{\ln(1 - \text{turbine costs learning rate})}{\ln 2}
\]

And:

\[
\text{OandM and LRC costs per unit power} = \text{initial annual OPEX costs per unit energy} \cdot \text{ratio of total to initial turbine installation experience}^{\text{exponent OPEX}}
\]

Where:

\[
\text{exponent OPEX} = \frac{\ln(1 - \text{turbine OPEX learning rate})}{\ln 2}
\]

The model takes ratio of total to initial turbine installation experience from the total cumulative global turbine installation experience over a reference number of turbines installed by the year 1980. In the model analysis, we only simulate a subset of nations and states. However, learning is a global process and excluding the rest of the world turbine installation experience would lead to an underestimation of the technology scaling increases and cost reductions. Thus, the turbine supply for the rest of the world (excluding the modeled subset) is an exogenous input to the model. To do this, the python script accesses the data sheet that has cumulative turbine installations by year.

Figure 6-XV: Model view of technology and cost learning which is driven by experience in global wind turbine installations.
From this, the model removes the turbine production from the modeled nations and states and then feeds the remaining turbine total to the parameter rest of world construction rate via a lookup table:

**Total turbine construction completions**

\[ \text{Total turbine construction completions} = \text{SUM}(\text{Simulated turbine construction finish rate}[\text{States}]) + \text{rest of world turbine construction start rate} \]

Where:

\[ \text{rest of world construction start rate} = \text{Historical rest of world turbine construction start rate}(\text{Time}) \]

This variable for rest of world turbine construction also feeds the turbine supply chain model as well in the next sub-section. The model diagram for the learning curves for technology and cost is above.

### 6.3.2.3 Wind Projects and the Industry Supply Chain

The final sub-model includes the project development along with the industry dynamics. The core flow of the model is the development of projects.

![Diagram of the model project development pipeline.](image)

**Figure 6-XVI:** Diagram of the model project development pipeline.
Wind plant developers are the main drivers of the industry and develop a certain number of projects at a time (based on their size and a number of other factors). The pipeline for project development is above.

Based on the attractiveness of a given market and the relative developer capacity in that market, the developer will begin project development. Wind plant development follows a standard process including prospecting, development, construction and commissioning (the point at which the plant enters into the installed base of the wind energy sector). Developers plan on typical timelines and success rates for these projects that include (Splettstosser, 2016):

- For every one project that is built, the developer will prospect five sites.
- Of those five prospected sites, roughly four will make it to the development stage.
- Another three of those four will fail at the development stage so that only one project gets through to construction.

Thus, the model contains five prospecting sites per developer project, a percent project deemed developable of 0.8, and a percent projects failing in development of 0.75. Furthermore, the whole process takes about five years including one year in prospecting and four years in development for site design, leasing land, obtaining environmental and other regulatory permits, and signing agreements for interconnection, power purchase and financing (Splettstosser, 2016). Then the developer will construct the project in roughly a year or less (Splestosser interview 2016). In the early years of wind development, the timeframe for development was much shorter and there is an associated time dependence of Permitting and PPA decision time on the year. The following equations are the key flows of the model's development pipeline.

Firstly, project prospecting depends on the total profitable sites available for development and the current capacity for development of regional developers:

\[
\text{project prospecting start rate [States]} = \text{MIN} \left( \text{developer project capacity [States]} \times \text{prospecting sites per developer project}, \text{total profitable undeveloped projects [States]} \right)
\]

The next sub-section describes the developer capacity sub-model. The percent of profitable land undeveloped, the fraction of land available for wind development and the land-use per project determine the total profitable undeveloped projects:

\[
\text{total profitable undeveloped projects} = \text{total potential land [States]} \times \text{fraction of land available for wind development [States]} \times \text{percent profitable land undeveloped [States]/land use per project}
\]

The fraction of land available for wind development is set to a constant value of 15% in the model. Future versions of the model will include factors that make this a dynamic relationship with increasing wind energy deployment.
From the projects that go into development, a percentage will be developable and will move on to the next stages. If market conditions change and become unfavorable, then all projects will be undevelopable and released.

\[
\text{project development start rate} \text{[States]} = \min(\text{developer project capacity} \text{[States]}, \text{Projects in Prospect} \text{[States]} \times \text{Percent projects deemed developable} \text{[States]})
\]

\[
\text{project prospecting failure rate} \text{[States]} = (1 - \text{Percent projects deemed developable} \text{[States]}) \times \text{Projects in Prospect} \text{[States]}
\]

For the projects in development, a certain percentage again will fail (about 75%) and that again can increase to all current projects in development if market conditions become unfavorable. Once the developer obtains all necessary permits and signs a PPA with a utility or other buyer of the electricity, typically 4 years, the successful projects will move on to construction.

\[
\text{project construction start rate} \text{[States]} = \left(1 - \text{percent projects failing} \text{[States]}\right) \times \text{Projects in Development} \text{[States]}
\]

\[
\text{permitting and PPA decision time}
\]

\[
\text{project development failure rate} \text{[States]} = \frac{\text{Projects in Development} \text{[States]} \times \text{percent projects failing} \text{[States]}}{\text{permitting and PPA decision time}}
\]

Projects in construction will complete on average in under a year unless there is a delivery delay due to a backlog in wind turbine inventory. The delivery delay is the total backlog over the current turbine industry production capacity.

\[
\text{project construction finish rate} \text{[States]} = \text{ZIDZ} \left(\frac{\text{Projects in Construction} \text{[States]}}{\max(\text{delivery delay, average construction time})}\right)
\]

Once installed, developers eventually decommission projects once the lifetime of the project ends (typically 25 year) but most go through repowering so only a small portion decommission.

\[
\text{project decommission rate} \text{[States]} = \text{ZIDZ} \left(\frac{\text{Projects Installed Base} \text{[States]} \times \text{percent decommissioned}}{\text{average project lifetime}}\right)
\]

Repowering often involves larger capacity than the original machines and more modern technology for higher expected annual energy production. This model does not currently capture the aspects of repowering that will become more prevalent as the industry ages. Future work will look at including repowering in a more formal structure.
Both the turbine supply chain the regional wind industry's development capacity affects the project
development pipeline. The total profitable undeveloped projects (based on the previously discussed
breakeven energy production analysis) would directly drive the project development flow except for the
limitation on developer capacity. Developers have finite size and resources and have a limit to how fast
they can grow. Thus, the relative capacity for project development is much less than the total market
potential and grows the longer the exogenous conditions sustain market profitability. A small sub-
model (see figure below) for developer capacity dynamics is included and limits the number of projects
per year that enter the development pipeline.

The model hinges on the developer capacity growth rate that is limited from year to year and aims for a
desired capacity based on market conditions:

\[
developer\ capacity\ growth\ rate[States] = MIN(\frac{desired\ capacity[States] - developer\ project\ capacity[States]}{developer\ capacity\ adjustment\ time}, \\
\frac{developer\ project\ capacity[States]}{maximum\ percent\ growth\ rate})
\]

The maximum growth rate based on analysis of global data is 40% so the current model constraints the
growth in development capacity each year by this amount (Eco-Indicators 2010, GWEC, 2014). The
desired capacity stems from the total profitable projects over the average project lifetime and has a
minimum of the initial developer or "cold-start" developer capacity that is 15 projects based on the
early California data (Folkecenter, 1985).
In addition to limits on growth for developer capacity, the turbine supply available for deployment may be less than the market demand. Firms can only build up manufacturing capacity so quickly to match a fast growing market, especially for large equipment as if wind turbines that have unique components that require skilled labor, large facilities, specialized equipment, etc. Prior studies have linked the increasing cost of turbines in 2000s to supply constraints among other factors (Bolinger and Wiser, 2011). During the 1990s, the technology evolved from a relatively small machine to a multi-megawatt machine with blades of the length of 30 m or more. By the end of the 1990s, 1 MW machines were hitting the market. In 2001, due to a series of favorable policies, the market for wind energy machines grew by 71% and continued to grow the next several years with year-to-year growth rates on average of 35% between 2005 and 2010 (GWEC, 2014). Most production came from a small number of top-tier OEMs and their profits were higher than ever in this seller's market (Bolinger and Wiser, 2011). Turbine costs in 2014 USD rose from under $1000/kW to over $1500/kW or more - a markup of at least 50%. While commodity price increases were a factor in this, so was the tight turbine market supply (Bolinger and Wiser, 2011). In the system dynamics model, we use a standard supply chain model that allows for a wind turbine backlog and an increase in cost of the turbine due to constrained supply. The model bases the turbine supply required on projected installations.

Figure 6-XVIII: Turbine industry capacity and backlog based on Sterman, 2000.
The model formulation for the above sub-model is the canonical model from Sterman, 2000. Key equations include the flows of turbine orders received that include the turbines needed for projects going into construction in the states under simulation plus historical turbine demand for the rest of the world for that year. These enter into the turbine backlog and production then is either the full turbine backlog or the industry turbine capacity, whichever is lower:

\[
\text{Turbine production} = \min(\text{Turbine Backlog}, \min(\text{desired turbine production}, \text{turbine industry turbine capacity}))
\]

As demand outpaces supply, the backlog will grow. The model attempts to correct this by updating the desired turbine production of the industry:

\[
\text{desired turbine production} = \text{Average Expected Turbine Orders} + \text{backlog correction}
\]

Where the average expected turbine orders adjusts to total projects expected in development:

\[
\text{Average Expected Turbine Orders} = \frac{\sum(\text{turbine development start rate} \times \text{permit failure rate}) - \text{Average Expected Turbine Orders}}{\text{time to average turbine orders}}
\]

In the wind industry, while turbine contracts are typically signed at the time when the project goes from development to construction (along with the PPA and financing contracts), sites are designed with specific turbines in mind early in the development process (Splettstosser, 2016). Thus, industry reacts not just to current demand but also expected demand from projects in development. The full sub-model formulation is in the appendix. While turbine industry production capacity is global, the developer capacity is local (as discussed above). Developers build up capability in a region and that capability is not immediately transferable to other regions where the turbine industry can sell its product anywhere.

6.3.2.4 Co-flows for Land Use, Capacity, and Generation

In addition to the development pipeline, there are also co-flows for turbines, land-use, capacity and electricity generation. In a system dynamics model, a co-flow is one that tracks a primary flow with the same basic structure and flows that depend on those of the primary. The co-flows for turbines, land-use, capacity and electricity generation thus directly mirror the project development pipeline and are in the appendix. Developers have a target capacity in mind at the inception of a project.
The co-flow for capacity uses the number of projects going into development:

\[
\text{capacity project start rate} = \text{Project prospecting start rate} \times \text{average project capacity}
\]

Average project capacity over time for wind projects has fluctuated substantially from very small projects of a few megawatts to large-scale projects of a Gigawatt or more. Average size based on data from the Windpower.net is about 40 MW. Early projects were quite small with 1-7 MW in the late 1970s and early 1980s scaling up to by the mid 1980’s (Folkecenter, 1985). With turbines in the size range of 22 to 55 kW, this still meant project sizes of 100 to over 300 turbines. The model uses a lookup curve to allow the project size to grow from 1 MW to 40 MW.

Figure 6-XX: Function for average capacity over time. Average begins around 3 MW for early 1980s projects to 7 MW by the mid-1980s to 40 MW as the current average (though many projects are far larger; there is a huge amount of variation in project size) (Folkecenter, 1985; Winpower.net, 2015).
The turbine co-flow uses the current marginal turbine power rating and the total capacity going into development. Note that the turbine and generation pipelines start at the development stage since developers do not select turbines at the prospecting stage.

![Turbine co-flow structure](image)

**Simulated Turbine Development Rate [States]**

$$\text{Simulated Turbine Development Rate} = \frac{\text{average project capacity} \times \text{Project development start rate}}{\text{marginal turbine power rating}}$$

The generation co-flow determines the expected generation for the marginal turbine and the project size.

![Generation co-flow structure](image)

**Generation development start rate [States]**

$$\text{generation development start rate} = \frac{\text{expected annual energy}}{\text{Simulated Turbine Development Rate}}$$

The land-use co-flow uses total footprint of each turbine times the number of turbines going into development.
land project start rate[States] = land use per project \cdot Project prospecting start rate[States]

And:

land use per project[States] = number of turbines per project \cdot area per turbine

And:

area per turbine = (Simulated marginal rotor diameter \cdot Simulated marginal rotor diameter) \cdot \text{spacing per turbine}

Spacing per turbine is based on industry heuristics of 7x7-rotor diameter spacing (AWS Scientific, 1997).

Figure 6-XXIII: Land-use co-flow structure.
Figure 5-XXIV: Model structure for calculating the land-use per project as well as the land available for development that in the wind project sub-section.

Having described the major elements of the model formulation, the next step involves selection of cases for study, data acquisition, and model calibration. The model is flexible to accommodate a number of different partitions of states grouped as desired. For the purposes of this study, we use the major countries and states for wind development over the last several decades for analysis.

6.4 Model Input Specifications and Calibration
This section describes how we select the cases for analysis and the estimation of several model inputs and outputs from available data.

6.4.1 Case Selection
While the wind turbine market is relatively global, the markets for wind power plants are local and depend significantly on local conditions including many factors such as the strength of the wind resource, the overall cost of electricity due to the local make-up of the electricity generation portfolio, transmission, market type and other factors, the availability of undeveloped land and population density, and more. In addition, over time, local market conditions can change due primarily to the influence of regional and national policies that affect the viability of wind energy. On a national level, the states with significant levels of installed wind capacity are those that at some point over the last few decades have put policy in place to support wind energy. The table below shows the total global wind capacity along with the installed capacity in nations with greater than 5 GW of installations.
Table 6-1: Installed Wind Capacity (in MW) since 1980 for the world and nations with over 5 GW of capacity in 2015 (Eco-Indicators 2010, GWE, 2014).

<table>
<thead>
<tr>
<th>Year</th>
<th>China</th>
<th>U.S.</th>
<th>Germany</th>
<th>India</th>
<th>Spain</th>
<th>United Kingdom</th>
<th>Canada</th>
<th>France</th>
<th>Italy</th>
<th>Brazil</th>
<th>Sweden</th>
<th>Poland</th>
<th>Denmark</th>
<th>Portugal</th>
<th>World</th>
</tr>
</thead>
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<td>1,580</td>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>1991</td>
<td>1,528</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>1992</td>
<td>1,570</td>
<td>0</td>
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</tr>
</tbody>
</table>

In addition to those listed above, many countries have between 500 MW and 5 GW of installed wind capacity including Turkey (4.7 GW), Australia (4.2 GW), Netherlands (3.4 GW), Mexico (3.0 GW), Japan (3.0 GW), Romania (3.0 GW), Austria, (2.4 GW), Ireland, (2.5 GW), Belgium (2.2 GW), Greece (2.2 GW), Finland (1.0 GW), Norway (0.8 GW), Korea (0.8 GW), New Zealand (0.6 GW), Czech Republic (0.3 GW), Hungary (0.3 GW). All of these nations have employed policies to support wind energy development at a national level and thus serve as candidates for analysis.

In addition to national level policies, however, certain countries have significant heterogeneity in regional electricity markets and policies. The most prominent examples of this are the United States and Canada. In each of these cases, important state- or province-level policies have enabled the deployment of wind energy over the last several years.
Table 6-2: Installed Wind Capacity (in MW) since 1999 for the United States and states with over 2 GW of capacity in 2015 (WindExchange 2015).

<table>
<thead>
<tr>
<th>Year</th>
<th>Texas</th>
<th>Iowa</th>
<th>California</th>
<th>Oklahoma</th>
<th>Illinois</th>
<th>Kansas</th>
<th>Minnesota</th>
<th>Oregon</th>
<th>Washington</th>
<th>Colorado</th>
<th>North Dakota</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>184</td>
<td>242</td>
<td>1,616</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>273</td>
<td>25</td>
<td>0</td>
<td>22</td>
<td>0</td>
<td>2,472</td>
</tr>
<tr>
<td>2000</td>
<td>184</td>
<td>242</td>
<td>1,616</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>291</td>
<td>25</td>
<td>0</td>
<td>22</td>
<td>0</td>
<td>2,539</td>
</tr>
<tr>
<td>2001</td>
<td>1,096</td>
<td>324</td>
<td>1,683</td>
<td>0</td>
<td>0</td>
<td>114</td>
<td>320</td>
<td>157</td>
<td>180</td>
<td>61</td>
<td>0</td>
<td>4,232</td>
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<tr>
<td>2002</td>
<td>1,096</td>
<td>423</td>
<td>1,823</td>
<td>0</td>
<td>0</td>
<td>114</td>
<td>338</td>
<td>218</td>
<td>228</td>
<td>61</td>
<td>5</td>
<td>4,687</td>
</tr>
<tr>
<td>2003</td>
<td>1,290</td>
<td>472</td>
<td>2,025</td>
<td>176</td>
<td>50</td>
<td>114</td>
<td>558</td>
<td>259</td>
<td>244</td>
<td>223</td>
<td>66</td>
<td>6,350</td>
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<tr>
<td>2004</td>
<td>1,290</td>
<td>634</td>
<td>2,095</td>
<td>176</td>
<td>51</td>
<td>114</td>
<td>600</td>
<td>263</td>
<td>241</td>
<td>231</td>
<td>66</td>
<td>6,723</td>
</tr>
<tr>
<td>2005</td>
<td>1,992</td>
<td>836</td>
<td>2,149</td>
<td>475</td>
<td>107</td>
<td>264</td>
<td>745</td>
<td>338</td>
<td>390</td>
<td>231</td>
<td>98</td>
<td>9,147</td>
</tr>
<tr>
<td>2006</td>
<td>2,236</td>
<td>932</td>
<td>2,376</td>
<td>135</td>
<td>107</td>
<td>364</td>
<td>896</td>
<td>438</td>
<td>818</td>
<td>251</td>
<td>178</td>
<td>11,575</td>
</tr>
<tr>
<td>2007</td>
<td>4,353</td>
<td>1,273</td>
<td>2,439</td>
<td>689</td>
<td>698</td>
<td>364</td>
<td>1,300</td>
<td>885</td>
<td>1,163</td>
<td>1,067</td>
<td>345</td>
<td>16,907</td>
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<tr>
<td>2008</td>
<td>7,113</td>
<td>2,791</td>
<td>2,537</td>
<td>708</td>
<td>915</td>
<td>921</td>
<td>1,753</td>
<td>1,067</td>
<td>1,375</td>
<td>1,068</td>
<td>714</td>
<td>25,410</td>
</tr>
<tr>
<td>2009</td>
<td>9,403</td>
<td>3,604</td>
<td>2,798</td>
<td>1,031</td>
<td>1,547</td>
<td>1,021</td>
<td>1,810</td>
<td>1,758</td>
<td>1,849</td>
<td>1,244</td>
<td>1,203</td>
<td>34,863</td>
</tr>
<tr>
<td>2010</td>
<td>10,889</td>
<td>3,675</td>
<td>3,253</td>
<td>1,482</td>
<td>2,045</td>
<td>1,074</td>
<td>2,205</td>
<td>2,104</td>
<td>2,104</td>
<td>1,299</td>
<td>1,424</td>
<td>40,267</td>
</tr>
<tr>
<td>2011</td>
<td>10,394</td>
<td>4,322</td>
<td>3,917</td>
<td>2,007</td>
<td>2,742</td>
<td>1,274</td>
<td>2,718</td>
<td>2,513</td>
<td>2,573</td>
<td>1,805</td>
<td>1,445</td>
<td>46,916</td>
</tr>
<tr>
<td>2012</td>
<td>12,214</td>
<td>5,133</td>
<td>5,542</td>
<td>3,134</td>
<td>3,568</td>
<td>2,713</td>
<td>2,987</td>
<td>3,153</td>
<td>2,808</td>
<td>2,301</td>
<td>1,680</td>
<td>60,005</td>
</tr>
<tr>
<td>2013</td>
<td>13,855</td>
<td>5,178</td>
<td>5,839</td>
<td>3,134</td>
<td>3,568</td>
<td>2,967</td>
<td>2,907</td>
<td>3,153</td>
<td>2,808</td>
<td>2,332</td>
<td>1,681</td>
<td>61,108</td>
</tr>
<tr>
<td>2014</td>
<td>14,098</td>
<td>5,689</td>
<td>5,917</td>
<td>3,782</td>
<td>3,568</td>
<td>2,967</td>
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<td>3,153</td>
<td>3,075</td>
<td>2,593</td>
<td>1,866</td>
<td>65,877</td>
</tr>
<tr>
<td>2015</td>
<td>17,713</td>
<td>6,212</td>
<td>6,108</td>
<td>5,184</td>
<td>3,843</td>
<td>3,766</td>
<td>3,335</td>
<td>3,153</td>
<td>3,075</td>
<td>2,992</td>
<td>2,143</td>
<td>74,472</td>
</tr>
</tbody>
</table>

In addition to the above states, many others have as much installed capacity or more than many of the nations listed above: Indiana (1.9 GW), New York (1.7 GW), Michigan (1.5 GW), Wyoming (1.4 GW), Pennsylvania (1.3 GW), New Mexico (1.1 GW), South Dakota (1.0 GW), Idaho (1.0 GW), Nebraska (0.9 GW), Montana (0.7 GW), Wisconsin (0.6 GW), Maine (0.6 GW), West Virginia (0.6 GW), Missouri (0.5 GW) and several others have at least 100 MW installed. In Canada, both Alberta (>1 GW) and Ontario (>3 GW) have significant installations. While national policies are important to wind development, the federal policies have often not been sufficient by themselves and the state- and province-level policies in these nations have played a key role in catalyzing wind energy deployment.

Therefore, the approach for case selection involves a mixture of nations and states/provinces where appropriate. The list above of nations and states includes then 45 jurisdictions that can be included in the analysis. This is a large number of countries and we reduce the number to those who have made the most significant contribution to global wind capacity. However, the model is flexible to accommodate any combination of jurisdictions that the user would like to analyze. To do this, we created a Python script to sort the input and output data according to a user-defined grouping of the nations and states. For instance, one potential grouping is every nation, US state, and Canadian province in the world. This would give 312 separate jurisdictions for the model. A more historic analysis may consider only those jurisdictions with significant installed capacity prior to 2001 (after which the number of nations and states that had policies to support wind energy development grew substantially). Such a historical selection would include (according to the tables above), Denmark, Germany, Spain, India, and the US state of California. An analysis focused more on the present day might include the 45 jurisdictions above. The subsequent case studies and scenarios will use a select set of nations and states from the 45. We will provide additional details about these cases in the simulation section. The next sections describe data collection for each nation and state/province as well as global data about technology trends.
6.4.2 Data Collection

The data collection for each of the sub-models described in the model formulation includes data for wind resource, LCOE, technology innovation and cost trends, and wind projects.

6.4.2.1 Wind Resource

Estimating the long term wind resource at the site is critical to the project’s success and will involve a data collection campaign for at least a year with a meteorological tower on site, the use of ever-increasingly sophisticated models to process the data, leverage large wind resource data sets, mesoscale atmospheric models and other information sources to predict long-term estimates of the resource at the site. Given the significance of this type of data to wind project development, many countries have supported efforts to collect resource data and develop “wind resource maps” that can support site-prospecting activities. In the US, the National Renewable Energy Laboratory has created maps of the wind resource at various heights of interest and even a tool for analyzing specific sites (NREL, 2016). In Europe, there are similar efforts to provide a European wind atlas (DTU Wind Energy, 2016) with ongoing efforts to update the data sets. Of course, these data sets focus on certain parts of the world. The Atmospheric Science Center of NASA, in contrast, published a global “Surface Meteorology and Solar Energy” database which contains long term estimates of 10 year average wind speeds at 50 m heights using data collected from 1993 to 2003 (NASA, 2016). While less accurate than the sophisticated resource data sets produced by wind research groups at NREL and DTU, the data set is comprehensive for the whole world at 1 km resolution.

In order to develop a wind resource supply curve for each state in the analysis, a method of aggregating and fitting the data was used and is updated based on the user defined grouping of states. The method to fit the data is as follows:

1. Based on the grouping (i.e. the user selects a single state, California, for the analysis) the global dataset is searched for and all the wind resource data for each state is added to an array
2. The filtered data for 50 m 10 year annual wind speed is sorted from the maximum to the minimum and a cumulative distribution of the wind speed is created as a function of the total land in the state
3. Python NumPy (numerical Python) library method “polyfit” fits a quadratic function to the data and the model uses resulting coefficients for the intercept, linear and quadratic terms for the state(s) of interest.

As an example, below is a plot of the data for the state of California and the resulting polyfit function.
Cumulative distribution of 50 m wind speed resource in California and polynomial data fit

Wind resource = 6.46 - 1.97*(% Land Use) + 0.64*(% Land Use)

$R^2 = 0.93$

While using a quadratic polynomial to fit the data does not capture the full complexity of the distribution and a higher order polynomial could provide an even better fit, the agreement between the fit and the data is satisfactory (with an adjusted $R^2$ value of 0.93) and captures the general trend of the wind resource for the state. We sacrifice higher accuracy in order to limit the complexity of the wind resource function in the model (where there is a separate function for each state in the analysis).

The percentage of developable land determines the available resource so the land area of each country and state was imported to the model via the Python script and assigned to the potential land area variable for the relevant state. Most land, however, cannot be developed for wind projects since it has already been developed, is sensitive for environmental, security or other reasons, is too steep a grade or there are other issues which would make installation of turbines difficult to impossible, or it is too close to a population that is likely to protest due to NIMBY concerns. The total land area will drop by 80-95% of the actual land area for a region so that only 5-20% has potential for development (Gray-Searles, 2007). Of course, this will vary substantially by region and the large studies such as the US DOE Wind Vision take great pains to process large quantities of GIS to determine what land is developable in a given region (U.S. Department of Energy, 2015). We assume for this model that the available land...
percentage is a uniform cut across the nation or state since it is beyond the scope of this effort to resolve these types of regional specifics. The model reduces total land available for development by a factor to a more reasonable size available for project development.

6.4.2.2 Cost of Energy and Policy
As described earlier, the model converts the wind resource distribution into an expected energy distribution to compare the site with the highest available expected energy to the breakeven expected annual energy. If the expected energy for that marginal site is higher than the breakeven level, then project development will begin. To determine the breakeven expected annual energy, information about the project costs and potential revenues must be available. The next section discusses the cost side while this section addresses the revenue streams (including an expected price per unit energy produced including any applicable incentives).

