Evaluating the Technical Innovation Landscape for Wind Energy’s Competitive Future:

A Value Creation – Value Capture Analysis

By

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Submitted to the System Design and Management Program
In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management
at the
Massachusetts Institute of Technology

September 2014

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“As yet, the wind is an untamed, and unharnessed force; and quite possibly one of the greatest discoveries hereafter to be made, will be the taming, and harnessing of the wind”

- Abraham Lincoln, “Discoveries and Inventions”, 1858
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Abstract

This thesis utilizes a systems approach to develop a framework to analyze the value creation and value capture potential of technical innovations in the wind energy sector of the electric power industry. Six technical innovations are considered for the analysis, including Grid-Scale Storage, On-Site Manufacturing Systems, Transmission Power Flow Control, Near-Term Forecasting, Long-Term Forecasting and Predictive Maintenance. Several comparative techniques are employed, including Pugh selection, weighted stakeholder occurrence based on stakeholder value networks, and a multi-attribute utility method. The technologies are compared across multiple possible future scenarios and scored based on their value contribution to stakeholders of both the wind power plant as well as the entire electric power system.

Of the technical innovations analyzed in this framework, Grid-Scale Storage, On-Site Manufacturing Systems and Predictive Maintenance promise to contribute the greatest value to industry stakeholders and thus are the most likely to improve the competitiveness of the wind industry. A combined application of the multi-attribute utility method with the weighted stakeholder occurrence method based on stakeholder value networks was the most effective in distinguishing value contribution from the technologies. A value creation – value capture matrix provides a useful method for visualizing value contribution to industry stakeholders and is used to inform commercialization strategy of the selected technologies. In addition, trade plots are utilized for selecting which technologies contribute the highest value across multiple possible future scenarios.

Thesis Supervisor: Stephen Connors

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List of Acronyms

AGC – Automatic Generation Control
AWEA – American Wind Energy Association
CT – Combustion Turbine
CO – Carbon Offset
DA – Day-Ahead
EIA – Energy Information Administration
EPA – Environmental Protection Agency
EPC – Engineering, Procurement and Construction
FERC – Federal Energy Regulatory Commission
GSS – Grid-Scale Storage
IPP – Independent Power Producer
IRR – Internal Rate of Return
ISO – Independent System Operator
kW/kWh – Kilowatt/Kilowatt-hour
LCOE – Levelized Cost of Electricity
LMP – Locational Marginal Price
LSE – Load-Serving Entity
LTF – Long-Term Forecasting
MAE – Mean Absolute Error
MAU – Multi-Attribute Utility
MW/MWh – Megawatt/Megawatt-Hour
NCAR – National Center for Atmospheric Research
NGO – Non-Governmental Organization
NREL – National Renewable Energy Laboratory
NTF – Near-Term Forecasting
O&M – Operations and Maintenance
OEM – Original Equipment Manufacturer
OSMS – On-Site Manufacturing Systems
PdM – Predictive Maintenance
PFC – (Transmission) Power Flow Control
PPA – Power Purchase Agreement
PTC – Production Tax Credit
REC – Renewable Energy Credit (Certificate)
RPM – Reliability Pricing Model
RPS – Renewable Portfolio Standard
RT – Real-Time
RTEP – Regional Transmission Expansion Plan
RTO – Regional Transmission Operator
SCADA – Supervisory Control and Data Acquisition
SVN – Stakeholder Value Network
TCA – Topology Control Algorithms
TO – Transmission Owner
WSO – Weighted Stakeholder Occurrence
Introduction

This thesis utilizes a systems approach to develop a framework to analyze the value creation and value capture potential of technical innovations in the wind energy sector of the electric power industry. Six technical innovations are considered for the analysis, including Grid-Scale Storage, On-Site Manufacturing Systems, Transmission Power Flow Control, Near-Term Forecasting, Long-Term Forecasting and Predictive Maintenance. Several comparative techniques are employed, including Pugh selection, weighted stakeholder occurrence based on stakeholder value networks, and a multi-attribute utility method. The technologies are compared across multiple possible future scenarios and scored based on their value contribution to stakeholders of both the wind power plant as well as the entire electric power system. Those technologies with the highest value contribution are discussed and further analyzed to understand the commercialization challenges and possible strategies for the technology firm to consider. The proposed value creation – value capture framework is a robust tool for evaluating the technical innovation landscape of the wind industry, and can highlight those technologies that are poised to greatly increase the competitiveness of the industry. Furthermore, the application of this analysis can aid technology firms in understanding their commercialization strategy by visualizing how value is distributed to industry stakeholders.

Motivation

As an active member of the wind energy industry in the US, I often hear the outlook that through technological advancements, wind turbine prices will continue to fall to the point at which wind energy is at “grid parity” in competitive electrical power systems. This sense of optimism continues to inspire my work in the industry, however, I have not yet seen an analysis of how such a cost reduction - and subsequent industry growth - will manifest via the commercialization of technical innovations.

Numerous studies have analyzed aspects of wind energy systems and identified opportunities for cost reduction or energy production improvement. Businesses, entrepreneurs and universities continue to invent technologies that exploit these opportunities to create value for the industry. Several impact studies have analyzed the effects of integrating more wind power into electric power systems and have quantified the capacity for system-wide adoption of wind (which is quite large). Yet none have suggested a structure for how the value creation opportunities in wind are actually captured by industry stakeholders and exploited through sustainable business formats to lower the cost of wind energy for consumers.

In this thesis I sought to explore how some of the latest technologies in the wind sector contribute value to the electric power system and further the penetration of wind into the energy mix. I wanted to define a framework that would aid in determining how commercially viable these technologies are – knowing that wind is a tough industry for technology adoption – and what commercialization strategy should be used for the most promising technologies. I also wanted to take a “non-traditional” view of technology innovation and, rather than focus on re-architecting the wind generator, cast a wider net to consider enabling technologies elsewhere in the value chain that will impact the overall power system in addition to wind power plants.
Research Methods
The information gathered for the context and discussion of the analytical work in this thesis was largely sourced from my first-hand experiences working in multiple roles in the wind industry over the last seven years. From 2007-2013 I was employed as an engineer and product manager by Second Wind, an original equipment manufacturer and supplier of wind resource assessment technology to Project Developers and Wind Plant Owners/Operators. It was during this time that I learned the project development or “plant” side of the wind industry and I use this knowledge to describe the wind industry in Part 1B and 1C, construct the Project Developer-focused stakeholder value network, and analyze the impact of technologies on stakeholder business models. At Second Wind I also worked on several projects to integrate our measurement equipment into Near-Term Forecasting services, and I use these experiences to supplement my description and value analysis of that technology.