For some of the listed cases, electricity price data is readily available while not for others. In particular, there are good public resources for electricity prices in the US, Canada and Europe while not for India, China, Brazil and Mexico. For the former, we compiled data from various sources including the US DOE Energy Information Administration (EIA), the Organization for Co-Operation and Economic Development’s (OECD’s) International Energy Agency (IEA) and the European Union (EU). Each group maintains large databases of information on energy generation, consumption and costs over time for their respective regions of interest. The OECD/IEA database was the primary source of information on historical electricity prices for European countries, Canada, and Australia since it has information over the entire period of interest (back to 1980 and before) while we used the EU’s Eurostat database for countries that were not available from the IEA database. For the US, the EIA database provided the necessary information. The chart shows historical electricity prices for four of the earliest adopters of wind energy.
We collected data for as many of the countries of interest as possible and for other countries that may be part of future work. We adjusted the data for currency and normalized to the year of interest, 2014, so that the final data set was in 2014 USD/kWh. The python script then creates a lookup function of the data by year for each state.

While knowing the electricity price that represents the cost of the current energy portfolio is necessary to determine the breakeven annual energy production, all of the countries under study also used policy measures to accelerate adoption of wind energy. There are a huge number of different potential ways to provide incentives for deployment of a technology. Generally, these incentives either will affect the price of the technology or will involve some quota requiring adoption of the technology. Depending on the country and region of the world, many different types of policies have existed over the last several decades to promote wind energy deployment. The most prominent approaches have been:

- Production or investment incentives such as the well-known Production Tax Credit (PTC) and Investment Tax Credit (ITC) used by the US federal government to provide a tax credit based on production (at a rate of X $/kWh) or a percentage of the upfront investment.
- Feed-in-tariff (FIT) incentives that provide a more or less stable purchase price for electricity from wind energy that is set at the national level either as a fixed value or as fluctuating with electricity prices. FIT’s have been the dominant policy of choice for European countries since the 1990’s and more recently, some US states (such as California and a few others).
- Renewable Portfolio Standards (RPS) with or without a mandatory Renewable Energy Certificate (REC) program that mandate a certain amount of electricity generation from sources such as wind by certain dates. Often these programs involve a penalty for not meeting the mandate and allow participation in a REC program to trade credits for generation from renewable sources. RPS programs have been the dominant policy of choice by US states since the early 2000's and a few European countries have used them as well.

- Europe has used a carbon tax system (either a cap-and-trade or a straight tax on Carbon) to directly include the cost of carbon from fossil fuel based electricity generation into the electricity price. The European Union has had a carbon cap-and-trade program in place since 2005.

The below tables summarize the main policies used by the countries and states of interest in this study:

**Table 6-3: Countries, installed wind capacity and their policies for supporting wind energy (IEA 2015 b)**

<table>
<thead>
<tr>
<th>Country</th>
<th>Policy Type and Year(s) of Adoption</th>
<th>2015 Cumulative Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Federal policy for regional FIT programs since 2008</td>
<td>145 GW</td>
</tr>
<tr>
<td>United States</td>
<td>ITC from 1980 to 1985, PTC from 1991 to present with periodic expirations of PTC</td>
<td>74 GW</td>
</tr>
<tr>
<td>Germany</td>
<td>FIT program since 1991</td>
<td>45 GW</td>
</tr>
<tr>
<td>India</td>
<td>FIT program since 2011</td>
<td>27 GW</td>
</tr>
<tr>
<td>Spain</td>
<td>FIT program since 1994 discontinued in 2012</td>
<td>23 GW</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>RPS / REC program since 2002</td>
<td>14 GW</td>
</tr>
<tr>
<td>Canada</td>
<td>Production incentive from 2007 to 2011</td>
<td>11 GW</td>
</tr>
<tr>
<td>France</td>
<td>FIT program since 2001</td>
<td>10 GW</td>
</tr>
<tr>
<td>Italy</td>
<td>RPS / REC program since early 2000s</td>
<td>9 GW</td>
</tr>
<tr>
<td>Brazil</td>
<td>FIT program began in 2002, along with auction system since 2009</td>
<td>9 GW</td>
</tr>
<tr>
<td>Sweden</td>
<td>RPS / REC program began in 2007</td>
<td>6 GW</td>
</tr>
<tr>
<td>Poland</td>
<td>RPS / REC program began in 2005</td>
<td>5 GW</td>
</tr>
<tr>
<td>Denmark</td>
<td>PTC and ITC in early 1980s and periodically to present</td>
<td>5 GW</td>
</tr>
<tr>
<td>Portugal</td>
<td>FIT program since 2001</td>
<td>5 GW</td>
</tr>
<tr>
<td>Turkey</td>
<td>FIT program since 2011</td>
<td>5 GW</td>
</tr>
<tr>
<td>Australia</td>
<td>Investment Grant Program from 1999 to 2007, RPS/RECs program from 2001</td>
<td>4 GW</td>
</tr>
</tbody>
</table>
Table 6-4: States and their policies for supporting wind energy adoption (DSIRE 2016, LBNL 2015)

<table>
<thead>
<tr>
<th>State</th>
<th>Policy Type and Year(s) of Adoption</th>
<th>2015 Cumulative Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas</td>
<td>RPS/REC program since 2002</td>
<td>18 GW</td>
</tr>
<tr>
<td>Iowa</td>
<td>RPS/REC program since 1991</td>
<td>6 GW</td>
</tr>
<tr>
<td>California</td>
<td>Investment incentives in early 1980s, RPS/REC program since 2003 now a FIT program</td>
<td>6 GW</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>Non-binding RPS</td>
<td>5 GW</td>
</tr>
<tr>
<td>Illinois</td>
<td>RPS/REC program since 2008</td>
<td>4 GW</td>
</tr>
<tr>
<td>Kansas</td>
<td>RPS/REC program since 2011</td>
<td>4 GW</td>
</tr>
<tr>
<td>Minnesota</td>
<td>RPS/REC program since 2002</td>
<td>3 GW</td>
</tr>
<tr>
<td>Oregon</td>
<td>RPS/REC program since 2011, now a FIT program</td>
<td>3 GW</td>
</tr>
<tr>
<td>Washington</td>
<td>RPS/REC program since 2012, now a FIT program</td>
<td>3 GW</td>
</tr>
<tr>
<td>Colorado</td>
<td>RPS/REC program since 2007</td>
<td>3 GW</td>
</tr>
</tbody>
</table>

Estimates of the quantitative value of these incentives over time have been taken from a large number of data sources. It is difficult to get exact information about the value of these incentives, and the model uses interpolation or estimation from related sources where specific data were not available. We compiled the data into a workbook and then use a Python script to pull the data into lookup tables by year for each nation/state in the analysis.

The overall incentives and electricity prices determine the marginal LCOE for the next project in each state by year. The model does not explicitly use the simulated LCOE as a causal variable since and instead uses the viability of the project by the breakeven expected annual energy. However, the model calculates the marginal LCOE in a country as a function of current technology, available wind resource, costs and incentives and compares it to available data. Below is a plot of the average LCOE for wind plants constructed across the world from 1980 to the present day. The estimates from the IEA Wind Task 26 on wind cost of energy include international sources from Denmark while the Wind Vision focuses on the United States. Wind Vision estimates of historical LCOE values are very high for the early 1980's and we judge the early Danish estimates as more reasonable. The data show that there has been a downward trend in wind plant LCOE over time from the 1980's to today with the exception of the period around 2010 when LCOE actual increased for about 5 years straight before descending again.

There are several explanations for this increase in LCOE during the period of the late 2000's with the largest contributing factor being increased turbine prices due to 1) constrained supply and very high demand growth, and 2) increased commodity prices due to high fuel costs and other factors (Bolinger and Wiser, 2011). The former is particularly important and will be addressed in the turbine supply chain sub-model. Several nations and states adopted policies to support wind in the early 2000's and the result was strong growth across many countries at the same time. Indeed, from today's perspective, 2001, was the beginning of a period of exponential growth in the industry – from roughly 25 GW to 430 GW in 2015. This growth resulted in supply bottlenecks and backlogs of turbine orders. The supply chain sub-model discussion addresses this topic further.
6.4.2.3 Technology Innovation

In order to determine how turbine technology has changed over time, and in particular, how it has changed as a function of deployment, the model needs both turbine and corresponding project data. There are a myriad of data sources about wind energy projects but, just as with the wind resource data, the data is often regional. For instance, the American Wind Energy Association maintains a comprehensive database of US wind projects and associated wind turbines. National research organizations use this database along with additional proprietary data to do a large range of studies around wind energy market and technology trends (Mone, C. et. al., 2015; Wiser and Bolinger, 2015; U.S. Department of Energy, 2015). However, for this effort, a global database is necessary. There are various public sources of global wind project data from several organizations including the Global Wind Energy Council (GWEC), the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). However, this data does not include specifics about the technology. A proprietary wind turbine and project database from The Wind Power.net includes project data across the world and associated turbine data. While this study has identified several data quality issues (in terms of missing

Figure 6-XXVII: LCOE over time from various data sources and a combined estimation (Lantz, Wiser and Hand, 2012; U.S. Department of Energy, 2015; Wiser and Bolinger, 2015).
data or improperly categorized data), it is a comprehensive database available to researchers and useful to this study.\textsuperscript{65}

The first machines to see large-scale deployment were 22 kW Danish machines installed in the early 1980’s that had rotor diameters of just 10 m. Current machines today typically have rated power in excess of 2 MW and rotor diameters in excess of 100 m – an increase by a factor of 10 for both configuration parameters. Wind turbines today are arguably the largest dynamic machines in the world and deal with some of the most complex and uncertain physics that a system can experience. Historically, we looked at how certain conservative design principles allowed Danish machines to become dominant in the marketplace. Once dominant, industry scaled up these machines with increasing deployment of wind energy across the world. With the “dominant design” established, a learning process took place over the last few decades where the machines were scaled up to take advantage of economies of scale in materials use, manufacturing, transportation, installation and even operations.

As earlier mentioned, the model uses a standard learning curve model formulation for the wind turbine rotor diameter, rated power, and hub height. In the basic model, a learning curve parameter sets the rate at which the system improves or reduces cost as a function of cumulative experience. Here, experience is turbines produced and installed, and the learning curve fits to the actual data. To fit the data, a simple method of using excel goal seek to minimize the least squared error was used. We judge the fitness afterwards through a regression of the fitted to the actual data. The fitted learning curve for rotor diameter has a learning rate of 0.25 and results in a rotor diameter exponent of $\frac{\ln(1.025)}{\ln(2)}$ or 0.32. The resulting adjusted R-squared for the fitted function regressed to the data is 0.98 where the coefficient is 1.0 with a p-value of 4e-20.

\textsuperscript{65} There are a few other databases that are known: MAKE Consulting also has a database for turbines and projects but The Wind Power’s database was already purchased. In the future, it may be worth looking into MAKE Consulting’s product offerings and also potentially Bloomberg New Energy Finance which has a projects database as well.
For rated power, there is a significant correlation to rotor diameter for turbine designs over time. Until very recently, we could describe rated power well as a function of rotor diameter. Recently, “low-wind-speed” technology with low specific power (rated power per unit swept area) turbines have become popular for land-based applications which means that the relative size of the rotor diameter to rated power has increased for recent product offerings. For this study, we are neglecting this trend and directly fitting rated power to rotor diameter. Thus, the learning curve is adapted and rather than turbine installation experience, we use the relative increase in rotor diameter from the baseline as the independent variable and the best fit exponent then is 2.0 such that:

$$\text{Marginal rated power} = \frac{\text{reference rated power}}{\text{reference rotor diameter}} \times \left(\frac{\text{marginal rotor diameter}}{\text{reference rotor diameter}}\right)^{2.0}$$

The adjusted R-squared for the fitted function is above 0.98 where the coefficient of the functional fit is 1.0 with a p-value of 3e-20. Note that there is a pronounced discrepancy between the data and the
function fit for the most recent years of 2013-2015. In reality, the turbine sizes have indeed continued to increase on average and the database is likely less reliable for the most recent years with either missing data or incomplete data for various projects. The functional fit and regression analysis exclude the data from most recent years for rated power.

![Rated power for new wind turbines over time](image)

Figure 6-XXIX: Rated power over time with the fitted data from a function of rated power to rotor diameter. Actual data from The Wind Power 2015.

The scaling of wind turbine technology also includes hub height. For a given turbine model, there may be many hub heights available. This has historically made it different from rated power and rotor diameter. The main benefit of increasing hub height is to take advantage of wind shear where wind speed typically increase with hub height. As earlier described, the power in the wind depends on the swept area of the rotor (or diameter squared) and the cube of the wind speed. Thus, increasing wind speed by 25% leads to a near doubling of the power output for a given turbine design. Thus, the increasing hub height is not as much about economies of scale as it is about accessing more wind energy.
For hub height, the learning curve method was used in the same way as for the rotor diameter. We found the learning rate that provided the best fit of the data to the actual data where the hub height was a function of overall turbine installation rate. The fitted learning curve for hub height has a learning rate of 0.22 and thus a hub height exponent of \( \frac{\ln(1.21)}{\ln(2)} \) or 0.29. The adjusted R-squared for the fitted data to the actual data is 0.95 where the coefficient is 1.0 and the associated p-value is 7e-19. As can be seen in the plot, the trend in actual hub height data is much less smooth than for rotor diameter or rated power. This could be due to errors in the data source or the fact that hub heights are more site specific and depend on the site wind resources and other factors.

![Hub height for new turbines over time](image)

Figure 6-XXX: Hub height actual data and fitted data using the learning curve function. Actual data from The Wind Power 2015.

Finally, there has been improvement over time in turbine and overall wind plant availability. Availability is the percent of time that the turbines at the plant are able to produce electricity. More data on availability is necessary, but there was a significant increase in availability over the early years of plant operation followed by a steady increase over time with more experience. The fitted learning rate for availability is 0.015 with an exponent of 0.02. There is too little data at present to perform regression.
analysis. The below table summarizes the final technology learning curve equations and the graph for availability with actual and fitted data is also provided.

![Availability of wind plants over time](figure)

**Figure 6-XXXI: Availability of wind plants over time. Availability data from Folkecenter, 1985 and Wind Energy Update.**

<table>
<thead>
<tr>
<th></th>
<th>Rotor Diameter</th>
<th>Rated Power</th>
<th>Hub Height</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference value (1980)</td>
<td>10 m</td>
<td>22 kW</td>
<td>15 m</td>
<td>0.80</td>
</tr>
<tr>
<td>Learning rate (r)</td>
<td>0.25</td>
<td>0.22</td>
<td></td>
<td>0.015</td>
</tr>
<tr>
<td>Learning curve exponent</td>
<td>0.32</td>
<td>2</td>
<td>0.29</td>
<td>0.02</td>
</tr>
<tr>
<td>ln(1+r)/ln(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experience Baseline</td>
<td>100 turbines</td>
<td>10 m rotor</td>
<td>100 turbines</td>
<td>100 turbines</td>
</tr>
</tbody>
</table>

Table 6-5: Summary of technology learning curves
6.4.2.4 Cost Trends

The scaling of the technology discussed in the previous section enables the economies of scale moving to larger turbines. The result is decreasing costs per unit power for the wind plant. However, scaling of the technology is only one part of the overall technology learning and innovation that leads to these per unit power cost reductions. Thus, learning curves for cost are developed independent from the scaling and use the same structure: the learning rate is estimated by fitting a function of turbine installation to the actual cost data for the different cost components of the plant: the turbine capital costs, balance of plant costs and operational expenditures.

Unfortunately, unlike the technology trends, cost trends for wind turbines and plants have not been monotonically decreasing over time. As mentioned earlier, supply bottlenecks due to unprecedented market growth along with increased commodity and fuel prices led to an increase in wind turbine and overall project costs in the early 2000’s as can be seen in the below graph.
Figure 6-XXXII: Turbine capital cost data from the early 1980's to today (Wiser and Bolinger, 2015; Folkecenter, 1985; Petersen, 1987; Schmid and Palz, 1986)
Average turbine cost per unit power compared to fitted learning curve

Figure 6-XXXIII: Turbine cost trends and fitted data. Average turbine cost taken by averaging across the data in the previous figure.

The bump in costs due to increased turbine cost fed into overall project costs in the early 2000s. The graph below clearly shows an increase in overall project costs after 2004 that peaks around 2010 and then begins to decrease again.
Removing the turbine cost to the rest of the costs associated with the plant, there is still an increase in costs over the period due to a number of potential factors including supply constraints on balance of system components, equipment, increased commodity and fuel prices, etc. Thus, just as with the turbine learning curve, built by fitting the data through 2004. Even with the latest data filtered out, there is a large amount of scatter in the average balance of plant costs in the above graph and the figure of the fitted data. This reflects significant variance in plant costs. We expect this as projects can vary significantly in size, topography of the location, existing infrastructure, transportation and logistics, and more. Thus, the adjusted R-squared for fitting the data is extremely low (0.05) and more work is necessary to sort the project data by type and acquire more overall data on balance of station costs in order to produce a better fit. Given these limitations, we still fit the data and find a learning rate of -0.07 for an exponent of -0.10. The actual data and fitted learning curve are shown in the below figure.
Finally, O&M costs also have shown a decrease over time. The following data shows the trend in O&M costs over time and following that is the averaged data and fitted learning curve. Unlike the turbine and project cost, the increase in the early 2000s is absent from the O&M data and the full data set can be used as a training set. The result is a slightly higher learning rate of -0.14 resulting in an exponent of -0.22. The adjusted R-squared for the data is better as well at 0.67. Overall, the cost data were more difficult to fit and showed less clear trends than the technology data. Costs can vary substantially from project to project (as seen in the figures) and there are many factors that are difficult to isolate that can contribute to these differences.
Figure 6-XXXVI: Trends in operational expenditures for wind plants over time as an average of annual costs over their lifetime (Wiser and Bolinger, 2015).
Operational expenditure costs per unit energy produced over time

Figure 6-XXXVII: Operational expenditure averages of actual data and fitted learning curve. Averages taken from previous figure data (Wiser and Bolinger, 2015).

The learning curves capture the average behavior and general trends for decreasing costs over time. The table below summarizes the learning curves for cost.

<table>
<thead>
<tr>
<th>Table 6-6: Summary of cost learning curves</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference value</strong></td>
</tr>
<tr>
<td>Turbine Capital Cost</td>
</tr>
<tr>
<td>Balance of Station Cost</td>
</tr>
<tr>
<td>Operational Expenditures</td>
</tr>
<tr>
<td><strong>(1980)</strong></td>
</tr>
<tr>
<td>2000 USD/kW</td>
</tr>
<tr>
<td>1000 USD/kW</td>
</tr>
<tr>
<td>50 USD/kWh</td>
</tr>
<tr>
<td><strong>Learning rate (r)</strong></td>
</tr>
<tr>
<td>-0.07</td>
</tr>
<tr>
<td>-0.07</td>
</tr>
<tr>
<td>-0.14</td>
</tr>
<tr>
<td><strong>Learning curve exponent</strong></td>
</tr>
<tr>
<td>-0.10</td>
</tr>
<tr>
<td>-0.10</td>
</tr>
<tr>
<td>-0.22</td>
</tr>
<tr>
<td><strong>ln(1+r)/ln(2)</strong></td>
</tr>
<tr>
<td><strong>Experience Baseline</strong></td>
</tr>
<tr>
<td>100 turbines installed</td>
</tr>
<tr>
<td>10 m rotor diameter</td>
</tr>
<tr>
<td>100 turbines installed</td>
</tr>
<tr>
<td><strong>Adjusted R² for fit</strong></td>
</tr>
<tr>
<td>0.80</td>
</tr>
<tr>
<td>0.05</td>
</tr>
<tr>
<td>0.67</td>
</tr>
</tbody>
</table>


to actual data
6.4.3 Case Study Simulation
We present two sets of simulation for the cases identified in the previous section. Firstly, we simulate the four countries who were the earliest adopters of wind energy to calibrate a few key model parameters around the developer capacity and turbine supply chain. Then, we run a second simulation involving the largest wind markets in the world including several US states. As will be discussed, we exclude a few large wind energy-adopting nations due to lack of available data for key input parameters like electricity prices and policies.

6.4.3.1 Historically dominant wind markets
The first nations and states to begin to adopt wind energy in significant quantities were respectively: Denmark, California in the United States, Germany and then Spain. We will refer to all of these jurisdictions as states for the remainder of this section. These states all have regions with strong wind resources. Spain has the largest area followed by California, then Germany and Denmark:

<table>
<thead>
<tr>
<th>Country</th>
<th>Land Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain</td>
<td>503,250 km²</td>
</tr>
<tr>
<td>California</td>
<td>403,470 km²</td>
</tr>
<tr>
<td>Germany</td>
<td>355,250 km²</td>
</tr>
<tr>
<td>Denmark</td>
<td>41,100 km²</td>
</tr>
</tbody>
</table>

Like much of the world, all of these countries felt the effects of the oil crisis and began to look at renewable energy to replace fossil-fuel based generation sources. In the historical case study, we took an in-depth look at the situations in Denmark and California. These states were the first to put in place policies that would allow wind to be competitive with other wind energy sources. Denmark used investment subsidies and loan guarantees while California, in addition to taking advantage of federal ITCs of 25%, used an in-state program offered an additional ITC of 25% and an accelerated depreciation tax incentive amounted to nearly another 50% investment tax credit (Folkecenter, 1985). Essentially, California was giving away money to anyone who would invest in wind projects. These had some negative unintended consequences, but it was effective in enabling the “wind rush” of massive deployment (relative to the period).

The change of administrations in 1984 in both California and in the federal government then led to a hasty removal of the proactive renewable energy policies and by the start of 1986, the government had fully removed all of the key policy incentives for wind energy. While Denmark continued to reinforce its own market and keep the tiny industry alive, the global market stagnated until 1989 when Germany enacted the first ever feed-in-tariff for renewables that benefited wind energy. Germany became the next hot spot for wind energy deployment until the year 2000 when additional nations, first Spain then others, followed suite with their own FIT or alternative incentive programs.

Thus, we are looking for a few key dynamics from our initial simulation case:
• The boom-and-bust of the California market and phased continuous growth of the Danish, then German, and finally Spanish markets
• The feedback between the aggregation of market development across the cases along with the rest of world growth (as an input) leading to technology learning in terms of technology scaling and cost reductions per unit power

The following graph shows the resulting simulation of cumulative installed wind energy capacity for the simulated and actual data.

![Installed Wind Capacity from Simulations and Actual Data by State](image)

Figure 6-XXXVIII: The above figure shows the actual and simulated trends in installed capacity for Denmark and California.

Immediately, differences between the simulated and actual data are apparent. The simulation for California shows more significant growth in the early 1980s and less aggressive (but more continuous growth) since 2010. For Denmark, the simulation does not quite keep up with the actual growth since 2000. This could be for two reasons: firstly, the policy data may not adequately represent the full suite of incentives over the past several years for projects in Denmark; a second likely factor is the lack of modeling the offshore wind market as its own entity. Denmark has aggressively pursued offshore wind
for the bulk of its recent capacity additions and nor the technology nor the resource are modeled in the current framework.

Figure 6-XXXIX: The above figure shows the actual and simulated trends in installed capacity for Germany and Spain.

For Spain and Germany, the main difference is that there seems to be a phase shift between the actual growth curve and the simulated growth curve. Thus, the simulated installed capacity lags the actual capacity in both cases. A key sensitivity of the model is the developer capacity model that limits the growth of the market to a reasonable level (otherwise, there would be an immediate massive increase in development once the government puts incentives in place in a given state). Allowing developer capacity to scale up more quickly allows the German and Spanish markets to grow much faster but the California market as well. A potential remedy would be to have the maximum developer capacity growth be a function over time that in the early days of the industry would be limited while it could accelerate as the industry matures. Right now, the average maximum growth rate for global historic data of 40% is used; this variable could be both time and geographically dependent. However, despite the discrepancies between the actual and simulated data, the model captures the basic trends of the growth dynamics. Statistics comparing the two data streams support this finding.
Table 6-8: Statistics of Model Fit to Actual Data for Installed Capacity;

Statistics are for the full simulation set from 1980 through 2014 inclusive

<table>
<thead>
<tr>
<th></th>
<th>California</th>
<th>Denmark</th>
<th>Germany</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Installed Capacity 2014 (GW)</td>
<td>5.7 GW</td>
<td>5.9 GW</td>
<td>48 GW</td>
<td>23 GW</td>
</tr>
<tr>
<td>Simulated Installed Capacity 2014 (GW)</td>
<td>6.7 GW</td>
<td>4.3 GW</td>
<td>43 GW</td>
<td>37 GW</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.8769</td>
<td>0.8850</td>
<td>0.9944</td>
<td>0.9252</td>
</tr>
<tr>
<td>MAE / Mean</td>
<td>0.3716</td>
<td>0.4270</td>
<td>0.0751</td>
<td>0.2597</td>
</tr>
<tr>
<td>Theil Bias Fraction (Us)</td>
<td>0.4350</td>
<td>0.4424</td>
<td>0.1567</td>
<td>0.0084</td>
</tr>
<tr>
<td>Theil Unequal Variance Fraction (Us)</td>
<td>0.09402</td>
<td>0.3605</td>
<td>0.2735</td>
<td>0.2107</td>
</tr>
<tr>
<td>Theil Unequal Covariance Fraction (Uc)</td>
<td>0.4710</td>
<td>0.1971</td>
<td>0.5698</td>
<td>0.7809</td>
</tr>
</tbody>
</table>

The statistics show that the R-squared value is relatively high for all the cases meaning that the model explains the variance relatively low. However, the mean absolute error over the mean (MAE/mean) are relatively high. There are issues in capturing the growth dynamics of each case as we can see a phase shift where the model either is ahead of (as in the case of Germany) or lags (as in the case of Spain, Denmark and California) the actual data. The Theil statistics show some evidence of this bias (Um) and phasing issues (Uc). This is most prevalent for Germany and Spain where it is clear that both the slopes and phasing of the simulated versus actual data are different. Better quality and more disaggregation of data on many of the model inputs (electricity prices, policy, land-based and offshore technology) would allow a better calibration of the model and fit to the data on market growth. In addition, there are some assumptions based on a few data sources around the growth of the industry, supply chain and developer capacity that may be more complex than currently represented in the model. Future work may involve a data gathering effort focused specifically on the industry supply chain dynamics to inform the structure of these sub-models and input and calibration of the supply chain models rather than using simple data sources.

In addition to installed capacity, it is important to look at the year-to-year industry growth and the dynamics of how the simulation captures the stop-and-start of various state policies affecting the market. The graphs below show the year-to-year growth of capacity by state along with a table of statistics for the fit of simulated to actual data.

Table 6-9: Statistics for actual to simulated data on new capacity installations;

Statistics are for the full simulation set from 1980 through 2014 inclusive

<table>
<thead>
<tr>
<th></th>
<th>California</th>
<th>Denmark</th>
<th>Germany</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-squared</td>
<td>0.3015</td>
<td>0.0804</td>
<td>0.7479</td>
<td>0.4022</td>
</tr>
<tr>
<td>MAE over Mean</td>
<td>1.0</td>
<td>0.8931</td>
<td>0.325</td>
<td>0.8715</td>
</tr>
</tbody>
</table>

66 MAE/Mean is used here rather than root mean squared error or related statistics because it weights errors linearly. Since this is a growth model where the market is expected (and does) grow exponentially, RMSE or other metrics would give more weight to the larger absolute errors that occur later in time. In addition, because the market begins with no capacity, MAE/Mean is used instead of the mean absolute percentage error.
<table>
<thead>
<tr>
<th>Theil Bias Fraction (Um)</th>
<th>0.0227</th>
<th>0.0482</th>
<th>0.0022</th>
<th>0.1154</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theil Unequal Variance Fraction (Us)</td>
<td>0.1735</td>
<td>0.1850</td>
<td>0.1492</td>
<td>0.1770</td>
</tr>
<tr>
<td>Theil Unequal Covariance Fraction (Uc)</td>
<td>0.8038</td>
<td>0.7669</td>
<td>0.8486</td>
<td>0.7076</td>
</tr>
</tbody>
</table>
Figure 6-XL: Graph of simulated and actual new wind energy capacity additions for Germany and Spain
Figure 6-XLI: Graph of simulated and actual new wind energy capacity additions for California and Denmark.
Firstly, we note that the market for wind energy is much more volatile than the simulation can capture. The model captures certain important market instabilities: the boom-and-bust of the early 1980’s California market, the periodic cancellation of the US PTC incentive in 2000, 2002 and 2004 and some fluctuation of policy support in Denmark in the late 1990’s. However, the model does not capture a significant amount of volatility in the more recent years in Denmark, Spain and Germany. Further work to characterize the impact of policy on those respective markets and adjusting the policy inputs may help capture some of the variance that is not currently simulated. Notably, in the past few years the market in Spain has stagnated – the government removed the FIT program that had promoted most of the growth over the past decade and replaced it with a remuneration system (IEA Spain 2015).

However, Spain also has very high electricity prices and thus the removal of the FIT does not affect the simulation in the last few years. An important feedback missing from the model is the relationship between the amount of wind electricity in a system and the electricity price due to costs of integration. As previously mentioned, the model does not contain this structure, but Spain happens to be uniquely vulnerable to this dynamic because its system is relatively isolated (with only a few points of interconnection to France) and the level of wind energy generation in the system has been quite high (upwards of 10% and more). Future work will address this grid integration causal loop since it is increasingly important with the growth of wind energy in electric grid systems.

The differences between the simulated and actual data also appear in the statistics in Table 9 where you can see that the R-squared value for these simulations is quite low except for Germany (at 0.75) and the MAE/mean are quite high (again excepting Germany at 0.35). However, the Theil statistics show less systematic error than was present for the cumulative capacity simulations. Having the most of the error categorized as unequal covariation or unequal variation and covariation indicates that there are some systematic phasing issues (for instance the cycles in the California market or the lag in growth of the Spanish market) but generally, the trends and means are agreeing across the cases. While it would be ideal to have a perfect fit of the actual and simulated data, the system this model addresses has a very large scope with many important dynamics that are difficult to capture in a simplified way. The ability to capture the basic trends in growth and cyclic market behavior give sufficient confidence to move forward with additional analysis.

Before that, however, the other key area for the model fit is on the technology scaling and cost trends. The figures below show the actual versus simulation data on key turbine and plant attributes.
The model learning curves fit to technology trends data as we discussed earlier. Here, the technology trend fits are evidence of the model’s ability to capture the dynamics between the technology development and the capacity growth where the technology scaling helps to improve the breakeven expected annual energy generation and market growth in turn promotes further learning. Looking at the above and below graphs shows slightly faster than expected growth in the early years and slower growth in the more recent past. The statistics show good agreement with high R-squared and low MAE/mean and the different slopes in the rotor diameter and rated power graphs explain the high unequal variance fraction of the Theil statistics. For hub height, on the other hand, there is evidence of bias though overall there is good agreement in the trends.

<table>
<thead>
<tr>
<th>Statistics on technology parameter fits;</th>
<th>Rotor Diameter</th>
<th>Rated Power</th>
<th>Hub Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-squared</td>
<td>0.9840</td>
<td>0.9689</td>
<td>0.9578</td>
</tr>
<tr>
<td>MAE over Mean</td>
<td>0.1063</td>
<td>0.2114</td>
<td>0.1803</td>
</tr>
<tr>
<td>Theil Bias Fraction (Um)</td>
<td>0.0087</td>
<td>0.0857</td>
<td>0.7133</td>
</tr>
</tbody>
</table>
Theil Unequal Variance Fraction (Us) 0.7423 0.6229 0.0547
Theil Unequal Covariance Fraction (Uc) 0.2490 0.2914 0.2319

Actual versus Simulated Rated Power [kW]

Rated Power [kW]


Rated Power (Actual)  Rated Power (Simulated)

Figure 6-XLIII: Actual versus simulated rated power
Less favorable statistics result for the turbine and project cost trends. The R-squared values are weak though the MAE/mean values are not still low. The Theil statistics show some evidence of bias and different trends. As discussed earlier, the turbine cost data shows a bump in data around 2005 due to a variety of factors. The cost reduction learning curve excludes these effects so we do not expect as good a fit as for the technology that has scaled relatively smoothly over time. There is a markup function in the model for turbine cost due to supply constraints.

**Table 6-11: Statistics on technology parameter fits;**

Statistics are for the full simulation set from 1980 through 2014 inclusive

<table>
<thead>
<tr>
<th></th>
<th>Turbine Cost</th>
<th>Balance of Station Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-squared</td>
<td>0.4932</td>
<td>0.0459</td>
</tr>
<tr>
<td>MAE over Mean</td>
<td>0.2063</td>
<td>0.2882</td>
</tr>
<tr>
<td>Theil Bias Fraction (Um)</td>
<td>0.5016</td>
<td>0.3526</td>
</tr>
<tr>
<td>Theil Unequal Variance Fraction (Us)</td>
<td>0.0822</td>
<td>0.1525</td>
</tr>
<tr>
<td>Theil Unequal Covariance Fraction (Uc)</td>
<td>0.4162</td>
<td>0.4949</td>
</tr>
</tbody>
</table>
Having shown the model is capable of capturing the basic market dynamics of feedback in technology learning and market growth and the influence of policy measures on market growth, the next simulation set expands from our four historical cases of interest to a large set of states that make-up the dominant wind energy generating nations and states today.
6.4.3.2 Largest wind markets in 2015
From the largest model, we select a subset including Denmark, France, Germany, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Turkey, and the United Kingdom, and in the USA: California, Illinois, Iowa, Kansas, Minnesota, Oklahoma, Oregon, Texas, and Washington. Excluded from the set are India, China, Brazil and Mexico for which there is a lack of quantitative information around electricity prices and policy value. Also excluded are Australia and Canada for similar reasons since there is significant heterogeneity in across the states and provinces. Further work will look at gathering data on these and other countries so that they can be included in the model. Below is a graph of the simulated market growth for wind energy. The following series of graphs shows the results compared to actual data for the modeled cases.

Figure 6-XLV: Installed capacity for three of the largest installed capacity cases: Germany, Spain and Texas. Note that dashed lines are actual capacity while smooth lines are simulated capacity.
As we can see in the above graph, the trends from the previous simulations including Denmark, California, Germany and Spain are still present. There is somewhat early development of both the California and Danish markets that taper off and Germany dominates the market growth through the early 2000s followed by Spain and then a number of other countries. Significantly, the market for wind energy in Texas starts to develop and experiences exponential growth. The model overshoots the actual growth by a significant amount that may be an issue with the implementation of electricity prices or policy incentives. A host of other states follow suits and we see the strong exponential growth in several countries after the early 2000s that led to the global boom in wind energy and also the “seller’s market” for wind turbines from the mid-2000s onward (Bolinger and Wiser, 2011).
Figure 6-XLVII: Installed capacity for other European nations in the simulation: Italy, Portugal, the United Kingdom, the Netherlands, Poland, Sweden and Turkey. Note that dashed lines are actual capacity while smooth lines are simulated capacity.
Figure 6-XLVIII: Installed capacity for other US states in the simulation: Illinois, Iowa, Oklahoma, Kansas, Minnesota, Oregon, and Washington. Note that dashed lines are actual capacity while smooth lines are simulated capacity.
The above graphs show that the simulation lags the actual data (i.e. there is a systematic presence of a phase shift between the two curves for most cases. There could be various factors accounting for this phase shift including industry build-up in anticipation of policy implementation, where developers recognize that legislation to promote wind development in a state is forthcoming so they begin prospecting in advance of the actual policies put in place. Another reason could be that the developer capacity builds-up much quicker than expected. This may be true especially for recent years where the global wind industry has grown substantially so that when new markets become attractive, developers can more quickly ramp up development in those regions. Future versions of the model may allow this by including the expectation of future development to drive prospecting ahead of policy implementation as well as allowing developer capacity to ramp up more quickly in particular regions as the overall industry grows. Below are the statistics from the analysis for the installed base:

<table>
<thead>
<tr>
<th>Country</th>
<th>DK</th>
<th>FR</th>
<th>DE</th>
<th>IT</th>
<th>NL</th>
<th>PL</th>
<th>PT</th>
<th>ES</th>
<th>SE</th>
<th>TR</th>
<th>GB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Cap. 2014 [GW]</td>
<td>5.1</td>
<td>10.4</td>
<td>44.9</td>
<td>8.9</td>
<td>3.4</td>
<td>5.1</td>
<td>5.1</td>
<td>23.0</td>
<td>6.0</td>
<td>4.7</td>
<td>13.6</td>
</tr>
<tr>
<td>Simulated Cap. 2014 [GW]</td>
<td>4.2</td>
<td>7.9</td>
<td>42.6</td>
<td>5.3</td>
<td>2.9</td>
<td>3.6</td>
<td>9.5</td>
<td>37.1</td>
<td>3.1</td>
<td>1.6</td>
<td>6.5</td>
</tr>
<tr>
<td>% Diff.</td>
<td>-17%</td>
<td>-24%</td>
<td>-5%</td>
<td>-40%</td>
<td>-15%</td>
<td>-29%</td>
<td>86%</td>
<td>61%</td>
<td>-48%</td>
<td>-66%</td>
<td>-52%</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.88</td>
<td>0.82</td>
<td>0.99</td>
<td>0.74</td>
<td>0.97</td>
<td>0.83</td>
<td>0.96</td>
<td>0.93</td>
<td>0.81</td>
<td>0.84</td>
<td>0.94</td>
</tr>
<tr>
<td>MAE/Mean</td>
<td>0.44</td>
<td>0.71</td>
<td>0.08</td>
<td>0.82</td>
<td>0.19</td>
<td>0.47</td>
<td>1.01</td>
<td>0.26</td>
<td>0.72</td>
<td>0.85</td>
<td>0.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State</th>
<th>CA</th>
<th>IL</th>
<th>IA</th>
<th>KS</th>
<th>MN</th>
<th>OK</th>
<th>OR</th>
<th>TX</th>
<th>WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Cap. 2014 [GW]</td>
<td>5.1</td>
<td>3.8</td>
<td>6.2</td>
<td>3.8</td>
<td>3.2</td>
<td>5.2</td>
<td>3.1</td>
<td>17.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Simulated Cap. 2014 [GW]</td>
<td>8.6</td>
<td>1.2</td>
<td>3.3</td>
<td>3.5</td>
<td>3.5</td>
<td>3.3</td>
<td>2.0</td>
<td>21.2</td>
<td>1.3</td>
</tr>
<tr>
<td>% Diff.</td>
<td>69%</td>
<td>-68%</td>
<td>-47%</td>
<td>-8%</td>
<td>9%</td>
<td>-37%</td>
<td>-35%</td>
<td>19%</td>
<td>-58%</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.89</td>
<td>0.58</td>
<td>0.74</td>
<td>0.90</td>
<td>0.60</td>
<td>0.89</td>
<td>0.60</td>
<td>0.89</td>
<td>0.54</td>
</tr>
<tr>
<td>MAE/Mean</td>
<td>0.32</td>
<td>0.92</td>
<td>0.79</td>
<td>0.52</td>
<td>0.70</td>
<td>0.62</td>
<td>0.85</td>
<td>0.29</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Here again the statistics reinforce that the model performs well for the four cases used in the previous simulation. Each of Denmark, Spain and Germany has high R-squared values and relatively low MAE/mean values. The additional states also tend to have high R-squared values for the cumulative installed base that is the main metric of interest for the model. The US states generally have lower R-squared and higher MAE/mean values than the four historic cases with the exception of Texas that,
along with California, was an early adopter of wind energy in the United States. This reinforces the fact that for cases where the growth is more recent, the model is not capturing the speed at which these markets start to develop wind and the lag that is present in the graphs. This is true as well for countries in Europe who are more recent entrants to the market. For all of these more recent cases, there is an under-prediction of the capacity in 2014 due to the growth lag. For certain European nations with significant offshore wind development, such as Denmark and the United Kingdom, the use of only a single technology type in the model (land-based turbines) and excluding the offshore wind resources of those nations also exacerbates the shortfall of simulated to actual installed capacity. Ignoring grid integration issues potentially also affects two of the few cases where there is an over prediction of capacity. Both Texas and Spain have experiences issues with grid integration of wind-generated electricity, as both of these systems are relatively isolated. Adding dynamics for grid integration would be necessary to accurately capture the growth dynamics for these cases and this will become true for other cases as well as wind energy becomes a more significant portion of the overall electricity generation portfolio in a given state.

In addition to evaluating the model on the resulting installed capacity for each nation, the global technology trends results in the table below show a good fit for the technology scaling and an adequate fit for the balance of station costs since the actual costs include the increase in costs in the early 2000's.

<table>
<thead>
<tr>
<th>Rotor Diameter</th>
<th>Rated Power</th>
<th>Hub Height</th>
<th>Turbine Costs</th>
<th>BOS Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-squared</td>
<td>0.985</td>
<td>0.961</td>
<td>0.499</td>
<td>0.046</td>
</tr>
<tr>
<td>MAE/Mean</td>
<td>0.102</td>
<td>0.210</td>
<td>0.183</td>
<td>0.206</td>
</tr>
</tbody>
</table>

The ability of the model to capture the growth of various global wind markets over time gives us the confidence to consider scenario analysis where the policy environment differs from reality. The next section will look at future growth and technology trends considering presence or lack of policy support for wind energy development.
6.5 Scenario and Policy Analysis
Having explored realistic scenarios using historical input data for several states with wind energy development since the 1980's, we now turn to analysis looking ahead and backwards in time to explore the impact of policy changes in both cases.

6.5.1 Historical Analysis
As discussed in the beginning of the chapter, there are many theories regarding the diffusion of innovations such as the previously mentioned market push, demand-pull, user innovation. All of these drivers of innovation have been present in the historical development of wind energy. As discussed in the prior chapters, various government programs have supported research and demonstration projects of large-scale turbines that pushed the knowledge boundaries for the technology forward and unearthed the significant complexity and uncertainty facing the technology in its operating environment. User innovation is another potential theory of explanation given again the amount of uncertainty involved in the operation of the technology and certainly the experience with the technology in the field has led to many suggestions that have led to innovation not only in the operations and maintenance of the machines but also upfront design as well. However, the main driver for innovation that is the focus of the current model is around the demand-pull. The data analysis and the dynamic simulations just presented embody the core feedback loop between the development of the market(s) for wind energy and technology learning.

Here, we pose the question about the potential path for the technology had policy support for key wind energy market countries been absent thus essentially removing the important adoption/innovation feedbacks present in the industry from the 1980s. To model this scenario then, we eliminate the policy support from that early period (from Denmark and California) to see where the technology might be today had those markets not taken off at the time that they did. We remove all the policy support prior to 1990 and set to zero. This analysis thus ignores influence of the Danish and Californian policy experience on the rest of the world, and Europe in particular. For the purposes here, though, we assume that influence irrelevant and countries proceed implementing the programs they had historically from the year 2000 onward. In addition, the rest of the world turbine demand is thus an external input, and the analysis excludes feedback between the dynamics of other countries who have adopted wind technology and the rest of the global demand. This case is not trying to develop any indisputable conclusions but it is seeking to demonstrate that the strong feedback between market pull and technology innovation for wind turbine technology has been critical to the overall development of wind energy to the present day. Below are a series of graphs of the installed capacity from the simulation once we remove the policy supports from the 1980s through 1990.
Figure 6-XLIX: Simulated capacity by state for the scenario where we remove historical policy incentives.
We notice of course that the early growth in California, Denmark, Germany and Spain is negligible even though after 1990, the policy incentives are in place to support wind energy development. Overall, market growth across the entire industry is lower than in the previous simulation that aligned relatively well to actual data. Most notably, Texas and Spain had showed very strong growth in the previous simulation, but here, even with the same incentives in place, the final installed capacity in both countries is less 5 GW. The technology is not being deployed as rapidly in as large quantities as it was when the early policies promoting energy were included in the model. The rest of the countries and states are not shown but the trends are the same and the final installed capacity for most countries is even less than in those in the figures above. The tables below provide summary statistics of the difference in final capacity between the historically accurate policy simulation and this simulation with early policy support removed.

Table 6-15: Final values for prior simulation compared to current simulation without historical policy support.

<table>
<thead>
<tr>
<th></th>
<th>DK</th>
<th>FR</th>
<th>DE</th>
<th>IT</th>
<th>NL</th>
<th>PL</th>
<th>PT</th>
<th>ES</th>
<th>SE</th>
<th>TR</th>
<th>GB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Policy Sim. Final Cap. [GW]</td>
<td>4.2</td>
<td>7.9</td>
<td>42.6</td>
<td>5.3</td>
<td>2.9</td>
<td>3.6</td>
<td>9.5</td>
<td>37.1</td>
<td>3.1</td>
<td>1.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Historic Removed Sim. Final Cap. [GW]</td>
<td>1.3</td>
<td>3.1</td>
<td>8.3</td>
<td>0.6</td>
<td>1.4</td>
<td>3.3</td>
<td>3.4</td>
<td>2.5</td>
<td>0.6</td>
<td>0.9</td>
<td>6.2</td>
</tr>
<tr>
<td>% Diff.</td>
<td>-69%</td>
<td>-61%</td>
<td>-80%</td>
<td>-89%</td>
<td>-52%</td>
<td>-8%</td>
<td>-64%</td>
<td>-93%</td>
<td>-81%</td>
<td>-45%</td>
<td>-5%</td>
</tr>
</tbody>
</table>

Table 6-16: Final values for prior simulation compared to current simulation without historical policy support.

<table>
<thead>
<tr>
<th></th>
<th>CA</th>
<th>IL</th>
<th>IA</th>
<th>KS</th>
<th>MN</th>
<th>OK</th>
<th>OR</th>
<th>TX</th>
<th>WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Policy Sim. Final Cap. [GW]</td>
<td>8.6</td>
<td>1.2</td>
<td>3.3</td>
<td>3.5</td>
<td>3.5</td>
<td>3.3</td>
<td>2.0</td>
<td>21.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Historic Removed Sim. Final Cap. [GW]</td>
<td>4.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.7</td>
<td>0.0</td>
<td>0.7</td>
<td>0.3</td>
<td>2.8</td>
<td>0.1</td>
</tr>
<tr>
<td>% Diff.</td>
<td>-52%</td>
<td>--</td>
<td>-97%</td>
<td>-81%</td>
<td>--</td>
<td>-80%</td>
<td>-86%</td>
<td>-87%</td>
<td>-91%</td>
</tr>
</tbody>
</table>

A key aspect of this scenario is that we do not adjust the Feed-in-tariff policy incentives upward to account for the higher costs of wind energy at the time of implementation. Without the early technology development and rapid initial decrease in costs due to industry experience, technology remains unscaled and costs remain high. The below graphs demonstrate the difference in technology learning from this scenario to the previous simulation.
Simulated Turbine Rated Power for Different Scenarios

Figure 6-L: Simulated turbine rated power for the previous simulation using actual policies and this scenario with policies from Germany and California through the 1990s removed.

Simulated Turbine Cost for Different Scenarios

Figure 6-LI: Simulated turbine cost for the previous simulation using actual policies and this scenario with policies from Germany and California through the 1990s removed.
For both technology-learning variables of turbine rated power and cost, the key difference between this restricted policy scenario and the simulation accounting for the entire history of wind energy policy support is that there is a “learning lag.” The learning that would have taken place through the 1990s is essentially absent and though costs catch up and the turbine size mostly catches up with the fast growth of the market, there is not nearly as overall wind energy deployment. Essentially turning off the feedback of early learning in the industry obstructs market growth from the early 1900s to present day. This illustrates the importance of the early policies in creating the demand pull to kick-start the technology dynamics feedback loop, and the simulation provides evidence of the lasting effect that this has had on the overall development of the industry and innovation of wind energy technology. Having looked at the past, we now turn to the future.

6.5.2 Forward-Looking Analysis

Many have argued that wind energy technology has arrived, should no longer need support, and should compete with other energy technology in an incentive-free policy environment. On the other hand, there are many who suggest that wind energy still needs continued support to become competitive and achieve cost parity on an unsubsidized basis with fossil-fuel electricity generation technologies. Here, we look at two future policy scenarios for wind energy: 1) with all current policies maintained, and 2) with all current policies removed. There are several caveats to this analysis. Firstly, the model excludes the grid integration and NIMBY dynamics. This means that issues associated with higher levels of wind energy in the system, including increased operational costs, potential need for additional transmission build-out and storage, and even stability concerns, are not captured. All of these issues can create direct resistance from utilities to further wind investment or indirect resistance through increasing cost of energy for each additional megawatt of wind capacity. Similar to what we saw in the actual data form Spain and Texas, grid integration issues can stall wind development either for temporary periods or over the long-term. Innovation can circumvent these issues as well and to fully capture the grid integration dynamics a number of additions would be necessary to this model. If included, we would expect that grid integration issues would limit wind energy development past a certain point of generation in an electric grid system. Wind energy development needs greater policy supports in such cases in order to push power system operators to accept more wind energy into those systems. Innovation tempers that need over the long-term.

In addition, the model excludes the offshore markets. Offshore markets have grown substantially for certain European nations – most prominently Denmark and the United Kingdom. Europe is generally much more population dense and there is less available land area and less favorable land area (due to NIMBY concerns) for development. Offshore wind energy provides an avenue for expanding the potential wind energy generation in such countries. Offshore wind, however, is unique since the economies of scale become much more significant since the balance of system costs and operational expenditures are a much larger portion of overall cost of energy (Mone et al., 2015). Offshore technology has quickly grown into its own market segment with much larger turbines. In addition, countries often use separate mechanisms and policies to promote offshore versus land-based wind energy development. Thus, offshore again would need to be its own sub-model. If included, offshore
wind would expand the resource in a many states and countries and would likely need significant policy to support its development.

Finally, the rest of world turbine demand remains constant after the current year such that we are ignoring the policy impacts from those states. In actuality, the global potential of the wind industry is huge and there are many states that are just beginning to adopt wind energy. There is a huge amount of uncertainty and future work will look at including more states. For now, given the size of the global market, this is an oversimplification but is necessary to keep the analysis tractable.

In the simulation, policy removal does not have significant affects where there is already a growing wind industry, high electricity prices and strong wind resources. This includes all of the European nations and a few of the US states: Texas, Kansas and Oklahoma. Electricity prices are higher in Europe than in the US, so even without the policy support, wind energy remains attractive in those countries. It is important to note, that there are dynamics not included that would limit development of wind under the no-policy scenario in these nations and states. Many of these nations and states have a high percentage of wind energy generation coming from wind energy so grid integration issues are increasingly important. In addition, land congestion limits land-based development in European nations in particular, and we are not modeling offshore technology. Finally, there is the overall capacity for new development of electricity generation as a whole. The model does not include queuing and limits on overall development per year that are important to include and will be part of future work.

In the US, in contrast, most states do not develop wind energy once the policy is removed after 2015. This includes most states except the windiest states in the country (based on this data set that is Texas, Kansas and Oklahoma). For those countries that don’t have this combination of an semi-established industry, high electricity prices and strong wind resources, the removal of policies chokes off further development. The tables below show the final capacity for each nation and state in the simulation along with the differences between simulations. The graphs that follow show the difference in growth for those nations that experienced little to no growth in the case where we remove policy support in 2015.

<table>
<thead>
<tr>
<th>No Policy Cap.</th>
<th>With Policy Cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>14.0</td>
</tr>
<tr>
<td>IL</td>
<td>1.5</td>
</tr>
<tr>
<td>IA</td>
<td>3.9</td>
</tr>
<tr>
<td>KS</td>
<td>24.9</td>
</tr>
<tr>
<td>MN</td>
<td>4.0</td>
</tr>
<tr>
<td>OK</td>
<td>21.4</td>
</tr>
<tr>
<td>OR</td>
<td>8.1</td>
</tr>
<tr>
<td>TX</td>
<td>91.9</td>
</tr>
<tr>
<td>WA</td>
<td>2.8</td>
</tr>
<tr>
<td>% Diff.</td>
<td>-254%</td>
</tr>
<tr>
<td></td>
<td>-368%</td>
</tr>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>-213%</td>
</tr>
<tr>
<td></td>
<td>-517%</td>
</tr>
</tbody>
</table>

Table 6-17: Simulated data for policy / no policy cases and percent differences for US states.