Over the summer of 2013, I was employed as a research fellow at the US Department of Energy’s Advanced Research Projects Agency-Energy (ARPA-E). During my short time there, I examined new generator technology for offshore applications and compiled a volume of data, and subsequent intuition, about trends in wind technology and costs. I was also involved in the technology-to-market research for Transmission Power Flow Control technologies and their commercial application for integrating higher levels of renewable energy. Since my fellowship, I’ve continued to consult on an ARPA-E funded project for topology control algorithms – a software implementation of Power Flow Control. It is from these experiences that I can speak of the innovation landscape for wind as well as the more detailed benefits of Power Flow Control.

Since the fall of 2013 I have also been involved in two Boston-based wind startup companies. I am a co-founder of Cardinal Wind, a wind project finance platform based on innovations in wind energy prediction algorithms, which was formed through the MIT course 15.366 – Energy Ventures. I have also been employed part-time by Keystone Tower Systems as a business analyst. Keystone is developing an advanced manufacturing process to allow on-site production of steel towers for wind turbines. It is from my close and active involvement in each of these organizations that I can speak of Long-Term Forecasting and On-Site Manufacturing Systems; and I use these organizations as exemplars of the technical innovation categories.

My primary source of knowledge for the “system” side of the industry was obtained from the MIT course ESD.162J – Engineering, Economics and Regulation of the Electric Power System (the most informative course I’ve taken at MIT). I use this knowledge to describe the wind industry in Part 1B and 1C. In addition, my final coursework for ESD.162J is utilized for Part 1D – The Electric Power System and Market and Part 1E – The Benefits and Challenges of Wind Integration. It is also from this coursework that I was able to form the System Operator-focused and Electricity Consumer-focused system value networks.

The analytical framework developed in this thesis is largely a compilation of system analysis tools I gathered in my System Design and Management coursework beginning in January 2013. The discussion and categorization of innovation in Part 2B can be attributed to my learnings from 15.905 - Technology Strategy and ESD.33 - Systems Engineering. ESD.33 was also useful in guiding the application of the Pugh method and multi-attribute utility method. However, the largest contribution to the analysis was from ESD.34 – System Architecture, which guided the application of the system value network and weighted stakeholder occurrence techniques, as well as the architecture discussion in Part 1B.
In all possible instances I have located and cited a primary source for reported facts, figures and critical assumptions used in this thesis, some of which can be traced to specific lectures from the courses listed above. In other cases, the general knowledge used to create context and assumptions can be traced back to the experiences and coursework listed above and are not cited specifically.
Part 1 – Wind Industry and System Landscape

A. Utility-Scale Wind Power in the US

This thesis will focus on utility-scale electrical power from wind turbine generator systems. The American Wind Energy Association (AWEA) defines “utility-scale” wind as “wind turbines larger than 100 kilowatts [that] are developed with electricity delivered to the power grid and distributed to the end user by electric utilities or power system operators”. Alternatively, “small” and “distributed” wind turbines are operated behind a customer meter, on the distribution grid, or in some cases, in off-grid applications (AWEA). While the majority of capacity growth today is at the utility-scale, the industry arose from these smaller systems. The first small wind turbine to produce electricity was built in Denmark in 1891 and soon after wind turbine systems began to be introduced to the United States. By the 1930s, hundreds of thousands of small wind turbine systems were operating in the regions of rural America not yet connected to the electricity grid. The first utility-scale wind turbine, with a capacity of 1.25 MW, went into operation in Vermont in 1941 (Masters).

Throughout the mid-1900s, as the regulated, utility-owned electric power grid expanded into more communities and thermal and hydro generators continued to reduce costs through expanded economies of scale, wind power became a less attractive source of electricity. That is until the 1970s when a series of oil supply shocks increased the awareness for domestic energy security and seeded new policy to promote efficient and renewable energy sources (Masters). In addition to the oil energy crisis, it was becoming clear that the economies of scale for large thermal and hydro power plants had reached their limit, and the US government wanted to encourage more competition in the electric power industry to continue to reduce costs. In 1978, the Public Utility Regulatory Policies Act (PURPA) was signed into law which allowed that independent power producers (IPPs) could connect their energy generators to the utility-owned grid and that the utilities were required to purchase this electricity at fair market value. By guaranteeing a market, PURPA initiated the first phase of the competitive electric power industry, and many utility-scale wind turbine power plants (“wind plants”) were constructed shortly thereafter (Masters).

Following PURPA, the US wind industry growth ebbed and flowed with the creation, lapsing and renewal of economic benefits for wind plants. However in the last decade, despite the sporadic policy support, wind capacity has rapidly grown with a 10x capacity increase and more than 61 GW of capacity online in 2013 (enough to power 15 million average American homes). Arguably, the primary policy driver has been the Federal Production Tax Credit (PTC) which provides up-front tax relief for the wind plant of $0.023/kWh of energy produced for the first ten years of the plants operation. An important state-level policy driver has been the Renewable Portfolio Standard (RPS). Twenty-nine states and the District of Columbia have an RPS program that require a certain percentage of electricity sales to be procured from renewable sources (GWEC).
Whatever the policy or market causes may be, technical improvements and economies of scale in wind turbine generators have resulted in a 43% reduction in cost over the last four years. On a levelized cost of energy (LCOE) basis, on-shore wind plants are the second least expensive source of electricity in the country today next to natural gas (EIA). This is likely why in the past five years, wind plants accounted for 31% of the new generating capacity added in the US, and in several of those years, wind plants accounted for the most capacity added by technology (AWEA). This has attracted an average annual investment of $15 billion in the US wind industry. Compared internationally, the US has the second largest operational fleet of wind turbines in the world (GWEC).

As with any industry, several challenges are on the horizon. Despite the current scale and growth trajectory, wind contributes only 4% to the total electrical demand in the US (Gipe). At these levels, wind has been relatively inconsequential to the operation of the electric power system. As penetration levels grow, several systematic challenges will arise which may slow the adoption of wind. Furthermore, the industry growth has been tightly correlated with the existence of the PTC and RPS policies, whose future extension and expansion are uncertain. The current PTC is set to expire at the end of 2014 and overall, the RPS targets have been 86% fulfilled through 2011 (GWEC). This thesis will consider new technical innovations that may help to maintain the industry growth in light of these hurdles, and identify the best technologies that contribute value not only to the wind plant, but to the electric power system as a whole.
B. Wind System Architecture

Prior to describing and evaluating the technical innovations in the wind industry, a brief overview of the existing system architecture is presented in this section to establish a base for analysis. The hierarchical system abstractions shown in Figure 3 represent the wind turbine as the source of generation in a wind plant. The plant integrates to the power system at the interconnection point between the wind plant and the power system where a network of transmission lines transfers the flow of electricity for bulk power delivery.