Table 6-18: Simulated data for policy / no policy cases and percent differences for international states.
<table>
<thead>
<tr>
<th>Cap. [GW]</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Diff.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Simulation to 2030 of Installed Wind Energy Capacity with Policies at Current Levels (solid lines) and Removed after 2015 (dashed lines)

Figure 6-IU: Simulated installed capacity in the two policy scenarios.
The above graphics show the installed capacity for the different states included in the study where policy supports are at current levels and a second case where we remove them completely. This provides bookends for the potential for market growth and technology innovation looking forward.

Looking at the results, as mentioned before, removing the policy support with current levels of wind deployment chokes off the markets for most US states for the period from 2015 to 2030. Installed capacity stays constant for California, Illinois, Iowa and Minnesota. Wind development actually picks up towards the end of the period for Oregon and Washington. This indicates that global growth trends have pushed down the breakeven cost for those nations in the “no-policy” scenario to a level at which wind is naturally competitive in these windy states.

Technology learning indeed takes place and the differences between the resulting technology trends are small but present. Rotor diameter sizes surpass 100 m and beyond and rated power surpasses 3000 kW and more. This is consistent with current wind turbine technology trajectories. Costs are reducing continuously as well.

<table>
<thead>
<tr>
<th>Rotor Diameter (m)</th>
<th>Rated Power (kW)</th>
<th>Hub Height (m)</th>
<th>Turbine Cost (2014 USD / kW)</th>
<th>Balance of Station Costs (2014 USD / kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Policy</td>
<td>118</td>
<td>3089</td>
<td>136</td>
<td>864</td>
</tr>
<tr>
<td>With Policy</td>
<td>120</td>
<td>3153</td>
<td>137</td>
<td>861</td>
</tr>
<tr>
<td>% Difference</td>
<td>-1.0%</td>
<td>-2.0%</td>
<td>-0.9%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Given the significant global market for wind turbines even if certain markets are choked off, the technology dynamics will be present and the overall technology learning for scaling and cost will continue.

We note here once again that the current model does not address offshore wind technology and markets. The technology for these markets, which increasingly dominate new capacity in Europe, have their own technology trajectory and cost curves which would be an important addition to future work on this area. In addition to this, as mentioned before, we are neglecting in particular grid integration. As utilities add more wind energy to the grid, continuous unsubsidized growth will have to address the rising costs of integrating more and more of the variable resource into the system operation. Future work will also consider this important feedback loop affecting wind energy development.
6.6 Summary and Conclusions

This work explored the dynamics of diffusion and innovation around an inherently complex technology: wind energy. In particular, the study looked at how both the technology and markets for the technology have evolved since the oil crisis of the 1970s catalyzed their development. Looking at the available data on the development of the industry, it is readily apparent that there has been a relatively smooth exponential growth of global wind capacity while at the same time the growth of individual local markets has been extremely volatile. This is primarily due to the start-and-stop of government policy support for wind in the form of various incentive programs. One country or state may be the dominant market for wind for a period of a number of years only then to remove policy support altogether.

Figures 2 and 3 tell the story well by showing the nice smooth growth curve for global installations over time and an extremely abrupt and choppy graph of the percentage of installations coming from a given country at a given time. Even though the local markets have been volatile, wind energy technology and cost learning curves have shown relatively continuous improvements over time. Thus, while local markets and policies affect the installed capacity in their jurisdictions, wind energy technology overall has steadily improved performance and reduced costs over the years.

This interplay of a regional markets, global markets, and technology learning are the core of a system dynamics for “technology dynamics” which embody the idea that “demand pull” type of policies promote technology innovation and this in turn increases the attractiveness and the likely adoption of the technology. There are many other important dynamics to wind energy development and this model also included key feedback loops around resource use (in this case wind resource / land available in a region) and the supply chain for wind project development and turbine manufacturing. The model required large amount of data as input for each of these sub-models including wind resource data, available land area for different regions, and electricity prices and policy incentives for each region or state of interest. On top of this, we calibrated model parameters for technology scaling and cost learning based on historical data. We also collected data for comparison to model outputs of turbines installed and overall electricity generation capacity from wind by state. Data for many states were very sparse and ultimately limited modeling of some cases of interest (such as China, India and Brazil) while at the same time there was a wealth of data available for US and European states.

Once formulated, the first analysis was a historic analysis of four historic cases of interest: California, Denmark, Germany and Spain. These countries and states were the earliest adopters of large-scale wind energy generation and we calibrated the sub-model for developer capacity for good agreement with these cases. The final model showed a relatively good fit between the actual and simulation data for both the capacity installed for each country and the technology trends over time. Once completed, we modeled a larger set of cases, those most prominent in the wind industry today, and the overall statistics for the analysis agreed well with actual data in terms of the general dynamics.

Having completed this, additional scenarios were investigated including a backwards looking case of where the industry would likely be without the early action of California and Germany to promote wind adoption (the core technology dynamics) and a second case that looks at the necessity of policy support
to continue to grow the industry and improve the technology in the future. The former found that removing the early policy support from California and Germany thwarted market development in recent years since the technology performance lagged behind. The costs remained high and the technology did not scale as quickly, so that even though the technology learning was beginning to catch up by the end of the simulation (year 2015), the overall capacity for the different states was significantly lower. In the second case, we examined the question regarding necessity of continued support. With this model, we found that certain markets would continue to develop strong wind energy portfolios even without incentive programs while the scenario would block others, those without significant development capacity already existing, from further development. The technology learning would continue since the large strong markets would continue to support further technology development. There are many caveats to this result, however, since the model does not consider NIMBY issues, offshore markets and grid integration.

These areas represent two key topics for future research. Grid integration has been its own topic of research for some time, and there is significant work around the costs that wind energy and other variable resources impose in the grid, as they become a larger percentage of generation. The dynamics of grid integration are critical in particular to looking at future policy scenarios for wind energy. In addition, the model does not consider dynamic land constraint and NIMBY issues. Population density and NIMBY issues drastically limit further development of land-based wind projects in many places, such as Europe. Offshore wind plants are a solution to NIMBY limitations on wind energy development. These can have their own NIMBY issues, but they tend to be less significant and several European nations are aggressively pursuing offshore wind energy. However, the technology is much more costly and work looking at the future of wind energy should consider this as its own model within an overall wind energy deployment model.
6.7 References


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6.8 Appendix B: Model Source Code

This appendix contains the full source code of the VENSIM® system dynamics model for the both sets of cases including the four core states for analysis and the larger set used in the second simulation set.

6.8.1 Full model equations

The following list provides the variables, their equations, units and descriptions for the full model set except for those variables that are exogenous inputs to the model developed from the Python script. Those equations follow in the subsequent sections.

\[
\text{project prospecting start rate}[\text{States}] = \max(0, \text{MIN(}\text{developer project capacity}[\text{States}]\times \text{prospecting sites per developer project, total profitable undeveloped projects}[\text{States}] \times \text{per year}))
\]

Units: projects/Year

Description: Prospecting start rate is based on the minimum of either developer project capacity or the total profitable projects.

\[
\text{desired capacity}[\text{States}] = \max(\text{Initial development project capacity, total profitable projects}[\text{States}] / \text{average project lifetime})
\]

Units: projects/Year

Description: Desired capacity is the maximum between the initial capacity when no wind market is present and the steady-state development capacity of total profitable projects in the region over the average project lifetime.

\[
\text{total profitable projects}[\text{States}] = \text{total potential land}[\text{States}] \times \text{percent profitable land out of total}[\text{States}] \times \text{fraction of land available for wind development}[\text{States}] / \text{land use per project}
\]

Units: projects

Description: Total profitable projects based on current technology is the total land area of the region multiplied by the percent of the land that is profitable for wind development under current conditions over the amount of land used per project.

\[
\text{project decommission rate}[\text{States}] = \text{DELAY FIXED(Projects installed base}[\text{States}], \text{average project lifetime}, 0)
\]

Units: projects / Year

Description: Number of projects decommissioned each year is the total projects in the installed base multiplied by the percent decommissioned delayed by the average project lifetime.
Watt per kW = 1000
Units: dimensionless
Description: Watt to kW converter.

\[ \pi = 3.14159 \]
Units: dimensionless
Description: Mathematical constant \( \pi \).

turbine development start rate[States] = average project capacity * project development start rate[States] / (Simulated marginal turbine rated power * GW per kW)
Units: turbines / Year
Description: The simulated turbine development rate is the average turbines by project under prospect multiplied by the project development start rate.

Expected Generation from Construction Projects[States] = \( \text{INTEG} \) (generation construction start rate[States] - generation construction finish rate[States], 0)
Units: kW*hrs
Description: Expected generation from construction projects.

generation construction finish rate[States] = \( \max(0, \text{avg generation } UC[States] * \text{project construction finish rate[States]}) \)
Units: kW * hrs / Year
Description: Generation construction finish rate is the average generation under construction multiplied by the turbine construction finish rate.

generation development start rate[States] = expected annual energy[States] * turbine development start rate[States]
Units: kW * hrs / Year
Description: Generation development start rate is the expected annual energy for turbine coming onto the market multiplied by the expected number of turbines in development.

average generation IB[States] = \( \text{ZIDZ} \) (Generation Installed Base[States], Projects Installed Base[States])
Units: kW * hrs / project
Description: Average generation of the installed base is the generation of the installed base over the number of projects (by state).

$$\text{average capacity IB[States]} = \text{ZIDZ(Simulated Capacity installed base[States],Projects Installed Base[States])}$$

Units: GW / project

Description: Average capacity installed base is the capacity by state in the installed base over the number of projects by state in the installed base.

$$\text{average turbine lifetime} = 20$$

Units: Years

Description: Average turbine lifetime based on NREL Cost and Scaling Model and NREL Wind Cost of Energy Review (Fingersh et al 2006, Mone et al 2015).

$$\text{capacity project start rate[States]} = \max(0, \text{project prospecting start rate[States]} \times \text{average project capacity})$$

Units: GW / Year

Description: Co-flow for capacity project start rate is the project start rate for projects by the average project capacity.

$$\text{Simulated capacity construction finish rate[States]} = \max(0, \text{avg capacity UC[States]} \times \text{project construction finish rate[States]}$$

Units: GW / Year

Description: Capacity construction finish rate is the average capacity per project under construction multiplied by the project construction finish rate.

$$\text{Expected Capacity from Construction Projects[States]} = \text{INTEG (capacity construction start rate[States]-Simulated capacity construction finish rate[States],0)}$$

Units: GW

Description: Expected capacity from development projects.

$$\text{average project capacity} = \text{Historical average project capacity(Time)}$$

Units: GW / projects

Description: Average project capacity in GW. 50 MW is typical though projects can range in size from 1 MW to 2 or more GW. Statistics over time give an average value of 40 MW since
there are a lot more smaller projects than big projects. This has fluctuated over time so the function is based on a lookup table.

Historical average project capacity([[(1980,0) - (2010,0.06)],(1980,0.003),(1983,0.003),(1985,0.007),(1990,0.03),(1995,0.038),(2000,0.04),(2010,0.04)])

Units: GW / project
Description: Lookup function for average project capacity factor over time.

Historical IB[States]= Historical Capacity Installed Base[States](Time)

Units: GW
Description: Historical capacity installed base by state to export to results file.

Historical NB[States]= Historical Capacity Construction Rate[States](Time)

Units: GW/Year
Description: Historical new capacity installed base by state to export to results file.

total turbine construction start rate= SUM(turbine construction start rate[States!]) + rest of world turbine construction start rate

Units: turbines / Year
Description: Total turbine construction start rate including states under analysis and the rest of world.

Turbine production= MIN(Turbine Backlog* per year,MIN(desired turbine production,turbine industry turbine capacity))

Units: turbines / Year
Description: Turbine production each year is the minimum between desired turbine production, turbine industry production capacity and turbine backlog (so that the turbine backlog cannot go negative).

rest of world turbine construction start rate= Historical rest of world turbine construction start rate(Time)

Units: turbines / Year
Description: Construction rate for turbines for states outside of the current simulation set.

investment subsidy[States]= Historical investment subsidy[States](Time)

Units: dimensionless
Description: Investment subsidy per unit power produced from policy support by state.

feed in tariff rate[States] =

Historical feed in tariff rate[States](Time)

Units: $/(kW*hrs)

Description: FIT incentive per unit energy produced from policy support by state.

delivery delay =

\[ \max(0, \text{ZIDZ}(\text{Turbine Backlog}, \text{Turbine production})) \]

Units: Years

Description: Delivery delay based on current backlog and production rate by taking total backlog over production rate.

rec price[States] = Historical rec price[States](Time)

Units: $/(kW*hrs)

Description: REC incentive per unit energy produced from policy support by state.

production incentive[States] = Historical production incentive[States](Time)

Units: $/(kW*hrs)

Description: Production incentive per unit energy produced from policy support by state.

Turbine Backlog = \text{INTEG} (\text{Turbine orders received} - \text{Turbine production}, 0)

Units: turbines

Description: Turbine backlog due to excess orders relative to turbine industry production capacity where inflows are new orders received and outflows are annual turbine production.

project construction finish rate[States] = \text{ZIDZ}\left( \max(\text{Projects in Construction}[\text{States}], 0), \max(\text{delivery delay}, \text{average construction time}) \right)

Units: projects / Year

Description: Projects finishing construction is the total projects under construction over the average construction time for projects.

electricity price[States] = \text{Historical Electricity Prices}[\text{States}](\text{Time})

Units: $/(kW*hr)
Description: Wholesale electricity price by state in a given year.

backlog effect on turbine price mark([0,0]-(100000,1]),(0,0),(100,0.1),(500,0.25),(1000,0.3),(10000,0.5),(100000,1))

Units: dimensionless

Description: Look up table for the effect of the size of the wind turbine backlog on the prices seen by the developer. (Look-up table based on a 50% mark-up at 10000 turbines (GE 2008, Bolinger and Wiser, 2011).

initial hub height= 15

Units: meters

Description: Initial hub height of early 1980's wind turbines.

rotor exponent= 2

Units: dimensionless

Description: Rated power scaling exponent based on rotor diameter based on available data.

hub height learning rate= 0.22

Units: dimensionless

Description: Learning rate for turbine hub height based on analysis of available data.

initial power rating= 22

Units: kW / turbine

Description: Initial power rating for early Danish wind turbines of 22 kW

exponent hub height= \( \ln(1 + \text{hub height learning rate}) / \ln(2) \)

Units: dimensionless

Description: Exponent for hub height learning rate based on standard formulation.

marginal bos costs= Simulated BOS Costs per unit power*Simulated marginal turbine rated power

Units: $/turbine

Description: Marginal BOS costs taking the BOS costs per unit power multiplied by the marginal turbine power rating.
marginal turbine cost = Simulated marginal turbine rated power * Simulated turbine capital cost * (1 + markup on turbine cost due to supply)

Units: $/turbine

Description: Marginal turbine costs taking the turbine costs per unit power multiplied by the marginal turbine power rating.

hub height wind speed max[States] = max wind speed[States] * (Simulated marginal hub height/reference hub height)^wind shear exponent

Units: meters / second

Description: Standard hub height wind speed equation: marginal wind speed at hub height based on hub height relative to reference height scaled by wind shear exponent.

Potential annual energy max[States] = SUM (Cumulative Energy by Wind Speed max[States, windspeed])

Units: kW*hrs / turbine

Description: Total annual wind energy by summing energy for each wind speed bin.

Rayleigh wind speed probability max[States, windspeed] = ZIDZ(wind speed[windspeed], (hub height wind speed max[States]/SQRT(3.14157/2))^2)*exp(-(ZIDZ(wind speed[windspeed]^2, 2*(hub height wind speed max[States]/SQRT(3.14157/2))^2)))

Units: dimensionless

Description: Rayleigh probability by wind speed for site wind resource uses hub height mean wind speed as mean.

expected annual energy max[States] = Potential annual energy max[States] *(1-losses) * Simulated turbine availability

Units: kW * hr / turbine

Description: Total annual energy production by state for the marginal project per turbine by state after losses and turbine downtime are removed.

GW per kW = 1.00E-06

Units: dimensionless

Description: converter from kW units of turbine to GW units for generation and capacity

exponent availability = ln(1-turbine availability learning rate)/ln(2)

Units: dimensionless
Description: Exponent for availability learning rate based on standard formulation.

ratio of total to initial turbine installation experience = Simulated total turbine installation experience/initial turbine installation experience

Units: dimensionless

Description: Total installation experience over the initial installation experience.

initial turbine availability = 0.85

Units: dimensionless

Description: Initial turbine availability in the early 1980's

turbine availability learning rate = 0.02

Units: dimensionless

Description: Learning rate for turbine availability based on analysis of available data.

turbine project failure rate[States] = max(0, project development failure rate[States] * average turbines UD[States])

Units: turbines / Year

Description: Co-flow for turbines released each year because they are deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses).

Projects Installed Base[States] = INTEG (project construction finish rate[States] - project decommission rate[States], 0)

Units: projects

Description: Installed projects with inflows from projects that have finished construction as well as those that have gone through repowering and outflows for those going into repowering and those that are decommissioned.

avg LU UC[States] = ZIDZ(Expected land Use from Construction Projects[States], Projects in Construction[States])

Units: meters * meters / project

Description: Average land under construction is the total land under construction divided by the number of turbines under construction.

land construction start rate[States] = max(0, avg LU UD[States] * project construction start rate[States])

Units: meters * meters / Year
Description: Land construction start rate is the average land use per turbine under development multiplied by the number of turbines going into construction each year.

\[
\text{land decommission rate}[\text{States}] = \max(0, \text{avg \ LU IB}[\text{States}] \times \text{project decommission rate}[\text{States}])
\]

Units: meters * meters / Year

Description: Land that is decommissioned each year derived from the average land use of the installed base by the number of turbines being decommissioned each year.

\[
\text{generation construction start rate}[\text{States}] = \max(0, \text{avg generation UD}[\text{States}] \times \text{project construction start rate}[\text{States}])
\]

Units: kW * hrs / Year

Description: Generation construction start rate is the average generation under development multiplied by the simulated turbine construction start rate.

\[
\text{generation development failure rate}[\text{States}] = \text{avg generation UD}[\text{States}] \times \text{project development failure rate}[\text{States}]
\]

Units: kW * hrs / Year

Description: Co-flow for generation released each year because they are deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses).

\[
\text{avg generation UC}[\text{States}] = \text{ZIDZ(Expected Generation from Construction Projects}[\text{States}], \text{Projects in Construction}[\text{States}])
\]

Units: kW*hrs/project

Description: Average generation under construction is the expected generation under construction over the turbines under construction.

\[
\text{capacity development failure rate}[\text{States}] = \text{avg capacity UD}[\text{States}] \times \text{project development failure rate}[\text{States}]
\]

Units: GW / Year

Description: Co-flow for capacity released each year because they are deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses).

\[
\text{land construction finish rate}[\text{States}] = \max(0, \text{avg LU UC}[\text{States}] \times \text{project construction finish rate}[\text{States}])
\]

Units: meters * meters / Year
Land that is transitioning to the installed base is the average land per turbine under construction multiplied by the number of turbines whose construction is finished each year.

\[ \text{land use project fail rate}_{[\text{States}]} = \max(0, \text{avg LU UD}[\text{States}] \times \text{project development failure rate}_{[\text{States}]}) \]

Units: meters \* meters / Year

Description: Co-flow for land use under development released each year because it is deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses).

\[ \text{capacity prospecting failure rate}_{[\text{States}]} = \text{project prospecting failure rate}_{[\text{States}] \times \text{avg capacity UP}[\text{States}]} \]

Units: GW / Year

Description: Co-flow for capacity released each year because it is deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses).

\[ \text{land use prospecting failure rate}_{[\text{States}]} = \max(0, \text{avg LU UP}[\text{States}] \times \text{project prospecting failure rate}_{[\text{States}]}) \]

Units: meters \* meters / Year

Description: Co-flow for land use under prospect released each year because it is deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses).

\[ \text{project development failure rate}_{[\text{States}]} = \max(0, \text{Projects in Development}[\text{States}] \times \text{percent projects failing}[\text{States}] / \text{permitting and PPA decision time}) \]

Units: projects / Year

Description: Projects released each year because they are deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses). It is a multiplier of the current projects in development by percent of those projects that fail over the average time it takes for project permitting and signing contracts.

\[ \text{permit failure rate lookup}([[(1975,0)-(2010,0.8)],(1975,0),(1985,0),(2000,0.75),(2010,0.75)]) \]

Units: dimensionless

Description: The permit failure rate is 3 out of 4 projects (Splestosser interview 2016). Projects can fail in either early stage development (from environmental or other permit issues, significant NIMBY issues that surface or failing to secure a power purchase agreement (PPA). It is assumed that failure rates for projects in the 1970’s and early 1980’s would have had less of a failure rate due to the market urgency, lack of NIMBYism and generally easier environment for
permitting of the time period. Future model: NIMBY issues should come into the project pipeline through affecting this variable.

\[ \text{project construction start rate}[\text{States}] = \max(0, (1 - \text{percent projects failing}[\text{States}]) \times \text{Projects in Development}[\text{States}] / \text{permitting and PPA decision time}) \]

Units: projects/Year

Description: Project construction start rate is the percent of projects making it through development (1 - percent of those failing) multiplied by the total projects in development over the average time for project development. This is limited by the number of projects in development deemed profitable (which can change in the time projects move into development due to changing market dynamics.)

\[ \text{project development start rate}[\text{States}] = \max(0, \min(\text{developer project capacity}[\text{States}], \text{Projects in Prospect}[\text{States}] \times \text{Percent projects deemed developable}[\text{States}])) \]

Units: projects/Year

Description: Project development start rate is the overall projects in development multiplied the percent deemed developable each year.

\[ \text{Percent projects deemed developable}[\text{States}] = \begin{cases} 
  \text{IF THEN ELSE} & \text{total profitable prospective projects}[\text{States}] > 0, 0.8, 0 \\
  1 / \text{Year} & \text{otherwise} 
\end{cases} \]

Units: 1/Year

Description: Percent projects deemed developable has been estimated at 1 in 5 or 80% (Splestosser interview 2016). 1 in 5 projects will not be considered beyond prospecting because 20% of land lease rights were not obtained or meteorological information is unfavorable. If market conditions change and all projects are unprofitable, this percentage of success will drop to 0.

\[ \text{permitting and PPA decision time} = \text{permitting and PPA decision time lookup}(\text{Time} \times \text{per year}) \]

Units: Years

Description: Project development time is based on a lookup table that changes with time.

\[ \text{project prospecting failure rate}[\text{States}] = \max(0, (1 - \text{Percent projects deemed developable}[\text{States}]) \times \text{Projects in Prospect}[\text{States}]) \]

Units: projects/Year

Description: Projects deemed undevelopable released each year because it is deemed undevelopable (either due to fluctuating market conditions or particular project weaknesses)
percent profitable land in prospect and development[States] = max(0, percent profitable land out of total[States] - percent profitable land undeveloped[States] - percent land already built[States])

   Units: dimensionless
   Description: Percent profitable land in prospect and development is the percent profitable land out of total minus percent already built and that undeveloped.

Turbine orders received = total turbine construction start rate

   Units: turbines / Year
   Description: Turbine orders received is the total capacity construction start rate divided by the average marginal turbine power rating across all states.

percent land already built[States] = ZIDZ(Expected land Use from Construction Projects[States] + Simulated Land Use Installed Base[States], total potential land[States])

   Units: dimensionless
   Description: Percent land already built is the percent of land under construction + installed base + decommissioned land over the total potential land.

Expected land Use from Construction Projects[States] = INTEG(land construction start rate[States] - land construction finish rate[States], 0)

   Units: meters * meters
   Description: Land under construction for wind projects.

time to average turbine orders = 0.25

   Units: Years
   Description: Delay in averaging turbine order expectations.

desired turbine production = Average Expected Turbine Orders + backlog correction

   Units: turbines / Year
   Description: Desired turbine production is the sum of turbine orders across all the states and additional production needed to satisfy backlog.

turbine construction start rate[States] = max(0, average turbines UD[States] * project construction start rate[States])

   Units: turbines / Year
Description: Turbine construction start rate is the average turbines per project under development multiplied by the project construction start rate.

time allowed to correct backlog = 0.5

Units: Years

Description: Average time allowed to correct any existing backlog.

capacity construction start rate[States] = \max(0, \text{project construction start rate[States]} \times \text{avg capacity UD[States]})

Units: GW/Year

Description: Capacity construction start rate is the average capacity per project under development multiplied by the project construction start rate.

avg capacity UC[States] = \text{ZIDZ(Expected Capacity from Construction Projects[States], Projects in Construction[States])}

Units: GW/project

Description: Average capacity per project under construction is the total capacity under construction divided by the projects in construction.

backlog correction = Turbine Backlog/time allowed to correct backlog

Units: turbines/Year

Description: Backlog correction required in a year is the turbine backlog divided by the time allowed for backlog.

Initial developer project capacity = 15

Units: projects/Year

Description: Initial developer capacity based on early project development rates in California.

maximum percent growth rate = 0.4

Units: 1/Year

Description: Limitation on growth rate for developers by year based on maximum growth in available data.

area per turbine = (Simulated marginal rotor diameter \times \text{Simulated marginal rotor diameter}) \times \text{spacing per turbine}

Units: meters \times meters / turbine

494
Description: Area per turbine is the spacing between turbines (7 x 7 or 5 x 5) multiplied by rotor diameter in each direction.

average construction time= 1

Units: Years

Description: Average construction time (Splestosser interview 2016).

average project lifetime= 30

Units: Years

Description: Average project lifetime is estimated at 30 years. Typical project financing is 20 years but projects tend to last 25 years or more (Fingersh, Hand and Laxon, 2006).

per year= 1

Units: 1 / Year

Description: per year for delay functions and in comparison of absolute to per year quantities for capping growth rates

Projects in Construction[States]= INTEG (project construction start rate[States]-project construction finish rate[States],0)

Units: projects

Description: These projects are actively under development: initial resource analysis was favorable and there are efforts to permit the site, negotiate a power purchase agreement, and a turbine supply agreement.

average turbines UC[States]= ZIDZ(Expected Turbines from Construction Projects[States],Projects in Construction[States])

Units: turbines / projects

Description: Average turbines under construction is the expected turbines from construction projects divided by the projects in construction.

average turbines UD[States]= ZIDZ(Expected Turbines from Development Projects[States],Projects in Development[States])

Units: turbines / project

Description: Average turbines under development is the total turbines under development divided by the projects in development.
Expected Turbines from Construction Projects[States] = INTEG (turbine construction start rate[States] - Simulated turbine construction finish rate[States], 0)

Units: turbines

Description: Expected turbines from construction projects.

Projects in Prospect[States] = INTEG (project prospecting start rate[States] - project development start rate[States] - project prospecting failure rate[States], 0)

Units: projects

Description: These are all the wind projects under consideration by developers in different regions; where met tower data is currently being collected and analyzed. There are inflows of new projects being prospected and outflows for those that transition to development or those that have unfavorable results from prospecting.

Simulated turbine construction finish rate[States] = max(0, average turbines UC[States] * project construction finish rate[States])

Units: turbines / Year

Description: Turbine construction start rate is the average turbines under construction multiplied by the project construction finish rate.

Projects in Development[States] = INTEG (project development start rate[States] - project development failure rate[States] - project construction start rate[States], 0)

Units: projects

Description: Projects in development include inflows from new projects starting development and outflows for projects that failed in development and those that were successful.

Prospecting sites per developer project = 5

Units: dimensionless

Description: Ratio of number of sites that get prospect to those that actually get built (5:1 based on developer interviews. Over time has been reduced from 10:1 from better practices and is as low as 3:1 from optimistic estimates) (Splestosser interview 2016).

Average turbines IB[States] = ZIDZ(Simulated Turbine Installed Base[States], Projects Installed Base[States])

Units: turbines / projects
Description: Average turbines installed base is the total turbine installed base divided by the total projects installed base.

Projects Decommissioned[States]= INTEG (project decommission rate[States],0)

Units: projects

Description: Projects that are decommissioned due to poor performance - typically older plants that are operating beyond their initial project lifetime.

Rayleigh wind speed probability[States,windspeed]= ZIDZ(wind speed[windspeed],(hub height wind speed[States]/SQRT(pi/2))^2)*exp(-ZIDZ(wind speed[windspeed]^2,2*(hub height wind speed[States]/SQRT(pi/2))^2)))

Units: dimensionless

Description: Rayleigh probability by wind speed for site wind resource uses hub height mean wind speed as mean.

Power at wind speed[windspeed]= IF THEN ELSE(0.5*air density*Rotor Swept Area*(wind speed[windspeed]^3)*power coefficient/Watt per kW > Simulated marginal turbine rated power, Simulated marginal turbine rated power, 0.5*air density*Rotor Swept Area*(wind speed[windspeed]^3)*power coefficient/Watt per kW)

Units: kW/turbine

Description: Power output for the turbine at a particular wind speed based on standard turbine power formula.

annual maintenance cost[States]= Simulated OPEX per unit energy*expected annual energy[States]

Units: $/ (turbine)

Description: Total annual maintenance costs from maintenance costs per unit energy from the expected annual energy.

Rotor Swept Area= pi*(Simulated marginal rotor diameter/2)^2

Units: meters * meters

Description: Estimated rotor swept area from standard area equation (ignores coning and prebend).

Generation Installed Base[States]= INTEG (generation construction finish rate[States]-generation decommission rate[States],0)

Units: kW * hrs
Description: Generation installed base.

Expected Generation from Development Projects[States] = INTEG (generation development start rate[States]-generation construction start rate[States]-generation development failure rate[States],0)

Units: kW * hrs

Description: Expected generation from development projects.

Expected Turbines from Development Projects[States] = INTEG (turbine development start rate[States]-turbine construction start rate[States]-turbine project failure rate[States],0)

Units: turbines

Description: Expected turbines from development projects.

capacity decommission rate[States] = average capacity IB[States]*project decommission rate[States]

Units: GW / Year

Description: Capacity decommission rate by state.

generation decommission rate[States] = project decommission rate[States]*average generation IB[States]

Units: kW * hrs / Year

Description: Generation decommission rate based on generation vintage 3 outflow.

Expected Capacity from Prospective Projects[States] = INTEG (capacity project start rate[States]-capacity development start rate[States]-capacity prospecting failure rate[States],0)

Units: GW

Description: Expected capacity from projects under prospect.

annuity factor = (1-(1/(1+interest rate)^average turbine lifetime*per year)) / (interest rate)

Units: dimensionless

Description: Annuity factor based on NREL Cost and Scaling Model (Fingersh et al 2006).

Simulated Capacity installed base[States] = INTEG (Simulated capacity construction finish rate[States]-capacity decommission rate[States],0)

Units: GW

Description: Total simulated capacity in the installed base by state.
Average Expected Turbine Orders = INTEG ((SUM(turbine development start rate[States!])*permit failure rate-Average Expected Turbine Orders)/time to average turbine orders,100)

Units: turbines / Year

Description: Average turbine orders per year based on average between current year and reference year.

percent projects failing[States]=IF THEN ELSE(total profitable projects in development[States] > 0, permit failure rate, 1 )

Units: dimensionless

Description: The percent of projects which will fail is based the permit failure rate unless market conditions change and all projects are unprofitable, then the failure rate increases to 100%.

Total Turbine Construction Completions= SUM(Simulated turbine construction finish rate[States!])+rest of world turbine construction start rate

Units: turbines / Year

Description: Total turbine constructions per year is the sum of finished constructions across all states plus the rest of the world construction finish rate that is not included in the analysis set.

normalized upfront investments[States]= ((marginal bos costs+marginal turbine cost)* (1-investment subsidy[States]))/annuity factor

Units: $/(turbine)

Description: Normalized investment costs from upfront costs after subsidies are removed over the annuity factors.

unit revenue[States]= max(electricity price[States]*cost electricity price discount factor[States]+rec price[States] + production incentive[States], feed in tariff rate[States])

Units: $/ (kW * hr)

Description: Maximum between feed in tariff rate (if present) and the electricity price reduced by markdown and added to any existing production or REC incentive.

fraction of land available for wind development[States]= 0.2

Units: dimensionless

Description: Fraction of land available for development after fractions from NIMBYism, transmission, pre-developed and other restrictions are removed.
Simulated marginal hub height = initial hub height * (ratio of total to initial turbine installation experience)^exponent hub height

Units: meters

Description: Simulated marginal hub height scaled from the initial hub height scaled by the total experience to initial experience to the learning exponent.

Simulated Land Use Installed Base[States] = INTEG (land construction finish rate[States] - land decommission rate[States], 0)

Units: meters * meters

Description: Total land occupied by turbine projects (includes space between turbines).

Simulated marginal turbine rated power = initial power rating * (Simulated marginal rotor diameter / initial rotor size)^rotor exponent

Units: kW / turbine

Description: Scaling of power rating over time based on empirical relationship initial rotor diameter by power rating scaled by the rotor power exponent.

upfront investment costs[States] = marginal turbine cost + marginal bos costs

Units: $/turbine

Description: Upfront investment costs per turbine summing the turbine and balance of station costs per unit power multiplied turbine power rating.

annual breakeven costs[States] = annual maintenance cost[States] * (1-tax rate) + normalized upfront investments[States]

Units: $(turbine)

Description: Annual breakeven costs are the annual operations costs after tax exemptions added to normalized upfront investment costs.

Simulated marginal LCOE[States] = \( ZIDZ( \text{upfront investment costs[States]} * \text{fixed charge rate} + \text{annual maintenance cost[States]}*(1-\text{tax rate}), \text{expected annual energy[States]} \) \)

Units: $/(kW*hr)

Description: Simplified NREL Cost and Scaling Model LCOE calculation using fixed charge rate for financing, upfront investment costs and operational expenditures minus tax exemptions over expected annual energy.

markup on turbine cost due to supply = backlog effect on turbine price mark(Turbine Backlog)
Units: dimensionless

Description: Price mark-up on turbines due to supply constraints based on lookup function and the size of the current wind turbine backlog.

land use prospecting start rate[States] = IF THEN ELSE(Potential Land for Installation[States] * per year - land use per project * max(0, project prospecting start rate[States]) >= 0, land use per project * max(0, project prospecting start rate[States]), max(0, Potential Land for Installation[States] * per year))

Units: meters * meters / Years

Description: Transition rate from land that has never been prospected or developed for a wind project to one that is under prospecting. Derived from rate of projects beginning prospecting each year and the average land use per project. If all available land has already been considered for development, the value will be 0.

total profitable prospective projects[States] = Expected Land Use from Prospective Projects[States] / land use per project * percent profitable land in prospect and development[States]

Units: projects

Description: Projects that are profitable in prospect are those that have already begun prospecting and are profitable under current market conditions.

total profitable undeveloped projects[States] = total potential land[States] * fraction of land available for wind development[States] * percent profitable land undeveloped[States] / land use per project

Units: projects

Description: Total profitable projects is based on the percent of undeveloped land that is currently considered profitable multiplied by the total potential land available for wind development divided by the land use per project.

Cumulative Energy by Wind Speed max[States, windspeed] = Power at wind speed[windspeed] * Rayleigh wind speed probability max[States, windspeed] * hours per year

Units: kW * hrs / turbine

Description: Cumulative energy by wind speed based on Rayleigh probability and power output at that wind speed.

land use per project = number of turbines per project * area per turbine

Units: meters * meters / project
Description: Land use per project is the average project capacity divided by the capacity per turbine and multiplied by the area per turbine.

Number of turbines per project = average project capacity / (GW per kW * Simulated marginal turbine rated power)

Units: turbines / project

Description: Turbines per project are determined by the capacity of the project over the current marginal turbine rated power.

Cumulative Energy by Wind Speed: Power at wind speed * Rayleigh wind speed probability * hours per year

Units: kW*hrs / turbine

Description: Cumulative energy by wind speed based on Rayleigh probability and power output at that wind speed.

total profitable projects in development = Expected Land Use from Development Projects / land use per project * percent profitable land in prospect and development

Units: projects

Description: Projects that are profitable in development are those that have already begun prospecting and are profitable under current market conditions.

Percent profitable land out of total = IF THEN ELSE (breakeven expected annual energy - expected annual energy max, 0, MIN(1, ABS(ZD((breakeven expected annual energy - expected annual energy max) - linear term for wind speed by land use), ZD((breakeven expected annual energy - expected annual energy max) - quadratic term for wind speed by land use)))))

Units: dimensionless

Description: Percent profitable land based on breakeven annual energy and expected annual energy characteristics.

Simulated marginal rotor diameter = initial rotor size * (ratio of total to initial turbine installation experience) * exponent rotor diameter

Units: meters

Description: Simulated marginal rotor diameter scaled from the initial rotor diameter scaled by the total experience to initial experience to the learning exponent.
Simulated OPEX per unit energy = initial annual OPEX costs per unit energy \times (\text{ratio of total to initial turbine installation experience})^{\text{exponent OPEX}}

Units: $/(kW \times \text{hrs})

Description: Average overall O&M costs based for land lease, standard O&M and component replacements.

Simulated turbine capital cost = initial upfront turbine costs per unit power \times (\text{ratio of total to initial turbine installation experience})^{\text{exponent turbine costs}}

Units: $/kW

Description: Turbine costs per unit power over time based on initial cost estimate per unit power scaled by total to initial experience scaled by the cost exponent for the turbine cost learning rate.

initial annual OPEX costs per unit energy = 0.05

Units: $/(kW \times \text{hrs})

Description: Normal O&M costs for standard maintenance activities, land leases, etc.

Simulated turbine availability = initial turbine availability \times (1/((\text{ratio of total to initial turbine installation experience})^{\text{exponent availability}}))

Units: dimensionless

Description: Average turbine availability is the 1 minus the percent of turbine downtime (calculated by the average time lost per breakdown by total turbine breakdowns per year over the total time in a year).

Simulated BOS Costs per unit power = initial balance of station costs per unit power \times (\text{ratio of total to initial turbine installation experience})^{\text{exponent bos costs}}

Units: $/kW

Description: Balance of station costs per unit power over time based on initial cost estimate per unit power scaled by total to initial experience scaled by the cost exponent for the balance of station learning rate.

Potential Land for Installation[States] = \text{INTEG} (\text{land decommission rate[States]} + \text{land use prospecting failure rate[States]} + \text{land use project fail rate[States]} - \text{land use prospecting start rate[States]} - \text{total potential land[States]} - \text{Simulated Land Use Installed Base[States]} - \text{Expected Land Use from Development Projects[States]} - \text{Expected Land Use from Prospective Projects[States]})

Units: meters \times meters
Description: Potential land available for installations is all land that has never been prospected or begun development for wind energy (includes undevelopable land such as urban areas, environmentally sensitive areas, etc.)

Expected Land Use from Prospective Projects[States] = INTEG (land use prospecting start rate[States] - land use development start rate[States] - land use prospecting failure rate[States], 0)

Units: meters * meters

Description: Land under prospect for wind projects.

Expected Capacity from Development Projects[States] = INTEG (capacity development start rate[States] - capacity construction start rate[States] - capacity development failure rate[States], 0)

Units: GW

Description: Expected capacity from development projects.

avg generation UD[States] = ZIDZ(Expected Generation from Development Projects[States], Projects in Development[States])

Units: kW * hrs / project

Description: Average generation under development is the expected generation from development over the turbines from development.

land use development start rate[States] = max(0, avg LU UP[States] * project development start rate[States])

Units: meters * meters / Year

Description: Transition rate from land being prospected to land being developed based on average land use per turbine being prospected multiplied by the number of turbines transitioning from prospect to development.

avg LU IB[States] = ZIDZ(Simulated Land Use Installed Base[States], Projects Installed Base[States])

Units: (meters * meters) / project

Description: Average land use of installed base based on the total land of the install base and the number of turbines installed.

avg LU UD[States] = ZIDZ(Expected Land Use from Development Projects[States], Projects in Development[States])

Units: meters * meters / project
Description: Average land use under development is the land under development divided the number of turbines under development.

\[
\text{avg LU UP}[\text{States}] = \text{ZIDZ}([\text{Expected Land Use from Prospective Projects}[\text{States}]],[\text{Projects in Prospect}[\text{States}])
\]

Units: meters*meters / project

Description: Average land use per project under prospecting is derived from the current expected land use over the number of turbines in prospective projects.

Expected Land Use from Development Projects[States]= INTEG (land use development start rate[States]-land construction start rate[States]-land use project fail rate[States],0)

Units: meters*meters

Description: Land under development for wind projects.

permit failure rate= permit failure rate lookup(Time*per year)

Units: dimensionless [0,1,0.05]

Description: Permit failure rate is based on a lookup table that changes with time.

total land under development[States]= Expected Land Use from Prospective Projects[States]+Expected Land Use from Development Projects[States]+Expected land Use from Construction Projects[States]+Simulated Land Use Installed Base[States]

Units: meters * meters

Description: Total land under development is all land under prospect, development, construction, installed and land that has been decommissioned.

capacity development start rate[States]= max(0,avg capacity UP[States]*project development start rate[States])

Units: GW / Year

Description: Capacity development start rate is the average capacity per project under prospect multiplied by the project development start rate.

turbine industry turbine capacity= INTEG (turbine industry capacity change rate, initial industry capacity)

Units: turbines/Year

Description: Turbine industry annual production capacity.
avg capacity UP[States] = ZIDZ(Expected Capacity from Prospective Projects[States], Projects in Prospect[States])

Units: GW / project

Description: Average capacity per project under prospect based on the total capacity from prospective projects divided by the project under prospect.

avg capacity UD[States] = ZIDZ(Expected Capacity from Development Projects[States], Projects in Development[States])

Units: GW / project

Description: Average capacity per project under development is the total capacity under development divided by the number of projects in development.

turbine industry capacity change rate = (desired turbine production - turbine industry turbine capacity) / capacity adjustment time

Units: turbines / (Year * Year)

Description: Change in turbine industry production capacity each year is the difference in desired capacity to current capacity over the adjustment time.

developer project capacity[States] = INTEG (developer capacity growth rate[States], Initial developer project capacity)

Units: projects / Year

Description: Developer project development capacity by state which adjusts up or down (down if the developer capacity growth rate is negative).

developer capacity growth rate[States] = MIN((desired capacity[States] - developer project capacity[States]) / developer capacity adjustment time, developer project capacity[States] * maximum percent growth rate)

Units: projects / (Year * Year)

Description: Developer capacity by state adjusting to market demand by state.

Simulated Turbine Installed Base[States] = INTEG (Simulated turbine construction finish rate[States] - turbine decommission rate[States], 0)

Units: turbines

Description: Total simulated turbine installed base by state.
turbine decommission rate[States]= max(0,average turbines IB[States]*project decommission rate[States])

Units: turbines / Year

Description: Turbine decommission rate is the average turbines in the installed base multiplied by the project decommission rate.

interest rate= 0.08

Units: dimensionless

Description: Interest rate based on NREL Cost and Scaling Model (Fingersh et al 2006).

marginal install wind speed[States]= max(0,max wind speed[States]+linear term for wind speed by land use[States]*(percent land under development[States])+quadratic term for wind speed by land use[States]*(percent land under development[States])^2)

Units: meters / second

Description: Marginal mean wind speed based on look-up function by state based on GIS analysis.

percent land under development[States]= ZIDZ(total land under development[States],total potential land[States])

Units: dimensionless

Description: Percent land under development is total land under development by total potential land.

percent profitable land undeveloped[States]=max(percent profitable land out of total[States]-percent land under development[States],0)

Units: dimensionless

Description: Percent profitable land available for development is the percent of total profitable land minus that already under development.

breakeven expected annual energy[States]= ZIDZ(annual breakeven costs[States],unit revenue[States])

Units: kW * hrs / turbine

Description: Breakeven annual energy level required based on current costs divided by current revenue.

Potential annual energy[States]= SUM(Cumulative Energy by Wind Speed[States,windspeed!])
Units: kW*hrs / turbine

Description: Total annual wind energy by summing energy for each wind speed bin.

expected annual energy[States]= Potential annual energy[States]*(1-losses)*Simulated turbine availability

Units: kW * hr / turbine

Description: Total annual energy production by state for the marginal project per turbine by state after losses and turbine downtime are removed.

windspeed: w1, w2, w3, w4, w5, w6, w7, w8, w9, w10, w11, w12, w13, w14, w15, w16, w17, w18, w19, w20, w21, w22, w23, w24, w25

Units:

Description: wind speed subscript

air density= 1.225

Units: dimensionless

Description: Standard air density constant is 1.225 kg / m^3 at sea level at 15 degrees Celsius (AWS Scientific, 1997).

power coefficient= 0.43

Units: dimensionless

Description: The model uses a power coefficient that multiplies a reasonable rotor power coefficient of 0.47 by a reasonable drivetrain efficiency of 0.92 for a total of 0.43 (Fingersh, Hand and Laxon, 2006)

wind speed[w1]= 1 ~w|
wind speed[w2]= 2 ~w|
wind speed[w3]= 3 ~w|
wind speed[w4]= 4 ~w|
wind speed[w5]= 5 ~w|
wind speed[w6]= 6 ~w|
wind speed[w7]= 7 ~w|
wind speed[w8]= 8
wind speed[w9]= 9
wind speed[w10]= 10
wind speed[w11]= 11
wind speed[w12]= 12
wind speed[w13]= 13
wind speed[w14]= 14
wind speed[w15]= 15
wind speed[w16]= 16
wind speed[w17]= 17
wind speed[w18]= 18
wind speed[w19]= 19
wind speed[w20]= 20
wind speed[w21]= 21
wind speed[w22]= 22
wind speed[w23]= 23
wind speed[w24]= 24
wind speed[w25]= 25

Units: meters / second
Description: wind speed units constant for power curve calculations.

hub height wind speed[States]= marginal install wind speed[States] *(Simulated marginal hub height/reference hub height)^wind shear exponent

Units: meters / second
Description: Standard hub height wind speed equation: marginal wind speed at hub height based on hub height relative to reference height scaled by wind shear exponent.

reference hub height=50
Units: meters
Description: Reference hub height where wind speed data is measured.

wind shear exponent= 0.143
Units: dimensionless
Description: Standard wind shear exponent for flat terrain is 1/7 which equals 0.143 (AWS Scientific, 1997).

developer capacity adjustment time= 1
Units: Year
Description: Time it takes a developer to adjust capacity to desired capacity.

initial balance of station costs per unit power= 1000
Units: $/kW
Description: Initial balance of station costs per unit power.

turbine bos learning rate= 0.073
Units: dimensionless
Description: Learning rate for turbine bos costs based on analysis of available data.

exponent bos costs= \( \ln(1 - \text{turbine bos learning rate})/\ln(2) \)
Units: dimensionless
Description: Exponent for BOS costs learning using standard formulation.

tax rate= 0.4
Units: dimensionless
Description: Corporate tax exemption rate on operational expenditures based on NREL Cost and Scaling Model (Fingersh et al 2006).

losses= 0.15
Units: dimensionless
Description: Typical plant losses for an assortment of factors.

fixed charge rate= 0.12
Units: dimensionless


data: turbinesnew, turbinesbase, turbinestotal, capacitynew, capacitybase, capacitytotal, rating, rotordiameter, hubheight, turbinecosts, boscosts, opex, lcoe

Units:

Description: Data subscripts

exponent OPEX= \ln(1-\text{turbine OPEX learning rate})/\ln(2)

Units: dimensionless

Description: Exponent for reliability based on learning rate using standard learning rate formulation.

turbine OPEX learning rate= 0.073

Units: dimensionless

Description: Learning rate for turbine operational expenditures based on analysis of available data.

exponent turbine costs= \ln(1-\text{turbine cost learning rate})/\ln(2)

Units: dimensionless

Description: Exponent for turbine costs learning using standard formulation.

turbine cost learning rate= 0.073

Units: dimensionless

Description: Learning rate for turbine costs based on analysis of available data.

Simulated total turbine installation experience= \text{INTEG} (\text{Total Turbine Construction Completions - installation experience loss rate, initial turbine installation experience})

Units: turbines

Description: Simulated total turbine installation experience.

Decommissioned Turbines[States]= \text{INTEG} (turbine decommission rate[States],0)

Units: turbines
Description: Total decommissioned turbines.

rotor diameter learning rate = 0.25

Units: dimensionless

Description: Learning rate for turbine rotor diameter based on analysis of available data.

exponent rotor diameter = ln(1 + rotor diameter learning rate) / ln(2)

Units: dimensionless

Description: Exponent for rotor diameter learning rate based on standard formulation.

initial rotor size = 10

Units: meters

Description: Initial rotor size for turbines installed in the 1970s.

hours per year = 24 * 365

Units: hr

Description: Hours per year are 8760 (365 days * 24 hours per day)

capacity adjustment time = 0.25

Units: Years

Description: Time for turbine industry to adjust capacity up/down to target.

cost electricity price discount factor [States] = 0.6

Units: dimensionless

Description: Discount factor from wholesale or consumer electricity price to cost (i.e. to remove utility profit mark-up, and any embedded transmission or distribution costs).

initial upfront turbine costs per unit power = 2000

Units: $/kW

Description: Initial turbine costs per unit power.

permitting and PPA decision time lookup([1975,1)-(2010,4)],(1975,1),(1985,1),(1990,4),(2010,4))

Units: Years [0,2,0.02]
Project development time (including permitting and contracting) is typically 5 years including 1 year for prospecting (4 years in exclusion of prospecting time) for current projects (Splestosser interview 2016). It is assumed that early projects in the 70's or 80's were much easier to permit for a number of reasons including market urgency, lack of NIMBYism, and generally less complex permitting requirements during the time period.

**Initial Industry Capacity**

Initial industry capacity = 100

Units: turbines / Year

Description: Initial turbine industry capacity.

**Initial Turbine Installation Experience**

Initial turbine installation experience = 300

Units: turbines

Description: 300 turbines installed prior to 1980 in unknown years and is used as a starting point in the turbine technology and learning curves.

**Installation Experience Loss Rate**

Installation experience loss rate = Simulated total turbine installation experience * experience loss rate

Units: turbines / Year

Description: Experience loss rate is based on the total installation experience multiplied by the experience / knowledge loss rate.

Experience loss rate = 0

Units: 1 / Years

Description: Experience loss rate is the loss of knowledge experience per year. It is currently set to zero since learning rates are statistically estimated from cumulative installations.

**Spacing per Turbine**

Spacing per turbine = 50

Units: 1 / turbine

Description: Spacing per turbine is assumed to be a standard 7 x 7 rotor diameter spacing (or 5 x 10 for farms with more preferential directions) (AWS Scientific, 1997).

Simulated[turbinesbase,States] = Simulated Turbine Installed Base[States]

Simulated[turbinesnew,States] = Simulated Turbine Construction Finish Rate[States]

Simulated[turbinestotal, States] = SUM(Simulated Turbine Installed Base[States])

Simulated[capacitybase,States] = Simulated Capacity Installed Base[States]

Simulated[capacitynew, States] = Simulated Capacity Construction Finish Rate[States]
Simulated[rating, States]= Simulated marginal turbine rated power
Simulated[rotordiameter, States]= Simulated marginal rotor diameter
Simulated[lcoe, States]= Simulated marginal LCOE
Simulated[turbinecosts, States]= Simulated turbine capital cost
Simulated[boscosts, States]= Simulated BOS Costs per unit power
Simulated[opex, States]= Simulated OPEX per unit energy
Simulated[hubheight, States]= Simulated marginal hub height
Simulated[capacitytotal, States]= SUM(Simulated Capacity installed base[States])

- Units: Units
- Description: Set equal to the simulated data series.

Historical[turbinesbase, States]= Historical Turbine Installed Base[States](Time)
Historical[turbinesnew, States]= Historical Turbine Construction Rate[States](Time)
Historical[turbinestotal, States]= SUM(Historical Turbine Installed Base[States](Time))
Historical[capacitybase, States]= Historical Capacity Installed Base[States](Time)
Historical[capacitynew, States]= Historical Capacity Construction Rate[States](Time)
Historical[rating, States]= Historical Marginal Rated Power(Time)
Historical[rotordiameter, States]= Historical Marginal Rotor Diameter(Time)
Historical[lcoe, States]= Historical Marginal LCOE(Time)
Historical[turbinecosts, States]= Historical Turbine Cost(Time)
Historical[boscosts, States]= Historical BOS Costs(Time)
Historical[opex, States]= Historical OPEX Costs(Time)
Historical[hubheight, States]= Historical Marginal Hub Height(Time)
Historical[capacitytotal, States]= SUM(Historical Capacity Installed Base[States](Time))

- Units: Units
- Description: Set equal to the historical data series.
Control

FINAL TIME = 2015
Units: Year
Description: The final time for the simulation.