![Hierarchical System Boundaries](http://terawallpaper.com/wind-turbine-diagram/)

**Figure 3 - Hierarchical System Boundaries**

Wind Turbine

![Wind Turbine Decomposition](http://sweetclipart.com/wind-turbine-line-art-1190)

**Figure 4 - Wind Turbine Decomposition**

The industry standard utility-scale wind turbine generator system employs a three-bladed, horizontal-axis, up-wind design (Masters). Figure 5 shows a sketch of this design of wind turbine with a simplified decomposition of the wind turbine form in Figure 4. The kinetic energy from the wind is extracted by the wind turbine, which is facing into the oncoming wind direction, and converted to rotational energy (Manwell, McGowan and Rogers). The passing wind creates a lift force on the blades which cause the rotor to rotate from the moment of the blade connection at the rotor hub. The rotor powers a drive train consisting of a shaft, and, depending on the design, a gearbox. The rotational velocity is modified.

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US Transmission System Image: [www.geni.org](http://www.geni.org)
2 Figure 5 from [http://terawallpaper.com/wind-turbine-diagram/](http://terawallpaper.com/wind-turbine-diagram/)
by the drivetrain to meet requirements for the
electricity generator, which can be of various designs.
The electricity generator converts the rotational energy
to electromagnetic energy which is transferred out of
the turbine along conductors as electricity. There is
often electrical rectifying, inverting and filtering
components (“converter”), not shown in Figure 5, that
converts the electricity from the generator prior to
transferring out of the turbine to meet electrical
standards (in the US, 60-Hz AC). The blade and rotor set
mount to an enclosure called a nacelle, which houses
the drivetrain, generator and converter. The nacelle sits
atop a tower, often a steel monopole design, which
keeps the turbine aloft in higher winds above the
ground. The tower is mounted to the ground at a
concrete foundation pad.

Wind Plant

In a wind power system, the generating station is composed of a group of wind turbines and is referred
to as a “wind plant”. At each wind turbine in the wind plant there is typically a step-up transformer that
raises the voltage level of the electrical power received from the turbine for distribution throughout the
plant (higher voltage = less electrical loss) (Manwell, McGowan and Rogers). A system of electrical
conductors, generally underground, carry the electricity to a collector system for the plant, which again
steps up the voltage of the electricity. This is the interconnection point to the transmission network of
the power system. Within the plant there are also a network of sensors to record wind speed,
meteorological conditions, turbine power output and various other turbine conditions. These sensors
are located on each turbine as well as meteorological equipment installed at the plant. A supervisory
control and data acquisition (SCADA) system collects and stores all of this data and transmits reports to
a human operator in a control room, which may be remote from the wind plant. The operator can view
events such as equipment failures, gain operational awareness about the plant, and control the turbines
through the SCADA system interface.
The classic representation of an electric power system architecture, as seen in Figure 9, is from the electricity generator ("plant") at the delivery end of the system and the Electricity Consumers at the receiving end of the system (Masters). In between is the transmission (high voltage in blue) and distribution (low voltage in green) equipment that modify the voltage and phase of the electric energy to optimize delivery efficiency, reliability and safety. For purposes of simplicity, all customers will be referred to as “Electricity Consumers” regardless of their interconnection voltage. Furthermore, the distribution equipment is abstracted from hierarchical view in Figure 3 and will not be included in the system analysis.
C. Wind Plant Value Chain

The Wind Industry Model

The industry modelled in this thesis assumes a deregulated power system, where IPPs can provide services to the power system with a wind plant that is not utility owned or controlled. From the IPP perspective of building and operating a wind plant to generate electricity in a deregulated system, the wind industry value chain can be segmented into five functional elements: Develop, Finance, Equip, Operate and Market. This is not the value chain of a vertically integrated electric utility with a regulated monopoly. Instead, each of these five elements can involve a variety of stakeholder groups. Each of the stakeholder groups are introduced in bold text below under the subheadings that represent each value chain element.

Develop

A Project Developer is an organization that is central to the development phase of a wind plant. A “project”, or potential wind plant, must go through many stages of technical and economic studies and multi-party agreements which the Project Developer manages. Project Development organizations can take on several different business models. Some Project Developers focus only on the early-stage origination of projects, build a pipeline of good project candidates, and then sell these projects to another organization to continue developing. Others develop the entire project and continue to own and operate the wind plant for revenue. For this model, the focus will be on Project Developers that complete the entire development and construction of a wind plant and then sell it for a fee to another organization to operate.

Any new project is created by first identifying a business opportunity. This is the process of “prospecting”, in which physical resource data is collected and examined to qualify the potential of a project’s success. These early studies can include inspecting maps for wind resource, land ownership plots and topography, market demand and pricing, and electrical transmission infrastructure to identify potential locations that are favorable for a wind plant. Identified projects then progress into a series of engineering studies with more rigorous analysis of the:

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3 Figure 9 from http://en.wikipedia.org/wiki/Electric_power_transmission
• Wind turbine selection, layout, and long-term wind resource and energy production potential at each of the turbine locations
• Geotechnical assessment of sub-surface conditions for compatibility with hosting turbines and other plant infrastructure
• Environmental impact of the wind plant on the visual and auditory perception of nearby inhabitants (Local Community) as well as hazardous conditions for local wildlife
• Power system reliability and technical requirements for connecting the wind plant to the electrical transmission infrastructure.

In addition, the project must receive permission from stakeholders local to the project site. Land Owners hold ownership rights to the land of interest in the project. The Project Developers must negotiate with the Land Owners on an agreement to lease their land, typically for the amount of land used by each turbine and other plant infrastructure (i.e. the collector system). If the project is on non-Federal land, the Local Government is the governing authority, often a township or county, which has a permit granting body and process to allow permission for the wind plant construction and operation. Often the Local Community is involved in this process for their concerns to be heard and incorporated into the conditions and modifications of a project prior to permits being granted.

In addition, to secure outside investment and guarantee the operational success of the project, the Project Developer will often seek commercial agreements for equipment supply, electricity sales and interconnection to the power system, which will be described in subsequent portions of the value chain.

Finance
Most utility-scale wind projects require outside sources of investment as the Project Developer usually cannot contribute 100% of the project costs in its own equity. To begin the finance process, the Project Developer will provide the project data and engineering study information gathered during the development phase to an Independent Engineer. The Independent Engineer, or “IE”, acts as a third party consultant to perform technical, and sometimes financial, due diligence to determine the long-term performance of the wind plant and any risks associated with that performance. The IE report is often a requirement of Investors, organizations that are providers of financial investment, who use this reporting similar to a credit scoring to judge the risks and rewards associated with investing in a project.

Investors fall broadly into two categories, equity and debt. Project Developers typically put some amount of equity into the project but may partner with other strategic or institutional investors to complete the financing. These equity investors can be attracted to the project based solely on the promise of cash returns or, in the current policy environment, the tax benefits associated with the project (Harper, Karcher and Bolinger). The primary wind tax benefit in the US has been the PTC, which is offered by the Federal Government, and allows a reduction in the plant equity owner’s tax by $0.23/kWh of electricity produced and sold by the wind plant (DSIRE). Most Project Developers do not have a large tax expense and thus offer the tax benefits to outside equity investors that do. The current Federal Government PTC policy is expiring and it is uncertain when or if it will be renewed. Therefore, the future of the “tax equity” investor may be short-lived. Debt investors, or “lenders”, are commercial investment banks that lend to the project. Several types of loans exist for Project Developers, as well as other equity investors, to increase their leverage in the project with borrowed capital (Harper, Karcher and Bolinger).
At any point in the process the Project Developer may sell their equity share in the project to a **Wind Plant Owner and Operator** which is the firm that will retain ownership of the plant after development and operate the plant over its lifetime. In this model we assume that the Wind Plant Owner/Operator is an IPP whose business is to own generating assets and sell electric power services on the grid.

**Equip**
Alongside seeking financing, the Project Developer also negotiates supply agreements with wind energy **Suppliers and Original Equipment Manufacturers (OEMs)**. OEMs manufacture wind equipment such as the wind turbines for generating electrical power (blades, tower, nacelle, drivetrain and generator) as well as transformers and substation equipment for modifying the electrical power for distribution around the plant and delivery to the electrical transmission network. In some cases Suppliers act as the distributors that sell and deliver this equipment to their customers. Often these two groups are combined into a single function. Turbine supply agreements typically require a site suitability study by the wind turbine OEM in which the wind resource data collected by the Project Developer is analyzed to ensure that the selected turbine will be operating within its performance specifications. This study can inform which turbines are appropriate for the wind plant and are often a condition for the warranty and service contracts that are also provided by the Suppliers and OEMs. These parts and service relationships are carried forward to the Wind Plant Owner/Operators of the wind plant post-commissioning of the project.

Project Developers often hire an **Engineering, Procurement and Construction (EPC)** firm to be the interface with delivery of the wind plant equipment from the Suppliers & OEMs and handle the logistics of moving the equipment to and around the project site. The EPC firm performs the wind plant construction activities of installing roads, turbine foundations, the collector system and erecting each tower and turbine. Depending on the capability of the Project Developer, some or all of these functions can be done in-house, and in other instances the EPC takes more of a role in selecting and procuring the wind plant equipment.

**Operate**
For the wind plant to become an active generator in the power system the Project Developer must receive an interconnection agreement from the **System Operator**. The System Operator, often called an Independent System Operator (ISO) or Regional Transmission Operator (RTO), is an autonomous organization that is granted authority by **Federal Regulators** (the Federal Energy Regulatory Commission – FERC) to operate the power system, which includes the processes for allowing generators to connect to the system and transmit power (FERC). The interconnection agreement is given after an interconnection study is performed to quantify the impact of the plant to the system.

Upon completion of the project and commencement of operation, the System Operator will require telemetered data from the wind plant’s SCADA system that includes its operating status and available capacity, and in some cases, will also require additional meteorological data from the plant to inform a forecasting system that predicts how much wind power will become available (PJM). The System Operator uses this data for scheduling generating resources in the power system to meet the demand for electricity.
Market
With the wind plant physically connected to the system and the System Operator coordinating the plants' scheduling, the wind plant can now be an active participant in the electric power system's market. During the Develop stage, the Project Developer often seeks a long-term offtake agreement with other market participants to purchase a fixed amount of the power that the wind plant will produce (Batlle). These are called power purchase agreements, or PPAs. Load Serving Entities (LSEs) are often the counterparty to the PPA and are the organizations that provide electrical power to both wholesale and retail Electricity Consumers (ERCOT). These Electricity Consumers can be industrial, commercial or residential in nature and thus will have large variances in electricity demand and quality of supply. Local Regulators, such as state public utility commissions, are tasked with regulating the state's LSEs to protect the Electricity Consumers from high pricing and poor service.

Either in addition to or in place of a PPA, the wind plant could also sell its electric power into the wholesale market via the System Operator. For this model, it is assumed that the System Operator is also the market operator. In addition to electrical power, the Wind Plant Owner and Operator can offer additional products on the market, such as Renewable Energy Credits (RECs) which can be sold to LSEs that are required to procure a certain percentage of their electricity from qualified renewable generation sources in US states that have RPS obligations (Schmalensee). RECs are often combined with PPAs as a bundled delivery of both electricity and credits. Also, in markets where adding to the system capacity is rewarded, Wind Plant Owner and Operators can enter into forward capacity markets that provide fixed payments for maintaining the capacity of the plant to generate power when needed—often called “firm capacity” (Batlle).

Summary of Stakeholder Groups
For purposes of simplicity, some of the stakeholder groups are combined for the analysis, such as Local Government and Regulators and Federal Government and Regulators. Also, Investors includes all of the different classes of debt and equity investors. An additional group are the Non-Governmental Organizations (NGOs) which act as an aggregation of members from some stakeholder groups to lobby the Federal and Local Governments as well as educate other stakeholder groups. One example of an NGO is the Electric Power Research Institute (EPRI) which has large member support from LSEs, and conducts and publishes research in the electric power industry (EPRI). Table 1 shows the full list of stakeholder groups and the short-hand nomenclature used in later analysis. Figure 10 shows a value chain representation of the five elements of the wind industry and the stakeholder group involvement.
D. The Electric Power System & Market

There are dozens of power systems in the world and each has its own technical, regulatory, policy and market characteristics which make them unique in considering the integration of wind plants and adoption of new technology. The analysis in this thesis will assume a specific power system and corresponding market – the PJM Interconnection or “PJM”. PJM is one of the largest and most
sophisticated power systems in the world, but has less than 2% of generation capacity from wind (GE Energy Consulting). This makes PJM an interesting case study because its potential to more broadly adopt wind can inform the similar adoption by other power systems globally.

PJM Interconnection Overview
The PJM Interconnection is the largest US electrical power system comprising of 214,000 square miles, 60 million customers and 13 states plus the District of Columbia (PJM). The associated wholesale electricity markets include an energy market with a day-ahead and real-time spot market that uses locational marginal pricing calculated every five minutes at each transmission node. In addition there are capacity, reserves and ancillary services markets. Energy and capacity can also be traded bilaterally through independent brokers.