INITIAL TIME = 1980
Units: Year
Description: The initial time for the simulation.

SAVEPER = TIME STEP
Units: Year [0,?] 
Description: The frequency with which output is stored.

TIME STEP = 0.25
Units: Year [0,?] 
Description: The time step for the simulation.
6.8.2 First model set: historically dominant wind markets
States: Denmark, Germany, Spain, California

Units:
Description: States in the analysis.

Statescopy: Denmark, Germany, Spain, California

Units:
Description: Copy of States in the analysis for simulation.

total potential land[Denmark] = 4.11035e+010

total potential land[Germany] = 3.55246e+011

total potential land[Spain] = 5.0325e+011

total potential land[California] = 4.03466e+011

Units: meters * meters
Description: Total available land area in a given state.

max wind speed[Denmark] = 7.17

max wind speed[Germany] = 9.47

max wind speed[Spain] = 7.63

max wind speed[California] = 6.46

Units: meters / second
Description: Maximum wind speed in a given region.

linear term for wind speed by land use[Denmark] = -2.9574

linear term for wind speed by land use[Germany] = -5.65748
linear term for wind speed by land use[Spain] = -5.2201

linear term for wind speed by land use[California] = -1.97194

Units: meters / second
Description: Linear coefficient for polynomial fit of wind speed resource by land use.

quadratic term for wind speed by land use[Denmark] = -0.63987

quadratic term for wind speed by land use[Germany] = 2.58684

quadratic term for wind speed by land use[Spain] = 1.39668

quadratic term for wind speed by land use[California] = 0.64225

Units: meters / second
Description: Quadratic coefficient for polynomial fit of wind speed resource by land use.

Historical Electricity Prices[Denmark][(0,0)-(2014,10)], (1980, 0.022629), (1981, 0.037994), (1982, 0.052032), (1983, 0.058624), (1984, 0.057648), (1985, 0.070801), (1986, 0.068542), (1987, 0.060822), (1988, 0.069275), (1989, 0.079102), (1990, 0.08197), (1991, 0.07959), (1992, 0.082092), (1993, 0.076599), (1994, 0.075562), (1995, 0.075195), (1996, 0.078491), (1997, 0.078125), (1998, 0.082336), (1999, 0.083557), (2000, 0.086731), (2001, 0.093933), (2002, 0.1001), (2003, 0.10645), (2004, 0.10724), (2005, 0.10968), (2006, 0.12097), (2007, 0.12769), (2008, 0.14734), (2009, 0.13843), (2010, 0.13953), (2011, 0.13855), (2012, 0.13928), (2013, 0.13611), (2014, 0.13135)) ~~

Historical Electricity Prices[Germany][(0,0)-(2014,10)], (1980, 0.12292), (1981, 0.12207), (1982, 0.12164), (1983, 0.11945), (1984, 0.13184), (1985, 0.13464), (1986, 0.13403), (1987, 0.13879), (1988, 0.1355), (1989, 0.13342), (1990, 0.14209), (1991, 0.14819), (1992, 0.15442), (1993, 0.15417), (1994, 0.14807), (1995, 0.13367), (1996, 0.13477), (1997, 0.13757), (1998, 0.13623), (1999, 0.13525), (2000, 0.13379), (2001, 0.13831), (2002, 0.13538), (2003, 0.13989), (2004, 0.14063), (2005, 0.14209), (2006, 0.13928), (2007, 0.1322), (2008, 0.13025), (2009, 0.13147), (2010, 0.11963), (2011, 0.11957), (2012, 0.12042), (2013, 0.11859), (2014, 0.11597)) ~~

Historical Electricity Prices[Spain][(0,0)-(2014,10)], (1980, 0.018494), (1981, 0.018494), (1982, 0.054535), (1983, 0.070618), (1984, 0.068054), (1985, 0.093079), (1986, 0.091248), (1987, 0.092163), (1988, 0.10132), (1989, 0.1153), (1990, 0.11987), (1991, 0.13879), (1992, 0.14441), (1993, 0.13416), (1994, 0.12891), (1995, 0.13025), (1996, 0.1322), (1997, 0.12793), (1998, 0.11591), (1999, 0.11328), (2000, 0.10828), (2001, 0.10107), (2002, 0.10071), (2003, 0.10217), (2004, 0.10406), (2005, 0.10449), (2006, 0.11041), (2007, 0.12225), (2008, 0.14001), (2009, 0.15686), (2010, 0.17139), (2011, 0.17017), (2012, 0.17126), (2013, 0.16736), (2014, 0.16138)) ~~
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Units: $/ (kW * hrs)

Description: Lookup function for electricity price based on year.

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Units: $/ (kW * hrs)

Description: Lookup function for production incentive based on year.

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Units: $/ (kW * hrs)

Description: Lookup function for production incentive based on year.
Historical investment subsidy [Denmark]((0,0)-(2014,10)), (1980, 0.3999), (1981, 0.3999), (1982, 0.3999), (1983, 0.3999), (1984, 0.3999), (1985, 0.3999), (1986, 0.3999), (1987, 0.3999), (1988, 0.3999), (1989, 0.3999), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0) ~~~|


Units: dimensionless

Description: Lookup function for investment subsidy based on year.


Historical feed in tariff rate [Germany]((0,0)-(2014,10)), (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0.10956), (1995, 0.10974), (1996, 0.094971), (1997, 0.095032), (1998, 0.09375), (1999, 0.090271), (2000, 0.075012), (2001, 0.09436), (2002, 0.087891), (2003, 0.10254), (2004, 0.11987), (2005, 0.12512), (2006, 0.10516), (2007, 0.11438), (2008, 0.09845), (2009, 0.11639), (2010, 0.11865), (2011, 0.10706), (2012, 0.10095), (2013, 0.10181), (2014, 0.10474)) ~~~|

Historical feed in tariff rate [Spain]((0,0)-(2014,10)), (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0.094727), (1995, 0.094727), (1996, 0.094727), (1997, 0.094727), (1998, 0.094727), (1999, 0.094727), (2000, 0.094727), (2001, 0.085632), (2002, 0.079773), (2003, 0.093079), (2004, 0.10883), (2005, 0.094727), (2006, 0.094727), (2007, 0.094727), (2008, 0.094727), (2009, 0.094727), (2010, 0.094727), (2011, 0.094727), (2012, 0.094727), (2013, 0.094727), (2014, 0.094727))
Historical feed in tariff rate[California][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0.089233), (2009, 0.089233), (2010, 0.089233), (2011, 0.089233), (2012, 0.089233), (2013, 0.089233), (2014, 0.089233)]

Units: $/(kW * hrs)

Description: Lookup function for feed-in-tariff based on year.


Historical rec price[California][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0.029999), (2004, 0.029999), (2005, 0.029999), (2006, 0.029999), (2007, 0.029999), (2008, 0.029999), (2009, 0.029999), (2010, 0.010002), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Units: $/(kW * hrs)

Description: Lookup function for REC price based on year.


Units: $/kW

Description: Historical turbine costs per kW.


Units: $/kW

Description: Historical BOS costs per kW.


Units: $/(kW * hrs)

Description: Historical OPEX costs per kWh.

Historical Marginal LCOE([(0,0)-(2015,10)], (1980, 0.271425), (1981, 0.251373), (1982, 0.232811), (1983, 0.184569), (1984, 0.199722), (1985, 0.141141), (1986, 0.171362), (1987, 0.119427), (1988, 0.147051), (1989, 0.10857), (1990, 0.10857), (1991, 0.10857), (1992, 0.108338), (1993, 0.097713), (1994, 0.0930112), (1995, 0.0814275), (1996, 0.0814275), (1997, 0.075999), (1998, 0.0685875), (1999, 0.0597135), (2000, 0.0589114), (2001, 0.054285), (2002, 0.0506081), (2003, 0.054285), (2004, 0.056), (2005, 0.05226), (2006, 0.04951), (2007, 0.04791), (2008, 0.04642), (2009, 0.04506), (2010, 0.04382), (2011, 0.04269), (2012, 0.04167), (2013, 0.04077), (2014, 0.04000), (2015, 0.03935))

Units: $/kW
(2005, 0.056), (2006, 0.07), (2007, 0.071), (2008, 0.084), (2009, 0.088), (2010, 0.08), (2011, 0.064), (2012, 0.057), (2013, 0.046), (2014, 0.041))

Units: $/(kW*hrs)

Description: Historical LCOE in $/kWh.


Units: meters

Description: Historical rotor diameter in m.


Units: kW

Description: Historical rated power in kW.


Units: meters

Description: Historical hub height in m.


Units: turbines/Year

Description: Lookup function for turbine construction rate in a given state by year.


Units: turbines/Year

Description: Lookup function for turbine installed base in a given state by year.

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Units: turbines

Description: Lookup function for total turbines installed in a given state by year.

-- 1


Historical Capacity Installed Base [California] (1980, 0), (1981, 0), (1982, 0), (1983, 0.00576), (1984, 0.14006), (1985, 0.25008), (1986, 0.263118), (1987, 0.33957), (1988, 0.33957), (1989, 0.33957), (1990, 0.33957), (1991, 0.33957), (1992, 0.33957), (1993, 0.33957), (1994, 0.33957), (1995, 0.33957), (1996, 0.33957), (1997, 0.33957), (1998, 0.33957), (1999, 0.33957), (2000, 0.33957), (2001, 0.33957), (2002, 0.33957), (2003, 0.33957), (2004, 0.33957), (2005, 0.33957), (2006, 0.33957), (2007, 0.33957), (2008, 0.33957), (2009, 0.33957), (2010, 0.33957), (2011, 0.33957), (2012, 0.33957), (2013, 0.33957), (2014, 0.33957), (2015, 0.33957), (2016, 0.33957).

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Historical Capacity Construction Rate [Denmark] ([(0, 0)-(2015, 10)], (1980, 0.005), (1981, 0.002), (1982, 0.005), (1983, 0.008), (1984, 0.007), (1985, 0.023), (1986, 0.032), (1987, 0.033), (1988, 0.082), (1989, 0.065), (1990, 0.081), (1991, 0.07), (1992, 0.045), (1993, 0.033), (1994, 0.043725), (1995, 0.084), (1996, 0.226), (1997, 0.292175), (1998, 0.315043), (1999, 0.316), (2000, 0.636699), (2001, 0.10803), (2002, 0.51004), (2003, 0.24395), (2004, 0.008), (2005, 0.0296), (2006, 0.006), (2007, 0.00225), (2008, 0.06035), (2009, 0.3639), (2010, 0.349), (2011, 0.21285), (2012, 0.7521), (2013, 0.645), (2014, 0.038), (2015, 0.2193), (2016, 0)) ~~


Historical Capacity Construction Rate [California] ([(0, 0)-(2015, 10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0.00576), (1984, 0.1343), (1985, 0.11002), (1986, 0.013038), (1987, 0.076452), (1988, 0), (1989, 0.09853), (1990, 0.10497), (1991, 0), (1992, 0.00697), (1993, 0.07695), (1994, 0.01), (1995, 0.003), (1996, 0), (1997, 0.01785), (1998, 0.0524), (1999, 0.24547), (2000, 0), (2001, 0.0671), (2002, 0.139974), (2003, 0.21558), (2004, 0.09053), (2005, 0.06191), (2006, 0.24892), (2007, 0.063), (2008, 0.239), (2009, 0.261246), (2010, 0.454654), (2011, 0.664393), (2012, 1.625), (2013, 0.2915), (2014, 0.1064), (2015, 0.191), (2016, 0))

Units: GW

Description: Lookup function for total installed capacity in a given state by year.
Historical rest of world turbine construction start rate(((0,0)-(2015,10]), (1980, 0), (1981, 0), (1982, 0),

Units: turbines/Year

Description: Lookup function for turbine construction rate for the rest of the world not
included in the State group set by year.

6.8.3 Second model set: large wind markets in 2015
States: Denmark, France, Germany, Italy, Netherlands, Poland, Portugal, Spain, Sweden, Turkey, United
Kingdom, California, Illinois, Iowa, Kansas, Minnesota, Oklahoma, Oregon, Texas, Washington

Units:

Description: States in the analysis.

Statescopy:

Denmark, France, Germany, Italy, Netherlands, Poland, Portugal, Spain, Sweden, Turkey, United
Kingdom, California, Illinois, Iowa, Kansas, Minnesota, Oklahoma, Oregon, Texas, Washington

Units:

Description: Copy of States in the analysis for simulation.

\[
\begin{align*}
\text{total potential land}[\text{Denmark}] &= 4.11035e+10 \sim |
\text{total potential land}[\text{France}] &= 5.4697e+11 \sim |
\text{total potential land}[\text{Germany}] &= 3.55246e+11 \sim |
\text{total potential land}[\text{Italy}] &= 3.01101e+11 \sim |
\text{total potential land}[\text{Netherlands}] &= 3.46909e+10 \sim |
\text{total potential land}[\text{Poland}] &= 3.12136e+11 \sim |
\text{total potential land}[\text{Portugal}] &= 9.04111e+10 \sim |
\end{align*}
\]
total potential land[Spain] = 5.0325e+011
total potential land[Sweden] = 4.42246e+011
total potential land[Turkey] = 7.78602e+011
total potential land[United Kingdom] = 2.38074e+011
total potential land[California] = 4.03466e+011
total potential land[Illinois] = 1.43793e+011
total potential land[Iowa] = 1.44669e+011
total potential land[Kansas] = 2.11754e+011
total potential land[Minnesota] = 2.06232e+011
total potential land[Oklahoma] = 1.7766e+011
total potential land[Oregon] = 2.48608e+011
total potential land[Texas] = 6.76587e+011

Units: meters * meters
Description: Total available land area in a given state.

max wind speed[Denmark] = 7.17
max wind speed[France] = 7.67
max wind speed[Germany] = 9.47
max wind speed[Italy] = 6.19
max wind speed[Netherlands] = 8.12
max wind speed[Poland] = 9.27
max wind speed[Portugal] = 7.68
max wind speed[Spain] = 7.63
max wind speed[Sweden] = 7.65
max wind speed[Turkey] = 6.04
max wind speed[United Kingdom] = 9.84
max wind speed[California] = 6.46
max wind speed[Illinois] = 5.83
max wind speed[Iowa] = 6.09
max wind speed[Iowa] = 6.09
max wind speed[Kansas] = 7.24
max wind speed[Minnesota] = 5.81
max wind speed[Oklahoma] = 7.24
max wind speed[Oregon] = 6.57
max wind speed[Texas] = 6.92
max wind speed[Washington] = 6.36

Units: meters / second

Description: Maximum wind speed in a given region.

linear term for wind speed by land use[Denmark] = -2.9574
linear term for wind speed by land use[France] = -5.68816
linear term for wind speed by land use[Germany] = -5.65748
linear term for wind speed by land use[Italy] = -1.50489
linear term for wind speed by land use[Netherlands] = -2.08497
linear term for wind speed by land use[Poland] = -7.94948
linear term for wind speed by land use[Portugal] = -3.77839
linear term for wind speed by land use[Spain] = -5.2201
linear term for wind speed by land use[Sweden] = -3.85509
linear term for wind speed by land use[Turkey] = -1.61594
linear term for wind speed by land use[United Kingdom] = -3.89956
Linear term for wind speed by land use:

- **California**: -1.97194
- **Illinois**: -1.03714
- **Iowa**: -0.628645
- **Kansas**: -1.705
- **Minnesota**: -0.87965
- **Oklahoma**: 0.062071
- **Oregon**: -4.14243
- **Texas**: -3.79646
- **Washington**: -5.94899

Units: meters / second

Description: Linear coefficient for polynomial fit of wind speed resource by land use.

Quadratic term for wind speed by land use:

- **Denmark**: -0.63987
- **France**: 2.16976
- **Germany**: 2.58684
- **Italy**: -1.42839
- **Netherlands**: -0.43094
- **Poland**: 4.85985
- **Portugal**: 1.3207
- **Spain**: 1.39668
- **Sweden**: 1.33884
- **Turkey**: -0.39205
- **United Kingdom**: 0.484872
- **California**: 0.64225
- **Illinois**: 0.571429
quadratic term for wind speed by land use[Iowa]= 0.104084
quadratic term for wind speed by land use[Kansas]= 0.0417434
quadratic term for wind speed by land use[Minnesota]= -1.22015
quadratic term for wind speed by land use[Oklahoma]= -2.89168
quadratic term for wind speed by land use[Oregon]= 1.64238
quadratic term for wind speed by land use[Texas]= 0.938841
quadratic term for wind speed by land use[Washington]= 3.6625

Units:  meters / second

Description: Quadratic coefficient for polynomial fit of wind speed resource by land use.

Historical Electricity Prices[Denmark][[(0,0)-(2014,10)], (1980, 0.022629), (1981, 0.037994), (1982, 0.052032), (1983, 0.058648), (1984, 0.070801), (1985, 0.068642), (1986, 0.060822), (1987, 0.069275), (1988, 0.079102), (1989, 0.07959), (1990, 0.08197), (1991, 0.078491), (1992, 0.078125), (1993, 0.082336), (1994, 0.076599), (1995, 0.075562), (1996, 0.078491), (1997, 0.078125), (1998, 0.082336), (1999, 0.083557), (2000, 0.086731), (2001, 0.093933), (2002, 0.1001), (2003, 0.10645), (2004, 0.10724), (2005, 0.10968), (2006, 0.12097), (2007, 0.12769), (2008, 0.14734), (2009, 0.13843), (2010, 0.13953), (2011, 0.13855), (2012, 0.13928), (2013, 0.13611), (2014, 0.13135)]

Historical Electricity Prices[France][[(0,0)-(2014,10)], (1980, 0.062866), (1981, 0.067383), (1982, 0.077454), (1983, 0.089172), (1984, 0.09906), (1985, 0.10651), (1986, 0.10516), (1987, 0.1048), (1988, 0.10651), (1989, 0.10791), (1990, 0.11035), (1991, 0.11151), (1992, 0.1087), (1993, 0.11511), (1994, 0.11639), (1995, 0.11694), (1996, 0.11591), (1997, 0.11407), (1998, 0.1109), (1999, 0.10938), (2000, 0.10602), (2001, 0.10272), (2002, 0.10339), (2003, 0.10443), (2004, 0.10632), (2005, 0.10492), (2006, 0.1062), (2007, 0.10754), (2008, 0.1095), (2009, 0.11359), (2010, 0.1178), (2011, 0.12317), (2012, 0.13), (2013, 0.12793), (2014, 0.12122)]

Historical Electricity Prices[Germany][[(0,0)-(2014,10)], (1980, 0.12292), (1981, 0.12207), (1982, 0.12164), (1983, 0.11945), (1984, 0.13184), (1985, 0.13464), (1986, 0.13403), (1987, 0.13879), (1988, 0.1355), (1989, 0.13342), (1990, 0.14209), (1991, 0.14819), (1992, 0.15442), (1993, 0.15417), (1994, 0.14807), (1995, 0.13367), (1996, 0.13477), (1997, 0.13757), (1998, 0.13623), (1999, 0.13525), (2000, 0.13379), (2001, 0.13831), (2002, 0.13538), (2003, 0.13989), (2004, 0.14063), (2005, 0.14209), (2006, 0.13928), (2007, 0.1322), (2008, 0.13025), (2009, 0.13147), (2010, 0.11963), (2011, 0.11957), (2012, 0.12042), (2013, 0.11859), (2014, 0.11597)]

Historical Electricity Prices[Italy][[(0,0)-(2014,10)], (1980, 0.018494), (1981, 0.018494), (1982, 0.054535), (1983, 0.070618), (1984, 0.068054), (1985, 0.093079), (1986, 0.091248), (1987, 0.092163), (1988,
Historical Electricity Prices [Netherlands] ([(0,0)-(2014,10)]), (1980, 0.022629), (1981, 0.037994), (1982, 0.052032), (1983, 0.058624), (1984, 0.057648), (1985, 0.070801), (1986, 0.068542), (1987, 0.060822), (1988, 0.069275), (1989, 0.079102), (1990, 0.08197), (1991, 0.07959), (1992, 0.082092), (1993, 0.076599), (1994, 0.075562), (1995, 0.075195), (1996, 0.078491), (1997, 0.078125), (1998, 0.082336), (1999, 0.083557), (2000, 0.12097), (2001, 0.11536), (2002, 0.11017), (2003, 0.11603), (2004, 0.11292), (2005, 0.12769), (2006, 0.16382), (2007, 0.16943), (2008, 0.18799), (2009, 0.17371), (2010, 0.16785), (2011, 0.16748), (2012, 0.16846), (2013, 0.15918), (2014, 0.14404) ~

Historical Electricity Prices [Poland] ([(0,0)-(2014,10)]), (1980, 0.0057449), (1981, 0.0056381), (1982, 0.0056572), (1983, 0.0057144), (1984, 0.0057182), (1985, 0.0057373), (1986, 0.0057602), (1987, 0.0058479), (1988, 0.0060081), (1989, 0.0061684), (1990, 0.0094147), (1991, 0.014771), (1992, 0.021194), (1993, 0.026886), (1994, 0.035156), (1995, 0.043518), (1996, 0.049469), (1997, 0.05722), (1998, 0.064209), (1999, 0.070679), (2000, 0.0802), (2001, 0.085938), (2002, 0.090149), (2003, 0.088928), (2004, 0.084473), (2005, 0.095337), (2006, 0.10553), (2007, 0.1156), (2008, 0.11487), (2009, 0.11102), (2010, 0.12561), (2011, 0.12469), (2012, 0.12549), (2013, 0.12256), (2014, 0.11823) ~

Historical Electricity Prices [Portugal] ([(0,0)-(2014,10)]), (1980, 0.010483), (1981, 0.010483), (1982, 0.053955), (1983, 0.073242), (1984, 0.070251), (1985, 0.08551), (1986, 0.087769), (1987, 0.091003), (1988, 0.093628), (1989, 0.10535), (1990, 0.11749), (1991, 0.13232), (1992, 0.15027), (1993, 0.15698), (1994, 0.1521), (1995, 0.1532), (1996, 0.1532), (1997, 0.15527), (1998, 0.15332), (1999, 0.14758), (2000, 0.14453), (2001, 0.14124), (2002, 0.14331), (2003, 0.14734), (2004, 0.15088), (2005, 0.15234), (2006, 0.15662), (2007, 0.1582), (2008, 0.12482), (2009, 0.15515), (2010, 0.12683), (2011, 0.12598), (2012, 0.12671), (2013, 0.12384), (2014, 0.11945) ~

Historical Electricity Prices [Spain] ([(0,0)-(2014,10)]), (1980, 0.018494), (1981, 0.018494), (1982, 0.054535), (1983, 0.070618), (1984, 0.068054), (1985, 0.093079), (1986, 0.091248), (1987, 0.092163), (1988, 0.10132), (1989, 0.1153), (1990, 0.11987), (1991, 0.13879), (1992, 0.14441), (1993, 0.13416), (1994, 0.12891), (1995, 0.13025), (1996, 0.1322), (1997, 0.12793), (1998, 0.11591), (1999, 0.11328), (2000, 0.10828), (2001, 0.10107), (2002, 0.10071), (2003, 0.10217), (2004, 0.10406), (2005, 0.10449), (2006, 0.11041), (2007, 0.12225), (2008, 0.14001), (2009, 0.15686), (2010, 0.17139), (2011, 0.17017), (2012, 0.17126), (2013, 0.16736), (2014, 0.16138) ~

Historical Electricity Prices [Sweden] ([(0,0)-(2014,10)]), (1980, 0.024353), (1981, 0.037872), (1982, 0.050323), (1983, 0.056213), (1984, 0.055359), (1985, 0.059906), (1986, 0.060608), (1987, 0.062103), (1988, 0.06311), (1989, 0.06665), (1990, 0.070313), (1991, 0.074219), (1992, 0.078125), (1993, 0.080078), (1994, 0.08197), (1995, 0.082764), (1996, 0.080811), (1997, 0.082947), (1998, 0.084167), (1999, 0.078552), (2000, 0.078064), (2001, 0.077209), (2002, 0.081482), (2003, 0.099243), (2004,
Historical Electricity Prices[United Kingdom][[(0,0)-(2014,10)], (1980, 0.0054855), (1981, 0.0054855), (1982, 0.0054855), (1983, 0.0054855), (1984, 0.0054855), (1985, 0.0054855), (1986, 0.0054855), (1987, 0.0054855), (1988, 0.0054855), (1989, 0.0054855), (1990, 0.0054855), (1991, 0.0054855), (1992, 0.0054855), (1993, 0.0054855), (1994, 0.0054855), (1995, 0.0054855), (1996, 0.0054855), (1997, 0.0093536), (1998, 0.015808), (1999, 0.026917), (2000, 0.040039), (2001, 0.076599), (2002, 0.11005), (2003, 0.11719), (2004, 0.11444), (2005, 0.11841), (2006, 0.13306), (2007, 0.14807), (2008, 0.18909), (2009, 0.2218), (2010, 0.22778), (2011, 0.23315), (2012, 0.25732), (2013, 0.28003), (2014, 0.25928)] ~|
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Units: $/ (kW * hrs)

Description: Lookup function for electricity price based on year.