PJM was formed and operates in the context of a deregulated US electric power industry. The Energy Policy Act of 1992 laid the foundation for this deregulation, and transmission regulation was central to the policy as transmission had historically been bundled into vertically integrated monopolies (FERC). One needed to unbundle the transmission to allow it to be fairly accessed by competing IPPs. Following the Act, in 1996 FERC issued Orders 888 and 889 which required that:

- All utilities and transmission owners designate access of their owned transmission facilities to other network users
- Vertically integrated utilities unbundle generation and power marketing from transmission
- Regions create a regional transmission operator or independent system operator to maintain and enforce open access to transmission

System Operation
PJM System Operators monitor, operate and plan the power system to ensure that energy supply meets energy demand in real-time and across multiple future time periods from minutes, hours, months and years ahead. This involves committing an adequate volume of generation and transmission resources that are available for service. In the day-head to minutes-ahead time frame, PJM dispatches assets from their control room based on economic models that take into account grid reliability and possible contingencies. On shorter time scales, the power system design must be flexible to balance any changes in frequency and voltage (active and reactive). The tools or “ancillary services” that are used to provide this system flexibility are market products which PJM administers to satisfy the reliability of the system (Exeter Associates and GE Energy).

- Regulation reserves are on-line generation resources under automatic generation control (AGC) that adjust frequency so that supply closely matches demand in real-time. These reserves respond within one minute of frequency fluctuation.
- Contingency reserves are necessary to insure against major outages. There are several classes of these reserves differentiating on the time scale of their response (ranges from seconds to 30 minutes).
- Voltage control services and capabilities are required for the system to remain flexible by injecting or absorbing reactive power to maintain an appropriate power factor. Generators must provide or utilize these services to survive periods of voltage disturbances to prevent further

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4 As of 2011
cascading failures (one generator trips out due to low voltage, which lowers the voltage even further).

These services are particularly important to wind plants whose energy production profile is variable and imperfectly predictable. This creates short-term imbalances between the predicted wind power output and the actual output which regulation reserves can correct for (Exeter Associates and GE Energy).

Market Operation
PJM market operators design, coordinate and administer several markets for energy related products, all of which are federally regulated by FERC. For the wholesale energy market, PJM administers auctions at two time scales; a day-ahead (DA) and a five-minute/real-time (RT) (PJM). For the DA, PJM receives technical data from a plant’s generator units and the amount of power for each hour in the next day’s schedule, as well as demand bids and scheduled bilateral transactions. Using a security-constrained unit commitment optimization tool, PJM then selects which plants to schedule at each hour and calculates hourly locational marginal prices (LMPs) to be paid to each participating plant in the stack. The RT market, or balancing market, is based on the actual system operating conditions within the daily market and is used to adjust for deviations from the DA schedule. Plants bid into the RT market and are dispatched using a security-constrained economic dispatch optimization tool. Plants are paid at the clearing LMP, which are prices at each physical node calculated at five-minute intervals, transactions are settled hourly, and invoices are issued monthly.

\[ \text{LMP} = \text{System Energy Price} + \text{Transmission Congestion Cost} + \text{Cost of Marginal Losses} \]

Because LMPs include transmission congestion costs, they implicitly manage network congestion by placing a value on energy that is specific to the time and location that it is delivered. Increasing LMPs can be a sign of congestion which means more expensive energy must be dispatched thus raising the prices in those locations.

The RT market is also used to balance differences between DA bids and actual performance (PJM). For example, if a plant cannot deliver the amount of power it bid into the DA market, it will be required to buy the power from RT market or face an imbalance settlement based on the magnitude of its deviation. This has important implications for wind plants, for it is difficult to perfectly predict the hourly output of the wind plant for the next day. Also, the RT market is relied upon to provide flexibility to quickly follow the net load when wind generation ramps up or down. This is called ramping, and quick-reacting generators such as natural gas combustion turbines (CTs) can provide this service in the RT market.

PJM also operates several reserves and ancillary services markets (PJM). The DA reserves market accepts plant offers and then schedules 30-minute reserves for the following day, while the balancing operating reserves market compensates plants for RT use by System Operators. Plants are compensated with credits that are paid by PJM market participants as operating reserve charges. Likewise there are two ancillary services markets, the synchronized reserve and the regulation reserve markets. In each, a plant bids to be available to supply or reduce supply of energy on short notice. LSEs are obligated to provide these services, acquire them under contract or purchase them from these markets. The principle differentiating factor in these markets are the time horizons in which the services can be called upon and sustained. Additionally, PJM has a market for capacity – the reliability pricing model (RPM). This auction is to encourage long-term investment in adequate supply to meet the future peak demand by providing payments towards the fixed costs of the plant. PJM runs RPM auctions for three year time
horizons and the market is open to a multitude of technologies including wind plants.

System Planning
A third important function of PJM is planning the changes and expansion to the power system, particularly the transmission network. Transmission planning is coordinated and managed through PJM’s Regional Transmission Expansion Plan (RTEP) program (PJM). This is a FERC approved, 24-month, planning process. RTEP models expansion scenarios for 15 years in the future and identifies transmission system additions and upgrades necessary to meet national and regional standards. The process, run in collaboration with Transmission Owners (TOs) recommends one plan for each two-year period.

TOs that enact the plan are remunerated through a regulated rate of return on their investment. These costs are allocated to the network users. PJM has three different categories of cost allocation for transmission investment: Reliability, Economic and Generator Interconnection. Economic upgrades must pass a cost-benefit ratio threshold to be included in the plan. Interconnection upgrades are fully paid by the requesting plant if they fall outside of what the RTEP had planned. As most utility-scale wind plants connect with the medium to high voltage transmission network, this is another area of importance for wind which is distributed by nature and thus generally requires an investment in the transmission network.

Effective and Upcoming Wind Policy
The primary Federal Government policy instrument, first implemented in the Energy Policy Act of 1992, is the Production Tax Credit (PTC), which has since gone through several cycles of lapsing and extension (DSIRE). This is a price-based instrument, similar to a premium, that awards a $/kWh tax credit to the owner of the wind plant. While historically the Federal Government has used its tax policy to promote renewable energy sources like wind in place of a direct policy on carbon or emissions, a recent proposal from the US Environmental Protection Agency (EPA) may disrupt this trend. Under the proposed Clean Power Plan, US states would be held responsible for reducing their power sector carbon emissions, with the net effect of bringing the US power sector carbon emissions to 30% of 2005 levels by 2030 (Spees). While the exact policy measures are just starting to be considered, if the plan were enacted the wind power industry would likely benefit, especially in states that have disproportionately high carbon emissions from their power plants and which the EPA has identified as having the most opportunity for implementing renewables. An analysis by The Brattle Group, shown in Figure 11, suggests that there are several states in PJM that fit this category including Illinois, West Virginia and Maryland.
At the state level, the primary mechanism for incentivizing wind generation has been the RPS. A RPS is a requirement for the LSEs to procure a pre-determined amount of power from renewable energy sources, including wind (DSIRE). In PJM, only Kentucky and Tennessee do not have an RPS or other renewable goal, in place. These quantity-based mechanisms vary largely from state to state by the percentage of electricity sales that should be sourced from renewables, the technologies that are eligible, and the yearly targets. PJM has developed a tracking system to manage and market renewable energy credits (RECs) which are tradable certificates that LSEs can claim for RPS compliance. RECs are measured in increments of 1 MWh. Each REC produced has a unique digital signature and PJM’s Generation Attribute Tracking System (GATS) tracks the creation of RECs by renewable generators and retirement of RECs by LSEs (PJM). The state RPS has created a regional market for wind investment with liquidity provided by RECs. Often the RECs are bundled with the energy production into a long-term power purchase agreement (PPA) from a LSE.

Market Regulation for Wind
There are several important federal regulatory precedents that affect wind plants participating in the PJM market.
• FERC Order 890 – Corrected energy imbalance charge practices that were potentially discriminatory towards variable generators such as wind. Under this Order, energy imbalances are netted monthly and settlements for imbalances are tiered based on the percentage of underage or overage. Additionally, the System Operator is required to market ancillary services such as regulation reserves (Exeter Associates).

• FERC Order 764 – Requires System Operators to offer transmission scheduling at 15 minute intervals or less. Additionally, wind plants can be required to provide meteorological and operational data to System Operators to improve wind power forecasting (Exeter Associates and GE Energy).

• FERC Order 1000 – Directs System Operators to create transmission cost allocation rules that assign network costs to users commensurate with the benefits that they receive. This Order has been viewed to correct against discrimination of wind plants requesting interconnection and help share their network interconnection costs more broadly (AWEA).

While PJM has been progressive in adopting the standards of Order 890 and 764, it is unclear at this point what the final rules for Order 1000 compliance will be (PJM). It appears that PJM will be making the RTEP planning process more open for non-incumbent transmission developers. However, unless a transmission project can classify as a reliability line or an economic line (providing a positive cost-benefit ratio), then the Project Developer must pay the full amount of the network upgrades for interconnection of the wind plant. There has been little research to look at how to classify transmission lines for wind plants or how to formalize the cost-benefit allocation process for wind plants requesting interconnection.

A wind plant has several options for participating in PJM’s markets. After reaching a certain point in the interconnection process, a wind plant can bid into the RPM auction, the DA market and the RT market, and the wind plant is included in the RTEP planning process (PJM).

However, because of wind’s variable nature, the “firm capacity” or “capacity value” assigned to the wind plant for the RPM is very small compared to its annual average capacity factor. A de-rated value is logical because wind cannot be forced to blow when the system has peak demand. For new plants, PJM assigns a class average capacity value of 13% until operating data becomes available (PJM). The capacity value is then calculated as the three-year rolling average of the capacity factor during summer peak hours. This means that for a 100MW wind plant, the plant can only bid 13MW into the RPM. There are flaws in this approach as it does not accurately represent the inter-annual or geographic variability of wind. Furthermore, limiting a plant to the class average provides no additional incentive for the higher capacity plants to enter the market. In the most recent RPM auction, only 0.5% of the firm capacity mix was from wind.

If the wind plant enters the RPM it is assigned as a capacity resource, and will be required to submit offers into the DA market. Otherwise, non-capacity resources are allowed to offer into the DA but are not required. A wind plant can also choose to participate only in the RT market with a dispatch frequency of five minutes and receive RT LMPs for energy provided (Exeter Associates). Generally the wind plant is a “price-taker” because it is bidding at near-zero variable cost. However, if the wind plant is selected economically in the DA market it is allowed to set the market price. This price may be negative in circumstances of high wind penetration/low demand and with a guaranteed production benefit from a PTC.
As per Order 890, balancing operating reserve charges are allocated to wind plants for deviations between the DA schedule (if it participated) and the RT (Exeter Associates). However, a wind plant can self-schedule at a specific range of output and will not be subject to energy imbalance charges if the wind plant follows dispatch instructions from the System Operator. In this case, the wind plant can actually earn balancing reserve credits. Likewise, wind plants can participate in the ancillary services and regulations markets.

Technical Requirements for Wind
For PJM System Operators to consider wind plants as a dispatchable resource, they must be able to accept dispatch instructions and curtail to a desired MW base point within 15 minutes (Exeter Associates). Also, each wind plant’s control center must be connected to the System Operator and communicate power output and meteorological information gathered through the plant SCADA system (PJM). The wind plant must be equipped with at least one meteorological tower that sends information in near-real time to PJM who provides this to a wind power forecaster. PJM uses three different forecast horizons; 5 min – 6 hrs, 6 hrs – 48 hrs, 48 hrs – 168 hrs (Exeter Associates). These are used in various decision models to inform DA unit commitment and RT reliability assessments. In addition, PJM enforces reactive voltage and low-voltage ride through requirements for wind plants to ensure grid stability (PJM).

Wind Business Model
Today’s wind plant business model is not wholesale market-oriented. Typically an IPP collects revenue from the bundled sale of RECs and energy under a long-term PPA with a LSE or large consumer. The energy is priced per MWh at the levelized cost of energy with some return on investment margin – typically 8-10% (Harper, Karcher and Bolinger). Tax credits are an additional, and sometimes necessary, revenue stream when the business is partnered with a tax equity investor. The offtake structure is typically decoupled from the market performance, as sales are contracted so that wind plants will be remunerated at a set rate regardless of the wholesale energy prices. At low penetration levels, such a business model can be sustainable and help push wind plants up the cost learning curve. However, at larger penetration levels the REC market (and also PPAs) may be saturated, negative price conditions can arise during periods of high wind/low demand, and reliability curtailments will increase unless the system is well-adapted.

The current business model does not try to maximize system value or lower system costs, only recover the investment cost of the wind plant plus margin. In the longer term, wind plants have a great opportunity to participate in the PJM markets described above if the system and plant were better adapted to support wind turbine performance. Not only can wind produce energy and REC products, but also can provide capacity and regulation services. At higher penetration levels and without tax benefits or RPS mandates, wind plants may need to adapt to a more fully market-oriented model.

One hybrid approach that is emerging is the synthetic PPA, which is structured as a contract for differences between the wind plant and a market counterparty (Chadbourne & Parke LLP). This model incentivizes the wind plant to participate in the energy market while reducing its market risk. PJM is an ideal market for this model as it has a robust and active wholesale energy trade and there are many counterparties, such as power traders, that would be interested in a hedge product. The contract would set a strike price indexed to the wholesale market price for a pre-determined amount of energy. Regardless of performance, the wind plant would pay the counterparty the difference between
wholesale and strike price when above index and would receive the difference when below index for the volume of contracted energy. The synthetic PPA gives the wind plant a guaranteed revenue stream which will attract investors to finance the construction of the wind plant. Additionally, there is no longer an incentive for the plant to sell into a negative priced market.