Historical production incentive[Denmark][((0,0)-(2014,10)], (1980, 0.044006), (1981, 0.044006), (1982, 0.044006), (1983, 0.044006), (1984, 0.044006), (1985, 0.044006), (1986, 0.044006), (1987, 0.044006), (1988, 0.044006), (1989, 0.044006), (1990, 0.044006), (1991, 0.044006), (1992, 0.044006), (1993, 0.044006), (1994, 0.044006), (1995, 0.044006), (1996, 0.044006), (1997, 0.044006), (1998, 0.044006), (1999, 0.044006), (2000, 0.044006), (2001, 0.044006), (2002, 0.044006), (2003, 0.044006), (2004, 0.044006), (2005, 0.044006), (2006, 0.044006), (2007, 0.044006), (2008, 0.044006), (2009, 0.044006), (2010, 0.044006), (2011, 0.044006), (2012, 0.044006), (2013, 0.044006), (2014, 0.044006))


Historical production incentive[Italy][((0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0))

Historical production incentive[Netherlands][((0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0.031677), (1999, 0.033264), (2000, 0.027496), (2001, 0.024857), (2002, 0.023163), (2003, 0.027023), (2004, 0.031586), (2005, 0.032959), (2006, 0.02771), (2007, 0.030136), (2008, 0.025955), (2009, 0.03067), (2010, 0.031281), (2011, 0), (2012, 0), (2013, 0), (2014, 0))


Historical production incentive[California]([[0,0]-[2014,10]], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074), (1993, 0.031128), (1994, 0.03035), (1995, 0.02951), (1996, 0.028671), (1997, 0.02803), (1998, 0.027603), (1999, 0.026993), (2000, 0), (2001, 0.025391), (2002, 0), (2003, 0.024445), (2004, 0), (2005, 0.023026), (2006, 0.022308), (2007, 0.021698), (2008, 0.020889), (2009, 0.022995), (2010, 0.022995), (2011, 0.022995), (2012, 0.022995), (2013, 0.022995), (2014, 0.022995)) ~~~
Historical production incentive[Kansas][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074), (1993, 0.031128), (1994, 0.03035), (1995, 0.02951), (1996, 0.028671), (1997, 0.02803), (1998, 0.027603), (1999, 0.026993), (2000, 0), (2001, 0.025391), (2002, 0), (2003, 0.024445), (2004, 0), (2005, 0.023026), (2006, 0.022308), (2007, 0.021698), (2008, 0.020889), (2009, 0.022995), (2010, 0.022995), (2011, 0.022995), (2012, 0.022995), (2013, 0.022995), (2014, 0.022995)~~]

Historical production incentive[Minnesota][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074), (1993, 0.031128), (1994, 0.03035), (1995, 0.02951), (1996, 0.028671), (1997, 0.02803), (1998, 0.027603), (1999, 0.026993), (2000, 0), (2001, 0.025391), (2002, 0), (2003, 0.024445), (2004, 0), (2005, 0.023026), (2006, 0.022308), (2007, 0.021698), (2008, 0.020889), (2009, 0.022995), (2010, 0.022995), (2011, 0.022995), (2012, 0.022995), (2013, 0.022995), (2014, 0.022995)~~]

Historical production incentive[Oklahoma][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074), (1993, 0.031128), (1994, 0.03035), (1995, 0.02951), (1996, 0.028671), (1997, 0.02803), (1998, 0.027603), (1999, 0.026993), (2000, 0), (2001, 0.025391), (2002, 0), (2003, 0.024445), (2004, 0), (2005, 0.023026), (2006, 0.022308), (2007, 0.021698), (2008, 0.020889), (2009, 0.022995), (2010, 0.022995), (2011, 0.022995), (2012, 0.022995), (2013, 0.022995), (2014, 0.022995)~~]

Historical production incentive[Oregon][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074), (1993, 0.031128), (1994, 0.03035), (1995, 0.02951), (1996, 0.028671), (1997, 0.02803), (1998, 0.027603), (1999, 0.026993), (2000, 0), (2001, 0.025391), (2002, 0), (2003, 0.024445), (2004, 0), (2005, 0.023026), (2006, 0.022308), (2007, 0.021698), (2008, 0.020889), (2009, 0.022995), (2010, 0.022995), (2011, 0.022995), (2012, 0.022995), (2013, 0.022995), (2014, 0.022995)~~]

Historical production incentive[Texas][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074), (1993, 0.031128), (1994, 0.03035), (1995, 0.02951), (1996, 0.028671), (1997, 0.02803), (1998, 0.027603), (1999, 0.026993), (2000, 0), (2001, 0.025391), (2002, 0), (2003, 0.024445), (2004, 0), (2005, 0.023026), (2006, 0.022308), (2007, 0.021698), (2008, 0.020889), (2009, 0.022995), (2010, 0.022995), (2011, 0.022995), (2012, 0.022995), (2013, 0.022995), (2014, 0.022995)~~]

Historical production incentive[Washington][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.032074),
Units: $/ (kW * hrs)

Description: Lookup function for production incentive based on year.

Historical investment subsidy[Denmark][[(0,0)-(2014,10)], (1980, 0.3999), (1981, 0.3999), (1982, 0.3999), (1983, 0.3999), (1984, 0.3999), (1985, 0.3999), (1986, 0.3999), (1987, 0.3999), (1988, 0.3999), (1989, 0.3999), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)]


Historical investment subsidy[Italy][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)]


Historical investment subsidy[California][[(0,0)-(2014,10)], (1980, 0.9502), (1981, 0.9502), (1982, 0.9502), (1983, 0.9502), (1984, 0.9502), (1985, 0.9502), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)] ~|~

Historical investment subsidy[Illinois][[(0,0)-(2014,10)], (1980, 0.25), (1981, 0.25), (1982, 0.25), (1983, 0.25), (1984, 0.25), (1985, 0.25), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)] ~|~

Historical investment subsidy[Iowa][[(0,0)-(2014,10)], (1980, 0.25), (1981, 0.25), (1982, 0.25), (1983, 0.25), (1984, 0.25), (1985, 0.25), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)] ~|~
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Historical Feed in Tariff Rate [Denmark]

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Historical feed in tariff rate [Italy]([(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)) ~~ |


Historical feed in tariff rate\[Turkey\][\((0,0)-(2014,10)\), (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0.11279), (2012, 0.10638), (2013, 0.1073), (2014, 0.11041)]~~|

Historical feed in tariff rate\[United Kingdom\][\((0,0)-(2014,10)\), (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0.11279), (2012, 0.10638), (2013, 0.1073), (2014, 0.11041)]~~|

Historical feed in tariff rate\[California\][\((0,0)-(2014,10)\), (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0.089233), (2009, 0.089233), (2010, 0.089233), (2011, 0.089233), (2012, 0.089233), (2013, 0.089233), (2014, 0.089233)]~~|


Historical feed in tariff rate\[Iowa\][\((0,0)-(2014,10)\), (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)]~~|


541
Historical feed in tariff rate [Oklahoma]:

Units: $/(kW \cdot \text{hrs})

Description: Lookup function for feed-in-tariff based on year.
Historical rec price[Italy][([0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0)) ~


Historical rec price[California][([0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0),
Historical rec price[Illinois][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0.020004), (2009, 0.020004), (2010, 0.010002), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Historical rec price[Iowa][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.029999), (1993, 0.029999), (1994, 0.029999), (1995, 0.029999), (1996, 0.029999), (1997, 0.029999), (1998, 0.029999), (1999, 0.029999), (2000, 0.029999), (2001, 0.029999), (2002, 0.029999), (2003, 0.029999), (2004, 0.029999), (2005, 0.029999), (2006, 0.029999), (2007, 0.029999), (2008, 0.029999), (2009, 0.029999), (2010, 0.010002), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Historical rec price[Kansas][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Historical rec price[Minnesota][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0.029999), (2003, 0.029999), (2004, 0.029999), (2005, 0.029999), (2006, 0.029999), (2007, 0.029999), (2008, 0.029999), (2010, 0.010002), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Historical rec price[Oklahoma][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Historical rec price[Oregon][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0.010002), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)]

Historical rec price[Texas][[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995,
Historical rec price(Washington)[[(0,0)-(2014,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0), (2004, 0), (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0.010002), (2013, 0.010002), (2014, 0.010002)] ~| ~

Units: $/ (kW * hrs)

Description: Lookup function for REC price based on year.


Units: $/ kW

Description: Historical turbine costs per kW.


Units: $/ kW

Description: Historical BOS costs per kW.

Units: $/(\text{kW} \times \text{hrs})

Description: Historical OPEX costs per kWh.

Historical Marginal LCOE\(([[0,0]-[2015,10]], (1980, 0.271425), (1981, 0.251373), (1982, 0.232811), (1983, 0.184569), (1984, 0.199722), (1985, 0.141141), (1986, 0.171362), (1987, 0.119427), (1988, 0.147051), (1989, 0.10857), (1990, 0.10857), (1991, 0.10857), (1992, 0.108338), (1993, 0.097713), (1994, 0.0930112), (1995, 0.0814275), (1996, 0.0814275), (1997, 0.075999), (1998, 0.0685875), (1999, 0.0597135), (2000, 0.0589114), (2001, 0.054285), (2002, 0.0506081), (2003, 0.054285), (2004, 0.056), (2005, 0.056), (2006, 0.07), (2007, 0.071), (2008, 0.084), (2009, 0.088), (2010, 0.08), (2011, 0.064), (2012, 0.057), (2013, 0.046), (2014, 0.041))

Units: $/(\text{kW} \times \text{hrs})

Description: Historical LCOE in $/kWh.


Units: meters

Description: Historical rotor diameter in m.

Historical Marginal Hub Height:

- **Units:** kW
- **Description:** Historical rated power in kW.

Historical Turbine Construction Rate:

- **Denmark:**
- **France:**
- **Germany:**
- **Italy:**

Units: meters

Description: Historical hub height in m.


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</table>

Historical Turbine Construction Rate for various states is provided with the years and values listed above.

Units: turbines/Year

Description: Lookup function for turbine construction rate in a given state by year.


Historical Turbine Installed Base [Poland]

Historical Turbine Installed Base [Portugal]

Historical Turbine Installed Base [Spain]

Historical Turbine Installed Base [Sweden]

Historical Turbine Installed Base [Turkey]

Historical Turbine Installed Base [United Kingdom]

Historical Turbine Installed Base [California]

Units: turbines
Description: Lookup function for total turbines installed in a given state by year.


Historical Capacity Installed Base[Netherlands][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0.000275), (1991, 0.000525), (1992, 0.004485), (1993, 0.005445), (1994, 0.00567), (1995, 0.028915), (1996, 0.055125), (1997, 0.09315), (1998, 0.129555), (1999, 0.15551), (2000, 0.20582), (2001, 0.22629), (2002, 0.41231), (2003, 0.60142), (2004, 0.72056), (2005, 0.81571), (2006, 1.10157), (2007, 1.26897), (2008, 1.62082), (2009, 1.93335), (2010, 1.96685), (2011, 2.06445), (2012, 2.1431), (2013, 2.39935), (2014, 2.45903), (2015, 2.72163), (2016, 2.72163)]

Historical Capacity Installed Base[Poland][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0.00016), (1995, 0.00048), (1996, 0.00048), (1997, 0.00225), (1998, 0.00225), (1999, 0.00225), (2000, 0.00225), (2001, 0.00735), (2002, 0.02535), (2003, 0.05535), (2004, 0.05535), (2005, 0.06375), (2006, 0.23535), (2007, 0.40845), (2008, 0.50945), (2009, 0.9168), (2010, 1.2235), (2011, 1.4705), (2012, 1.7065), (2013, 2.2669), (2014, 2.3927), (2015, 2.8824), (2016, 2.8824)]


Historical Capacity Installed Base[Sweden][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0.000225), (1992, 0.000225), (1993, 0.000225), (1994, 0.000225), (1995, 0.000225), (1996, 0.0016545), (1997, 0.016545), (1998, 0.026935), (1999, 0.026935), (2000, 0.032215), (2001, 0.034915), (2002, 0.18799), (2003, 0.30452), (2004, 0.351045), (2005, 0.389645), (2006, 0.437645), (2007, 0.66867), (2008, 0.81587), (2009, 1.17457), (2010, 1.5588), (2011, 2.34275), (2012, 2.62525), (2013, 3.06995), (2014, 3.48585), (2015, 4.05515), (2016, 4.05515)]


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</table>


Units: GW
Description: Lookup function for total installed capacity in a given state by year.

Historical Capacity Construction Rate [Denmark][[(0,0)-(2015,10)], (2006, 0.2193), (2007, 0.3639), (2010, 0.349), (2011, 0.21285), (2012, 0.7521), (2013, 0.645), (2014, 0.038), (2015, 0.2193), (2016, 0)]
Historical Capacity Construction Rate[France][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0.0001), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0.001), (1992, 0), (1993, 0.0023), (1994, 0), (1995, 0), (1996, 0.003), (1997, 0.001), (1998, 0.008), (1999, 0.0007115), (2000, 0.04173), (2001, 0.03862), (2002, 0.07374), (2003, 0.09808), (2004, 0.141), (2005, 0.380125), (2006, 0.689), (2007, 0.808), (2008, 1.206), (2009, 1.20965), (2010, 1.39957), (2011, 1.14), (2012, 0.8399), (2013, 1.047), (2014, 1.05305), (2015, 1.073), (2016, 0)]


Historical Capacity Construction Rate[Italy][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0.0003), (1991, 0.001), (1992, 0.003), (1993, 0.011), (1994, 0.003), (1995, 0.001), (1996, 0.027), (1997, 0.085), (1998, 0.066), (1999, 0.0704), (2000, 2001, 0.131), (2002, 0.12809), (2003, 0.094), (2004, 2005, 0.253), (2005, 0.508), (2006, 0.267), (2007, 0.98849), (2008, 0.835), (2009, 1.313), (2010, 0.947), (2011, 0.95), (2012, 1.397), (2013, 0.414), (2014, 0.1198), (2015, 0.295), (2016, 0)]

Historical Capacity Construction Rate[Netherlands][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0.000275), (1991, 0.00025), (1992, 0.00396), (1993, 0.00096), (1994, 0.000225), (1995, 0.023245), (1996, 0.02621), (1997, 0.038025), (1998, 0.036405), (1999, 0.025955), (2000, 0.05031), (2001, 0.02047), (2002, 0.18602), (2003, 0.18911), (2004, 0.11914), (2005, 0.09515), (2006, 0.28586), (2007, 0.1674), (2008, 0.35185), (2009, 0.31253), (2010, 0.0335), (2011, 0.0976), (2012, 0.07865), (2013, 0.25625), (2014, 0.05968), (2015, 0.2626), (2016, 0)]

Historical Capacity Construction Rate[Poland][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0.00016), (1995, 0.00032), (1996, 0), (1997, 0.00177), (1998, 0), (1999, 0), (2000, 0), (2001, 0.0051), (2002, 0.018), (2003, 0.03), (2004, 0), (2005, 0.0084), (2006, 0.1716), (2007, 0.1731), (2008, 0.101), (2009, 0.40735), (2010, 0.3067), (2011, 0.247), (2012, 0.236), (2013, 0.5604), (2014, 0.1258), (2015, 0.4897), (2016, 0)]

Historical Capacity Construction Rate[Portugal][[(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.00206), (1993, 0.0027), (1994, 0), (1995, 0), (1996, 0.01065), (1997, 0), (1998, 0.0225), (1999, 0.00635), (2000, 0.04655), (2001, 0.03706), (2002, 0.06815), (2003, 0.1041), (2004, 0.26035), (2005, 0.4763), (2006, 0.72329), (2007, 0.35072), (2008, 0.69455), (2009, 0.75447), (2010, 0.3101), (2011, 0.536), (2012, 0.1752), (2013, 0.1291), (2014, 0.1918), (2015, 0), (2016, 0)]

Historical Capacity Construction Rate [Sweden][[(0,0)-(2015,10)]], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0.000225), (1992, 0), (1993, 0), (1994, 0), (1995, 0.00912), (1996, 0.0072), (1997, 0), (1998, 0.01039), (1999, 0), (2000, 0.00528), (2001, 0.0027), (2002, 0.153075), (2003, 0.11653), (2004, 0.046525), (2005, 0.0386), (2006, 0.048), (2007, 0.231025), (2008, 0.1472), (2009, 0.3587), (2010, 0.38423), (2011, 0.78395), (2012, 0.2825), (2013, 0.4447), (2014, 0.4159), (2015, 0.5693), (2016, 0) ~~ |

Historical Capacity Construction Rate [Turkey][[(0,0)-(2015,10)]], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0.0087), (1999, 0), (2000, 0.0552), (2001, 0), (2002, 0), (2003, 0.0012), (2004, 0), (2005, 0), (2006, 0.03085), (2007, 0.2872), (2008, 0.3631), (2009, 0.3211), (2010, 0.3015), (2011, 0.3045), (2012, 0.6056), (2013, 0.6047), (2014, 0.8841), (2015, 1.0415), (2016, 0) ~~ |

Historical Capacity Construction Rate [United Kingdom][[(0,0)-(2015,10)]], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0.01), (1991, 0.004), (1992, 0.038975), (1993, 0.081), (1994, 0.022), (1995, 0.047), (1996, 0.0758), (1997, 0.084), (1998, 0.018), (1999, 0.026), (2000, 0.0618), (2001, 0.08216), (2002, 0.107), (2003, 0.208), (2004, 0.241055), (2005, 0.632), (2006, 0.5936), (2007, 0.522), (2008, 0.811), (2009, 1.10583), (2010, 1.19523), (2011, 1.337), (2012, 2.38818), (2013, 2.38064), (2014, 2.05281), (2015, 1.163), (2016, 0) ~~ |

Historical Capacity Construction Rate [California][[(0,0)-(2015,10)]], (1980, 0), (1981, 0), (1982, 0), (1983, 0.00576), (1984, 0.1343), (1985, 0.11002), (1986, 0.013038), (1987, 0.076452), (1988, 0), (1989, 0.09853), (1990, 0.10497), (1991, 0), (1992, 0.00697), (1993, 0.07695), (1994, 0.01), (1995, 0.003), (1996, 0), (1997, 0.01785), (1998, 0.0524), (1999, 0.24547), (2000, 0), (2001, 0.0671), (2002, 0.139974), (2003, 0.21558), (2004, 0.09053), (2005, 0.06191), (2006, 0.24892), (2007, 0.063), (2008, 0.239), (2009, 0.261246), (2010, 0.454654), (2011, 0.664393), (2012, 1.625), (2013, 0.2915), (2014, 0.1064), (2015, 0.191), (2016, 0) ~~ |

Historical Capacity Construction Rate [Illinois][[(0,0)-(2015,10)]], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0), (2000, 0), (2001, 0), (2002, 0), (2003, 0.05015), (2004, 0.00066), (2005, 0.0561), (2006, 0), (2007, 0.5922), (2008, 0.2157), (2009, 0.6329), (2010, 0.7881), (2011, 0.69245), (2012, 0.39565), (2013, 0), (2014, 0), (2015, 0.2737), (2016, 0) ~~ |

Historical Capacity Construction Rate [Iowa][[(0,0)-(2015,10)]], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0.00025), (1993,
Historical Capacity Construction Rate [Kansas]([(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0), (1998, 0), (1999, 0.0014), (2000, 0), (2001, 0), (2002, 0.1122), (2003, 0), (2004, 0.15), (2005, 0.1005), (2007, 0), (2008, 0.3495), (2009, 0.2998), (2010, 0.1206), (2011, 0), (2012, 1.2845), (2013, 0.72415), (2014, 0), (2015, 0.52395), (2016, 0))

Historical Capacity Construction Rate [Minnesota]([(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0.02628), (1995, 0), (1996, 0), (1997, 0.00023), (1998, 0.10848), (1999, 0.13758), (2000, 0.02082), (2001, 0.02551), (2002, 0.01865), (2003, 0.2316), (2004, 0.0484), (2005, 0.15685), (2006, 0.15055), (2007, 0.403), (2008, 0.45635), (2009, 0.058), (2010, 0.39685), (2011, 0.52583), (2012, 0), (2013, 0.0075), (2014, 0.0476), (2015, 0.2), (2016, 0))

Historical Capacity Construction Rate [Oklahoma]([(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0.00023), (1998, 0.10848), (1999, 0.13758), (2000, 0.02082), (2001, 0.02551), (2002, 0.01865), (2003, 0.2316), (2004, 0.0484), (2005, 0.15685), (2006, 0.15055), (2007, 0.403), (2008, 0.45635), (2009, 0.058), (2010, 0.39685), (2011, 0.52583), (2012, 0), (2013, 0.0075), (2014, 0.0476), (2015, 0.2), (2016, 0))

Historical Capacity Construction Rate [Oregon]([(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0.00023), (1998, 0.10848), (1999, 0.13758), (2000, 0.02082), (2001, 0.02551), (2002, 0.01865), (2003, 0.2316), (2004, 0.0484), (2005, 0.15685), (2006, 0.15055), (2007, 0.403), (2008, 0.45635), (2009, 0.058), (2010, 0.39685), (2011, 0.52583), (2012, 0), (2013, 0.0075), (2014, 0.0476), (2015, 0.2), (2016, 0))


Historical Capacity Construction Rate [Washington]([(0,0)-(2015,10)], (1980, 0), (1981, 0), (1982, 0), (1983, 0), (1984, 0), (1985, 0), (1986, 0), (1987, 0), (1988, 0), (1989, 0), (1990, 0), (1991, 0), (1992, 0), (1993, 0), (1994, 0), (1995, 0), (1996, 0), (1997, 0.00046), (1998, 0.00023), (1999, 0), (2000, 0), (2001, 0.19848), (2002, 0.0481), (2003, 0.0192), (2004, 0.0006), (2005, 0.15), (2006, 0.597), (2007, 0.346755), (2008, 0.2116), (2009, 0.57235), (2010, 0.3562), (2011, 0.6532), (2012, 0.23515), (2013, 0.055), (2014, 0.2668), (2015, 0), (2016, 0))
Units: GW/Year

Description: Lookup function for capacity construction rate in a given state by year.

Historical rest of world turbine construction start rate:

Units: turbines/Year

Description: Lookup function for turbine construction rate for the rest of the world not included in the State group set by year.

6.9 Appendix C: Python Script for data pre-processing

#!/usr/bin/env python
# encoding: utf-8

""
readingexceldata2016.py
Created by Katherine Dykes 2010.
Copyright (c) Katherine Dykes. All rights reserved.

This script analyzes a workbook of historical data for the wind energy and parses it to develop code for the system dynamics model VENSIM. The current script is calibrated to output data for 1980 to 2014 inclusive. If the underlying workbook and data period are updated, the script must be updated in several places.

To use the script, first set the group of interest (variable = group). A custom group can be created in the "States" worksheet of the workbook by adding a new column.

Specify which variable set to run (if you have a large number of groups, then running full script can take a long time. You may want to run the full script once but then only run parts of it as necessary if specific areas of workbook have been updated.

Also specify if you would like to run a forward looking policy scenario:
- policy 1 will create a set-up where policy is held constant to 2030 after 2014.
- policy 2 will create a set-up where policy support is completely removed after 2014.

""

import xlrtd as EXCELREADER
import numpy as NP
```python
import operator as OP
import unicodedata as UC

# Step 0 - select which groups, variables and policies for VENSIM that you are updating; get workbook data

group = 5  # needs to be specified when run to get appropriate output; this is the group according to the excel sheet "States"

doland = True  # land area will be run if TRUE
dowind = True  # wind resource will be run if TRUE
doelec = True  # electricity prices will be run if TRUE
dopolicy = True  # policy incentives will be run if TRUE
docosttech = True  # historical cost and tech trends will be run if TRUE
dohistoric = True  # historic capacity and turbine will be run if TRUE

policy0 = False  # set to true if generation the set-up for policy 0 which disables policy supports prior to 2000
policy1 = False  # set to true if generating the set-up for policy 1 which keeps policy constant from 2015 to 2030
policy2 = False  # set to true of generating the set-up for policy 2 which keeps policy at 0 after 2014

# open data workbook and assign all the necessary sheets to variables
book = EXCELREADER.open_workbook("wind data - compiled 2015.xlsx")
statesheet = book.sheet_by_name('States')
windsheet = book.sheet_by_name('WindData')
projectsheet = book.sheet_by_name('Windfarms')
elecsheet = book.sheet_by_name('Electricity')
costsheet = book.sheet_by_name('Costs')
technsheet = book.sheet_by_name('Technology')
policyPIsheet = book.sheet_by_name('PolicyPI')
policyIIIsheet = book.sheet_by_name('PolicyII')
policyRECsheet = book.sheet_by_name('PolicyREC')
policyFITsheet = book.sheet_by_name('PolicyFIT')
totalsheet = book.sheet_by_name('Totals')

# Step 1 - Get groups for subsequent data analysis; Procedure for identifying which provinces and countries are joined with which groups
group_col = 8 + group

# find how many items are indexed - those with cell value 0 are excluded
count = 0
for x in range(1, statesheet.nrows):
    if statesheet.cell_value(x, group_col) != 0:
        count = count + 1
instring = OP.concat(OP.concat(str(count), 'i8, '), OP.concat(str(count), 'a25'))
group_array = NP.zeros(1, dtype=instring)

# extract groups with entry id and associated group id
count = 0
num_groups = 0
num_states = 0
for x in range(1, statesheet.nrows):
    if statesheet.cell_value(x, group_col) != 0:
        count = count + 1
instring = OP.concat(OP.concat(str(count), 'i8, '), OP.concat(str(count), 'a25'))
group_array = NP.zeros(1, dtype=instring)
```

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if statesheet.cell_value(x,group_col) != 0:
    num_states = num_states + 1
    group_array[0][0][count] = statesheet.cell_value(x,0)
    if statesheet.cell_value(x,group_col) in group_array[0][1][:]:
        group_array[0][1][count] = statesheet.cell_value(x,group_col)
    else:
        group_array[0][1][count] = statesheet.cell_value(x,group_col)
        num_groups = num_groups + 1
        count = count + 1

instring = OP.concat(str(num_groups),'a25')
group_list = NP.zeros(1,dtype=instring)
count = 0
year_col = 5
for x in range(1, statesheet.nrows):
    if statesheet.cell_value(x,group_col) in group_list[0,:]:
        count = count + 1
    elif statesheet.cell_value(x,group_col) != 0:
        if count < num_groups:
            group_list[0,count] = statesheet.cell_value(x,group_col)
            count = count + 1

# now print the group list to create the subscript functions for VENSIM
f = open('vensiminputtxt.txt','w')
f.write('States:
')
for x in range(0,num_groups):
    f.write(group_list[0,count])
    if count < (num_groups - 1):
        f.write(' ,
        count = count + 1
        if count < num_groups - 1:
            if OP.mod(count,10) == 0:
                f.write('

')
    f.write(' States in the analysis.

Statescopy:
')
for x in range(0,num_groups):
    f.write(group_list[0,count])
    if count < (num_groups - 1):
        f.write(' ,
        count = count + 1
        if count < num_groups - 1:
            if OP.mod(count,10) == 0:
                f.write('

')
    f.write(' Copy of States in the analysis for simulation.