E. The Benefits and Challenges of Wind Integration

Wind is not a uniformly occurring or performing resource. It varies in time and intensity across horizontal and vertical geographic dimensions and has minutely, hourly, daily, monthly and yearly patterns of fluctuation. The wind cannot be controlled, contained or perfectly predicted. Therefore, it is quite a unique resource in the context of energy generation within a finely coordinated and balanced power system and market.

The cost of deploying wind plants has been markedly reduced through exploitation of economies of scale, a mature system architecture, and efficiency improvements in both the turbine technology and its manufacturing processes. The most recent EIA cost summary put onshore, unsubsidized wind as the second least expensive electricity source at $80.3/MWh levelized cost of energy (EIA). The costs of wind energy are primarily driven by the upfront fixed cost of deploying the generators at a wind plant as well as the fixed operations and maintenance (O&M) for the wind turbines to keep them running at their optimum performance. However, the fuel cost is zero because the wind resource is free. Therefore, a wind plant bidding its marginal cost into the market will bid $0/MWh (or near zero if there is some variable O&M). Thus, wind has the opportunity to collect large infra-marginal rents in the PJM energy markets where prices are set by gas and other thermal plants with relatively large marginal costs.

Wind’s levelized cost and marginal cost of energy should not be confused with the true system costs of wind integration, nor the true market opportunity for wind plants. To understand the true costs and benefits of wind, the system’s wind resource properties must be analyzed in the context of the power system’s demand, generation and transmission characteristics as well as its operational flexibility and market design.

For example, because the wind resource cannot be controlled, wind generation is decoupled from system demand (Perez-Arriaga, Electricity Generation with Renewable Resources: A Discussion of Issues). Analyzing the wind resource profile’s coincidence with the system demand profile will inform how a wind plant can perform in the energy markets. Likewise, optimizing the wind plant location or performance to maximize the coincident resource and demand will improve the market performance of the plant.

Also, the degree of uncertainty in wind generation adds costs to the system, which become more apparent as the level of wind in the generation mix increases. These costs are related to the regulation reserve and load following services in the RT market that correct for energy imbalances from wind variability, imperfect wind power forecasts, and peaks in net load (Bird). As with other new plant additions, the transmission network must also be expanded or reinforced for wind plants. However, wind plants tend to be located far from network load centers due to visual impact concerns as well as proximity to better wind resource. Thus, the transmission expansion requirements for wind have been higher than for other generators.
The following sections will describe the resources, costs and benefits related to wind energy in PJM within the context of the current power system. Later sections will suggest the impacts of large levels of wind penetration and how the system could be adapted to maximize the wind benefit.

Wind Resource and Network Topology
Perhaps one of PJM’s most valuable resources is its diverse geographic region which includes a large amount of wind energy potential. PJM has three distinct wind resource areas circled in red and labeled on the wind map in Figure 12 (NREL).

“Region 1” in Western PJM is where the majority of the installed wind capacity is today because there is a good resource, good transmission network connection and a demand for wind energy created by state RPS goals. PJM has the opportunity to unlock an even greater amount of wind potential in “Region 2” with the adoption of technology that will bring wind turbines to higher heights or that will allow wind turbines to capture more energy from lower wind speeds. “Region 3” will begin to develop in the longer term as offshore wind technology and project development processes mature. This trend can be seen by analyzing PJM’s interconnection queue map which shows the location of proposed wind plants as shown in Figure 13 below. In 2013, PJM had over 19GW in the wind development pipeline with an increasing amount of projects in Regions 2 and 3 (PJM).
However, in some instances the transmission network has lagged the wind resource potential and development activity. As shown in Figure 14, it is apparent that Region 1 has the advantage of a well meshed transmission network (GENI). However, there is little high voltage transmission capacity connecting Western PJM to Eastern PJM (gap highlighted in red circle). Such a network would be necessary to take full advantage of wind development in Region 2, as well as connect Regions 1 and 2 to the high demand centers on the Eastern seaboard. Currently there is no offshore transmission network to exploit wind in Region 3 – this analysis will focus only on wind plant development onshore in Regions 1 and 2.
The insufficient transmission capacity between Western and Eastern PJM can lead to congestion scenarios similar to that shown in Figure 15, in which the zero marginal cost wind generation in Region 1 is captive to the Western portion of the market and more expensive thermal generators are dispatched to meet demand in the East.

Wind Resource and Demand Profile

In addition to the element of geography that is to be considered for wind integration into the PJM system, there is also an element of time. Wind systems have different time patterns of occurrence. A typical wind pattern is a large amount of wind blowing at night and less wind during the day (Manwell, McGowan and Rogers). However, the geophysical characteristics of the surrounding topography and the dynamics of the atmosphere create a large variation in the patterns of wind occurrence, and these patterns change over the course of time.

When analyzing wind generation in a power system, it is useful to consider the demand profile net of the wind generation profile – the net load (Perez-Arriaga, Electricity Generation with Renewable Resources: A Discussion of Issues). If wind plants are developed in high quantity within an area with the same wind generation profile, the net load can approach zero for the hours of the day when the wind is at its peak. This effect can create large peaks in the net load profile, which can be quite different than the peak load without wind generation. Peaks drive the system requirements for flexibility and reserves, which add costs to the system. Therefore, it is beneficial to smooth the wind generation profile to minimize peaks in the net load.
Smoothing of the wind generation profile can be done by aggregating a diverse volume of wind resource. For example, Figure 16 shows the individual profile of a Region 1 wind plant in Illinois (IL) and a Region 2 wind plant in Pennsylvania (PA). It then shows the profile for generators in the entire state and then the profile for the entire PJM system. For the aggregated cases, while the bulk of generation is at night, the peak load coincidence is much higher than for any individual plant. In addition, the short-term wind variability is much less (GE Energy Consulting).

**Impact of Wind Penetration**

The variability of the wind resource creates various magnitudes and timescales of uncertainty in the operations and planning of a power system and the functioning of the markets. To combat uncertainty and respond to variability, System Operators use several tools to provide system flexibility, including load following resources, regulation reserves, curtailment, and wind power forecasts. However, increasing system flexibility comes at a cost, and the allocation of these costs has been a topic for debate.

GE Energy Consulting group performed an in-depth study of the integration of renewables (wind and solar) into the PJM system (GE Energy Consulting). They modeled several scenarios from 14% (the average of RPS state goals in PJM) to 30% penetration of wind and solar energy into the power system and simulated the impact on system and market performance for the year 2026. The results give insight to the necessary flexibility of the system and the associated costs and benefits for each scenario. For high levels of wind penetration, flexibility will need to be added to the system. However, the system benefits of the added wind plants outweigh the system investment costs in all scenarios. The results of this study are discussed below.