# Step 2: Collect all the necessary variables for VENSIM for each identified group
# FUNCTION - Find total potential land for each group
# Procedure for aggregating total land area for each group as defined in Get groups function
if doland:
    area_col = 6
    instring = OP.concat(OP.concat(str(num_groups), 'a25,
'), OP.concat(str(num_groups), 'f4'))
    area_array = np.zeros(1, dtype=instring)

for x in range(0, num_groups):
    area_array[0][0][x] = group_list[0, x]

for y in range(1, statesheet.nrows):
    if statesheet.cell_value(y, group_col) == group_list[0, x]:
        area_array[0][1][x] = area_array[0][1][x] +
        statesheet.cell_value(y, area_col)*1000*1000

# now print the area to create the subscript functions for VENSIM
count = 0
f.write('

for x in range(0, num_groups):
    f.write('total potential land[')
    f.write(area_array[0][0][x])
    f.write(']=
    f.write(str(area_array[0][1][x]))
    if count < (num_groups - 1):
        f.write('~~|
    count = count + 1
    f.write('
	~	 meters * meters
    f.write('
	~	 Total available land area in a given state.

# FUNCTION - Find wind data by state
# Procedure of finding the wind resource polynomial fit coefficients for a region
if dowind:
    wind_col = 5
    state_col = 3
    prov_col = 4
    instring = OP.concat(OP.concat(str(num_groups), 'a25,
'), OP.concat(str(num_groups), 'f4'))
    max_array = np.zeros(1, dtype=instring)
    linear_array = np.zeros(1, dtype=instring)
    quad_array = np.zeros(1, dtype=instring)

for x in range(0, num_groups):
    max_array[0][0][x] = group_list[0, x]
    linear_array[0][0][x] = group_list[0, x]
    quad_array[0][0][x] = group_list[0, x]

windlist = []
landlist = []
count = 1.0
for w in range(0, num_states):
    for z in range(1, windsheet.nrows):
        if windsheet.cell_value(z, state_col) == group_array[0][0][w]:
            if group_array[0][1][w] == group_list[0, x]:
                windlist.append(windsheet.cell_value(z, wind_col))
                landlist.append(count)
                count = count + 1
        elif windsheet.cell_value(z, prov_col) == group_array[0][0][w]:
            if group_array[0][1][w] == group_list[0, x]:
                windlist.append(windsheet.cell_value(z, wind_col))
landlist.append(count)
count = count + 1
if count > 3:
    windreverse = np.array(windlist, reverse = True)
windsorted = np.array(windlist)
landordered = landlist
landsorted = landsorted / count
day = np.polyfit(landordered, windsorted, 2)
max_array[0][1][x] = windsorted[0]
linear_array[0][1][x] = day[1]
quad_array[0][1][x] = day[0]

# now print the wind data to the create the subscript functions for VENSIM
# # #
count = 0
f.write('\\n\\n')
for x in range(0,num_groups):
    f.write('max wind speed[\\n    f.write(max_array[0][0][x])
    f.write('] = ')
    f.write(str(max_array[0][1][x]))
    if count < (num_groups - 1):
        f.write('~~|\\n    count = count + 1
f.write('\\n\\t Maximum wind speed in a given region.\\n
    f.write('linear term for wind speed by land use[\\n    f.write(linear_array[0][0][x])
    f.write('] = ')
    f.write(str(linear_array[0][1][x]))
    if count < (num_groups - 1):
        f.write('~~|\\n    count = count + 1
f.write('\\n\\t Linear coefficient for polynomial fit of wind speed resource by land use.\\n
    f.write('quadratic term for wind speed by land use[\\n    f.write(quad_array[0][0][x])
    f.write('] = ')
    f.write(str(quad_array[0][1][x]))
    if count < (num_groups - 1):
        f.write('~~|\\n    count = count + 1

(564)
f.write('meters / second
')
f.write('Quadratic coefficient for polynomial fit of wind speed resource by land use.
')

# FUNCTION - Find electricity prices by year for the group
# Procedure of finding the long term electricity price trends for a group
if doelec:
    col_start = 6
    col_end = 41
    state_col = 4
    prov_col = 5
    instring = OP.concat(OP.concat(str(num_groups), 'a25, ')
               , OP.concat(OP.concat(str(col_end -
                          col_start), ','), OP.concat(str(num_groups), '}f2')))  
electricity_array = NP.zeros(1, dtype=instring)
for x in range(0, num_groups):
    electricity_array[0][0][x] = group_list[0, x]
for w in range(0, num_states):
    for z in range(1, elecsheet.nrows):
        if elecsheet.cell_value(z, state_col) ==
            group_array[0][0][w]:
            if group_array[0][1][w] ==
                group_list[0, x]:
                stategroup = 1
                for y in range(0, col_end - col_start):
                    if elecsheet.cell_value(z, col_start + y) != 0:
                        electricity_array[0][1][y][x] =
                            elecsheet.cell_value(z, col_start + y)
                if stategroup == 0:
                    if elecsheet.cell_value(z, prov_col) ==
                        group_array[0][0][w]:
                        if group_array[0][1][w] ==
                            group_list[0, x]:
                            for y in range(0, col_end - col_start):
                                if elecsheet.cell_value(z, col_start + y) != 0:
                                    electricity_array[0][1][y][x] =
                                        elecsheet.cell_value(z, col_start + y)

# now print the electricity prices to the create the subscript functions for VENSIM
count = 0
startyr = 1980
f.write('

')
for x in range(0, num_groups):
    trigger = 0
    f.write('Historical Electricity Prices[
')
f.write(electricity_array[0][0][x])
    f.write(']((0,0)-(2014,10)]
')
    for y in range(0, col_end - col_start):
        f.write(', (')
        f.write(str(startyr + y))
        f.write(', ')
        f.write(str(electricity_array[0][1][y][x]))
        f.write(')')
        trigger = trigger + 1
        if OP.mod(trigger, 10) == 0:
            f.write('\\n')
    f.write(')')
    f.write(')')

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if count < (num_groups - 1):
    f.write('~/\n')
    count = count + 1
f.write('
\n~\$ / (kW * hrs)\n')
f.write('~/t\nLookup function for electricity price based on year.\n\n# FUNCTION - Find policy incentives by year for the group
# Procedure of finding the long term policy trends for a group
if dopolicy:

    # Production Incentive policies
    col_start = 6
    col_end = 41
    state_col = 4
    prov_col = 5
    instring = "OP.concat(OP.concat(str(num_groups),"a25,
                        ",OP.concat(str(col_end-
                        
col_start),"),OP.concat(str(num_groups),"))f2")")
    policy_array = NP.zeros(1,dtype=instring)
    for x in range(0,num groups):
        policy_array[0][0][x] = grouplist[0,x]
        for w in range(0,num states):
            for z in range(1,policyPIsheet.nrows):
                if policyPIsheet.cell_value(z,prov_col)
                        == grouparray[0][0][w]:
                    if grouparray[0][1][w] == grouplist[0,x]:
                        stategroup = 0
                        if policyPIsheet.cell_value(z,prov_col)
                                == grouparray[0][0][w]:
                            if grouparray[0][1][w] == grouplist[0,x]:
                                if policyPIsheet.cell_value(z,col_start+y) != 0:
                                    policy_array[0][1][y][x] = policyPIsheet.cell_value(z,col_start + y)
        if stategroup == 0:
            if policyPIsheet.cell_value(z,prov_col) == grouparray[0][0][w]:
                if grouparray[0][1][w] == grouplist[0,x]:
                    for y in range(0, col_end - col_start):
                        if policyPIsheet.cell_value(z,col_start+y) != 0:
                            policy_array[0][1][y][x] = policyPIsheet.cell_value(z,col_start + y)
        # now print the production incentives to the create the subscript functions for
        VENSIM
        count = 0
        startyr = 1980
        f.write('~/\n')
        for x in range(0,num groups):
            trigger = 0
            f.write('Historical production incentive["
            f.write(policy_array[0][0][x])
            f.write(']((\(0,0)-(2014,10)])
            for y in range(0, col_end - col_start):
                if policy0:
                    if startyr + y < 1990:
f.write(str(0))
else:
f.write(str(policy_array[0][1][y][x])))
else:
f.write(str(policy_array[0][1][y][x])))
f.write(')
trigger = trigger + 1
if OP.mod(trigger,10) == 0:
f.write('\\n')
if policy1:
f.write(', (2030, ')
f.write(str(policy_array[0][1][y][x])))
f.write(')
if policy2:
f.write(', (2015, 0.0)')
f.write(')')
if count < (num_groups - 1):
f.write('~~\\n')
count = count + 1
f.write('\\n\t\t')
f.write('$ / (kW * hrs)\n\t\t$Lookup function for production incentive based on year.

# Investment Incentive policies
col_start = 6
col_end = 41
state_col = 4
prov_col = 5
instring = OP.concat(OP.concat(str(num_groups),'a25,'),OP.concat(OP.concat(str(col_end-col_start),''),OP.concat(str(num_groups),'f2')))policy_array = NP.zeros(1,dtype=instring)
for x in range(0,num_groups):
policy_array[0][0][x] = grouplist[0,x]
for w in range(0,num_states):
    for z in range(1,policyIIsheet.nrows):
        stategroup = 0
        if policyIIsheet.cell_value(z,state_col) == group_array[0][0][w]:
            if group_array[0][1][w] == group_list[0,x]:
                stategroup = 1
                for y in range(0, col_end - col_start):
                    if policyIIsheet.cell_value(z,col_start+y) != 0:
                        policy_array[0][1][y][x] = policyIIsheet.cell_value(z,col_start + y)
if stategroup == 0:
    if policyIIsheet.cell_value(z,prov_col) == group_array[0][0][w]:
        if group_array[0][1][w] == group_list[0,x]:
            for y in range(0, col_end - col_start):
                if policyIIsheet.cell_value(z,col_start+y) != 0:
                    policy_array[0][1][y][x] = policyIIsheet.cell_value(z,col_start + y)

# now print the investment subsidies to the create the subscript functions for
VENSIM
count = 0
startyr = 1980
f.write('

')
for x in range(0,numgroups):
    trigger = 0
    f.write('Historical investment subsidy[
')
    f.write(policyarray[0][0][x])
    f.write(']([(0,0)-(2014,10)]

for y in range(0, col_end - col_start):
    f.write(',
    f.write(str(startyr + y))
    f.write('
    if policy0:
        if startyr + y < 1990:
            f.write(str(0))
        else:
            f.write(str(policyarray[0][1][y][x]))
    else:
        f.write(str(policyarray[0][1][y][x]))
    f.write(')')
    trigger = trigger + 1
    if OP.mod(trigger,10) == 0:
        f.write('\n')
    if policy1:
        f.write(' (2030, ')
        f.write(str(policyarray[0][1][y][x]))
    f.write(')')
    if policy2:
        f.write(' (2015, 0.0)')
    if count < (num_groups - 1):
        f.write('~~\n')
    count = count + 1
f.write('dimensionless

tLookup function for investment subsidy based on
year.

# Feed in Tariff policies
col_start = 6
col_end = 41
state_col = 4
prov_col = 5
instring = OP.concat(OP.concat(str(num_groups),'a25,
(col_end-col_start),',OP.concat(str(num_groups),'f2'))
policy_array = NP.zeros(1,dtype=instring)
for x in range(0,num_groups):
    policy_array[0][0][x] = group_list[0,x]
for w in range(0,num_states):
    for z in range(1,policyFITsheet.nrows):
        stategroup = 0
        if policyFITsheet.cell_value(z,state_col) == group_array[0][0][w]:
            if group_array[0][1][w] == group_list[0,x]:
                stategroup = 1
            for y in range(0, col_end - col_start):

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if policyFITsheet.cell_value(z, col_start + y) != 0:
policy_array[0][1][y][x] = policyFITsheet.cell_value(z, col_start + y)
if stategroup == 0:
    if policyFITsheet.cell_value(z, prov_col) == group_array[0][0][w]:
        if group_array[0][1][w] == group_list[0, x]:
            for y in range(0, col_end - col_start):
                if policyFITsheet.cell_value(z, col_start + y) != 0:
                    policy_array[0][1][y][x] = policyFITsheet.cell_value(z, col_start + y)

# now print the feed in tariff rates to the create the subscript functions for VENSIM
count = 0
startyr = 1980
f.write('

')
for x in range(0, num_groups):
    trigger = 0
    f.write('Historical feed in tariff rate[
    f.write(policy_array[0][0][x])
    f.write(']([0,0)-(2014,10)]
    for y in range(0, col_end - col_start):
        f.write(', (')
        f.write(str(startyr + y))
        f.write(', ')
        if policy0:
            if startyr + y < 1990:
                f.write(str(0))
            else:
                f.write(str(policy_array[0][1][y][x]))
        else:
            f.write(str(policy_array[0][1][y][x]))
        f.write(')
    trigger = trigger + 1
    if OP.mod(trigger, 10) == 0:
        f.write('\\n')
    if policy1:
        f.write('(', 2030, ')
        f.write(str(policy_array[0][1][y][x]))
        f.write(')')
    if policy2:
        f.write('(', 2015, 0.0')
        f.write(')')
    if count < (num_groups - 1):
        f.write('~\n'
        count = count + 1
f.write('
	-	$ / (kW * hrs)\n	- Lookup function for feed-in-tariff based on year.\n	-

# REC Incentive policies
col_start = 6
col_end = 41
state_col = 4
prov_col = 5
instring = OP.concat(OP.concat(str(num_groups), 'a25,'),'NP.zeros(1,dtype=instring)
for x in range(0,num_groups):
policy_array[0][0][x] = group_list[0,x]
for w in range(0,num_states):
    for z in range(1,policyRECsheet.nrows):
        stategroup = 0
        if policyRECsheet.cell_value(z,statecol) == group_array[0][0][w]:
            if group_array[0][1][w] == group_list[0,x]:
                stategroup = 1
                for y in range(0, col_end - col_start):
                    if policyRECsheet.cell_value(z,col_start+y) != 0:
                        policy_array[0][1][y][x] = policyRECsheet.cell_value(z,col_start + y)
        if stategroup == 0:
            if policyRECsheet.cell_value(z,prov_col) == group_array[0][0][w]:
                if group_array[0][1][w] == group_list[0,x]:
                    for y in range(0, col_end - col_start):
                        if policyRECsheet.cell_value(z,col_start+y) != 0:
                            policy_array[0][1][y][x] = policyRECsheet.cell_value(z,col_start + y)
#
# now print the REC prices to the create the subscript functions for VENSIM

count = 0
startyr = 1980
f.write('

for x in range(0,num_groups):
    trigger = 0
    f.write('Historical rec price[')
    f.write(']([0,0)-(2014,10)]
    for y in range(0, col_end - col_start):
        f.write(', ('
        f.write(str(startyr + y))
        f.write(', ')
        if policy0:
            if startyr + y < 1990:
                f.write(str(0))
            else:
                f.write(str(policy_array[0][1][y][x]))
        else:
            f.write(str(policy_array[0][1][y][x]))
        if trigger == trigger + 1
        if OP.mod(trigger,10) == 0:
            f.write('\\n')
        if policy1:
            f.write(', (2030, ')
            f.write(str(policy_array[0][1][y][x]))
            f.write(')')
        if policy2:
            f.write(', (2015, 0.0)')
            f.write(')')
        if count < (num_groups - 1):
            f.write(')')

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f.write('~~|\n')
count = count + 1
f.write('\\t~\t')
f.write('${(kW * hrs)/-10} $/kW
	- Lookup function for REC price based on year.\n\t|\n')

# FUNCTION - Find cost and technology trends
# Procedure of finding the cost and technology trends
if docosttech:
    years = 35
turbcost_array = NP.zeros(35)
boscost_array = NP.zeros(35)
omcost_array = NP.zeros(35)
lcoecost_array = NP.zeros(35)
for x in range(0, 35):
    turbcost_array[x] = costsheet.cell_value(x+1,1)
boscost_array[x] = costsheet.cell_value(x+1,2)
omcost_array[x] = costsheet.cell_value(x+1,3)
lcoecost_array[x] = costsheet.cell_value(x+1,4)
rdtech_array = NP.zeros(35)
rptech_array = NP.zeros(35)
hhtech_array = NP.zeros(35)
for x in range(0, 35):
    rdtech_array[x] = techsheet.cell_value(x+1,1)
rptech_array[x] = techsheet.cell_value(x+1,2)
hhtech_array[x] = techsheet.cell_value(x+1,3)

f.write('Historical Turbine Cost([0,0)-(2015,10)])
for x in range(0,35):
    f.write(capitalize(str(1980 + x)) + ', ')
f.write(capitalize(str(turbcost_array[x])) + ', ')
f.write(')\n\t~/kW\n	- Historical turbine costs per kW.\n

f.write('Historical BOS Costs([0,0)-(2015,10)])
for x in range(0,35):
    f.write(capitalize(str(1980 + x)) + ', ')
f.write(capitalize(str(boscost_array[x])) + ', ')
f.write(')\n\t~/kW\n	- Historical BOS costs per kW.\n

f.write('Historical OPEX Costs([0,0)-(2015,10)])
for x in range(0,35):
    f.write(capitalize(str(1980 + x)) + ', ')
f.write(capitalize(str(omcost_array[x])) + ', ')
f.write(')\n\t$/kW\n	- Historical OPEX costs per kW.\n

f.write('Historical LCOE Costs([0,0)-(2015,10)])
for x in range(0,35):
    f.write(capitalize(str(1980 + x)) + ', ')
f.write(capitalize(str(lcoecost_array[x])) + ', ')
f.write(')\n\t$/kW\n	- Historical LCOE costs per kW.\n

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Historical OPEX costs per kWh.

Historical Marginal LCOE[(0,0)-(2015,10)]

Historical Marginal Rotor Diameter[(0,0)-(2015,10)]

Historical Marginal Rated Power[(0,0)-(2015,10)]

Historical Marginal Hub Height[(0,0)-(2015,10)]
# Function to aggregate historical variables for wind projects and technology
# Procedure to aggregate historical variables for wind projects and technology by
groups of interest.
if dohistoric:
    state_col = 3
    prov_col = 4
    year_col = 6
    turb_col = 7
    cap_col = 8
    power_col = 9
    diam_col = 10
    col_start = 4
    col_end = 41

    instring = OP.concat(OP.concat(str(num_groups),'a25, ('),OP.concat(OP.concat(str(col_end-col_start),','),OP.concat(str(num_groups),')f8'))

    newprojects_array = np.zeros(1,dtype=instring)
    newturbines_array = np.zeros(1,dtype=instring)
    newcapacity_array = np.zeros(1,dtype=instring)
    newpower_array = np.zeros(1,dtype=instring)
    indexpower_array = np.zeros(1,dtype=instring)
    newdiameter_array = np.zeros(1,dtype=instring)
    indexdiam_array = np.zeros(1,dtype=instring)

    for x in range(0,num_groups):
        newturbines_array[0][0][x] = group_list[0,x]
        newcapacity_array[0][0][x] = group_list[0,x]
        newpower_array[0][0][x] = group_list[0,x]
        newdiameter_array[0][0][x] = group_list[0,x]
    for w in range(0,num_states):
        for z in range(1,projectsheet.nrows):
            stategroup = 0
            if projectsheet.cell_value(z,state_col) == group_array[0][0][w]:
                if group_array[0][1][w] == group_list[0,x]:
                    stategroup = 1
            if (projectsheet.cell_value(z,year_col) != '') &
            (projectsheet.cell_value(z,year_col) <= 2015):
                y = projectsheet.cell_value(z,year_col) - 1980
                newprojects_array[0][1][y][x] = newprojects_array[0][1][y][x] + 1
                if projectsheet.cell_value(z,cap_col) > 0:
                    newcapacity_array[0][1][y][x] = newcapacity_array[0][1][y][x] +
                    projectsheet.cell_value(z,cap_col)
                if projectsheet.cell_value(z,turb_col) > 0:
                    newturbines_array[0][1][y][x] = newturbines_array[0][1][y][x] +
                    projectsheet.cell_value(z,turb_col)
                if projectsheet.cell_value(z,power_col) > 0:
                    newpower_array[0][1][y][x] = newpower_array[0][1][y][x] +
                    projectsheet.cell_value(z,power_col)*projectsheet.cell_value(z,turb_col)
                if projectsheet.cell_value(z,diam_col) > 0:
                    newdiameter_array[0][1][y][x] = newdiameter_array[0][1][y][x] +
                    projectsheet.cell_value(z,diam_col)*projectsheet.cell_value(z,turb_col)
indexdiam_array[0][1][y][x] = indexdiam_array[0][1][y][x] + 
 projectsheet.cell_value(z,turb_col)

    if stategroup == 0:
        if projectsheet.cell_value(z,prov_col) == group_array[0][0][w]:
            if group_array[0][1][w] == group_list[0][x]:
                y = projectsheet.cell_value(z,year_col) - 1980
                newprojects_array[0][1][y][x] = newprojects_array[0][1][y][x] + 1
                # print projectsheet.cell_value(z,year_col)
                if (projectsheet.cell_value(z,year_col) != ' '):
                    if projectsheet.cell_value(z,year_col) <= 2015):
                        if projectsheet.cell_value(z,cap_col) > 0:
                            newcapacity_array[0][1][y][x] = newcapacity_array[0][1][y][x] +
                            projectsheet.cell_value(z,cap_col)
                        if projectsheet.cell_value(z,turb_col) > 0:
                            newturbines_array[0][1][y][x] = newturbines_array[0][1][y][x] +
                            projectsheet.cell_value(z,turb_col)
                        if projectsheet.cell_value(z,power_col) > 0:
                            newpower_array[0][1][y][x] = newpower_array[0][1][y][x] +
                            projectsheet.cell_value(z,power_col)*projectsheet.cell_value(z,turb_col)
                            indexpower_array[0][1][y][x] = indexpower_array[0][1][y][x] +
                            projectsheet.cell_value(z,turb_col)
                        if projectsheet.cell_value(z,diam_col) > 0:
                            newdiameter_array[0][1][y][x] = newdiameter_array[0][1][y][x] +
                            projectsheet.cell_value(z,diam_col)*projectsheet.cell_value(z,turb_col)
                            indexdiameter_array[0][1][y][x] = indexdiameter_array[0][1][y][x] +
                            projectsheet.cell_value(z,turb_col)

    years = 35 # need to set if number of years is updated for data sources
    turbine_array = np.zeros(35)
    for x in range(0, 35):
        turbine_array[x] = totalsheet.cell_value(x+1,1)
    # now print the historical turbine and project data to the create the subscript functions for VENSIM
    count = 0
    startyr = 1980
    f.write('\\n')
    for x in range(0,num_groups):
        trigger = 0
        f.write('Historical Turbine Construction Rate[
')
        f.write(newturbines_array[0][0][x])
        f.write('][([0,0)-(2015,10)])
        for y in range(0, col_end - col_start):
            f.write(', (')
            f.write(str(startyr + y))
            f.write(', ')
            f.write(str(newturbines_array[0][1][y][x]))
            f.write(')')
            trigger = trigger + 1
            if op.mod(trigger,10) == 0:
                f.write('\\n')
        if count < (num_groups - 1):
            f.write('~~\\n')
        f.write(')')
    if count < (num_groups - 1):
        f.write('~~\\n')

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count = count + 1
f.write('
\t|\t')
f.write('turbines/Year\n')
f.write('\t|\tLookup function for turbine construction rate in a given state by year.\t|\n')

# # #
count = 0
startyr = 1980
f.write('\n\n')
for x in range(0,num_groups):
    trigger = 0
    f.write('Historical Turbine Installed Base[']
    f.write(newturbines_array[0][0][x])
    f.write('](\[(0,0)-(2015,10)\]')
turbinesIB = 0
for y in range(0, colend - colstart):
    f.write(', (')
    f.write(str(startyr + y))
    f.write(', ')
    turbinesIB = turbinesIB + newturbines_array[0][1][y][x]
    f.write(str(turbinesIB))
    f.write(')')
    trigger = trigger + 1
    if OP.mod(trigger,10) == 0:
        f.write('\\n')
    f.write(')')
    if count < (num_groups - 1):
        f.write('~|\n')
    count = count + 1
f.write('
\t|\t')
f.write('turbines\n')
f.write('\t~|Lookup function for total turbines installed in a given state by year.\t|\n')

# # #
count = 0
startyr = 1980
f.write('\n\n')
for x in range(0,num_groups):
    trigger = 0
    f.write('Historical Capacity Installed Base[']
    f.write(newcapacity_array[0][0][x])
    f.write('](\[(0,0)-(2015,10)\]')
capacityIB = 0
for y in range(0, col_end - col_start):
    f.write(', (')
    f.write(str(startyr + y))
    f.write(', ')
    capacityIB = capacityIB + newcapacity_array[0][1][y][x]/(1e6)
    f.write(str(capacityIB))
    f.write(')')
    trigger = trigger + 1
    if OP.mod(trigger,10) == 0:
        f.write('\\n')

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f.write(')
if count < (num_groups - 1):
    f.write('~~\n')
count = count + 1
f.write('\\n\t~
')
f.write('GW
')
for x in range(0, num_groups):
    trigger = 0
    f.write('Historical Capacity Construction Rate[
    f.write(newcapacity_array[0][0][x])
    f.write(']([0,0)-(2015,10])')
    for y in range(0, col-end - col_start):
        f.write(', ('
        f.write(str(startyr + y))
        f.write(', ')
        f.write(str(newcapacity_array[0][1][y][x]/(1e6)))
        f.write(')')
        trigger = trigger + 1
        if OP.mod(trigger,10) == 0:
            f.write('\\n')
    f.write(')')
if count < (num-groups - 1):
    f.write('~~|n')
count = count + 1
f.write('~
')
f.write('GW/Year
')
for x in range(0, num_groups):
    trigger = 0
    f.write('Historical rest of world turbine construction start rate')
    f.write(']([0,0)-(2015,10])')
    for y in range(0,35):
        trigger = 0
        turbineexperience = 0
        for x in range(0, num_groups):
            turbineexperience = turbineexperience + newturbines_array[0][1][y][x]
        f.write(', ('
        f.write(str(startyr + y))
        f.write(', ')
        f.write(str(turbine_array[y]-turbineexperience))
        f.write(')')
        trigger = trigger + 1
        if OP.mod(trigger,10) == 0:
            f.write('\\n')
    f.write(')')
f.write('n\t\t')
f.write('turbines/year\n')
f.write('n\t\tLookup function for turbine construction rate for the rest of the
world not included in the State group set by year.\t|n')

# final action close the file with all the input in order
f.close # last action of script is to close the open file that exists