**Benefits of Wind**

Increasing wind energy in a power system has the effect of lowering the system average cost of electricity, as there is an increased volume of energy that is displacing higher cost energy resources such as coal. The total production cost savings in PJM for the 14% penetration scenario is estimated at $6.8 billion per year (GE Energy Consulting).

With the effect of displacing coal and other thermal generators in the economic dispatch, wind penetration lowers the carbon emissions from the power system. An emissions impact study of wind in PJM found that meeting the 14% on-average RPS goals with renewable energy will reduce CO₂ emissions by 12%, with reductions up to 41% with a 30% penetration of wind (GE Energy Consulting). There is not yet a policy or market instrument for carbon despite the negative economic costs of its emissions. However, this may change with the proposed Clean Power Plan from the EPA.

Additionally, increasing the penetration of wind energy provides a long-term economic benefit to the power markets by hedging against fuel price volatility (Bolinger). Natural gas prices have been quite volatile over the recent years, and reducing the volume of natural gas consumption reduces the extent of the price shock during gas shortage events. Increasing wind energy in PJM displaces natural gas fuel consumption by 47% for the 14% on-average RPS goals (GE Energy Consulting).

**Effect on System Operation**

A critical timescale of wind variability is the ten-minute to one-hour range. Wind does not vary greatly below 10 minutes, and wind plants have some inertial effects to counteract slight second-to-second variations (a.k.a. turbulence). However, the ten-minute variability is large enough that for higher levels
of wind penetration, additional regulation reserves will be required to correct for energy imbalances between the scheduled and real-time performance of a wind plant. The GE simulations found the variability to be highest when production was in the middle of the capacity range as shown in Figure 17 (GE Energy Consulting).

![Figure 17- 10min Variability for 14%-30% Renewables (GE Energy Consulting)](image)

For the 30% renewable scenarios (which included 20% wind and 10% solar), the system required an additional 2,504 MW of regulation reserves to meet 99.7% (3-sigma) of the maximum 10-minute variability (GE Energy Consulting). As increasing the geographic distribution of the wind plants reduces the 10-minute variability, the simulation found that 2,286 MW of regulation reserves would be required to meet the same criteria with more geographically disperse wind plants.

Additional types of reserves were not required to meet any of the modeled scenarios (GE Energy Consulting). Because no wind plant has a very large capacity, and because the aggregate capacity of wind plants are distributed, the system does not take on more contingency risk with wind than it would in a business as usual scenario. Therefore, no other reserves were necessary to meet contingency requirements.

The PJM system will need to have flexible generation to follow wind ramps that cause peaks in net load, otherwise known as “load following” (GE Energy Consulting). Ramps are large upward or downward shifts in production over the timescale of one hour to several hours. GE found that PJMs current fleet can meet the ramp characteristics of all the modeled scenarios, and that additional ramping capabilities were not required. The dispatch of gas CTs however will take on a different use pattern than exists today. Figure 18 shows a scenario for 30% renewables in which the number of gas turbines committed in the RT market are plotted. Two distinct ramping patterns are shown for this day. The new use case will increase cycling of thermal units (primarily gas CTs) dispatched for this purpose which both increase variable costs and emissions. Cycling of the generators output up or down, in addition to starting up and shutting down causes fatigue and thermal stresses on the generator components, as well as less
efficient fuel consumption. This results in increased costs to repair or replace these components and increased emissions. The GE simulations found these costs and emissions to be negligible compared to the costs and emissions from the displaced fuel to meet energy demand. The added production costs due to cycling were only 2% for the 30% penetration case.

![Image of Demand vs. Renewable vs. RT CT Commitment](image)

**Figure 18 - Committed Gas Turbines to Follow Ramps (GE Energy Consulting)**

**Effect on System Planning**

PJM must plan the future of the system to have sufficient capacity to meet demand, plus some reserve margin. The firm capacity of traditional plants has been well characterized and in general can be relied upon when called for service with a high probability, as the capacity stays relatively constant for all hours of the day and days of the year. For wind, the different periods of variability present a statistical challenge to assigning a “capacity value” to a wind plant. The current PJM process which assigns one value to one plant for the entire year does not lend favorably to wind where capacity factor is constantly changing. The current workaround is to assign a low class average capacity of 13% and then update every year based on a 3-year rolling average (PJM). Results of the GE study suggest that 13% is well below the actual realized capacity of the simulated wind plants for most times of the year, and that PJM should adopt a different approach that assigns a capacity value on different time horizons (GE Energy Consulting).

For transmission planning impact, GE used the PJM RTEP models to run each scenario to identify new transmission lines and upgrades required to meet the least cost, security-constrained delivery of energy from the renewable generators (GE Energy Consulting). The models were modified slightly to include production cost analysis that accounted for wind’s variability. This was necessary to not overbuild a transmission line that a wind plant would be sharing with other generators, because the wind plant seldom requires network access for its nameplate capacity. The results for the 30% scenario (20% wind, 10% solar) were $13.7 billion dollars in new lines/upgrades. However, for the scenario where wind was dispersed across the PJM region, only $5 billion in new lines/upgrades were required because the line
capacity could be smaller as not all of the wind energy was coming from one transmission corridor. The bulk of the additions/upgrades required are in the 765kV and 345kV classes.

In a separate study by Synapse Energy Economics, similar results were found including a net benefit of wind penetration by lowering production costs via displacement of coal and gas generators (Synapse Energy Economics). This study also included a scenario where wind was imported by PJM from MISO to reach a similar level of penetration as the 30% scenario in the GE study. In this case, the benefit of the added capacity factor from the stronger wind resource in MISO was offset by the additional transmission investment required to import wind from a greater distance. Therefore, it is likely more economic for PJM to develop its own wind resources that require only a small transmission investment cost compared to the benefit.

Effect on Market Operation
The GE study used the GE MAPS modelling tool to run security-constrained unit commitment and economic dispatch for each of the scenarios for the study year 2026 (GE Energy Consulting). The study focused only on the hourly operation of the DA and RT energy markets. The model results showed overwhelmingly that larger amounts of wind displaced coal and natural gas generation, but left nuclear plants untouched. For all of the scenarios ranging from 14% to 30% penetration, on average 36% of the renewable energy displaced coal generation and 39% displaced gas-fired generation. In no scenario was there unserved load, and there was only a small amount of renewable curtailment due to local congestion.

The increased participation of wind energy reduces the average LMPs across the system, however, there are short periods of high LMPs when wind is ramping down and the flexible gas generators are being dispatched to follow the load (GE Energy Consulting). This effect increases “base-load cycling”, or the number of start-ups and shut-downs of generators, which increases O&M costs for these plants. This effect was more prevalent for gas generators, with a slight impact on coal plants as well. The lower capacity factors and lower market revenues for gas and coal generators, in addition to slightly higher variable operating costs, suggest that some of these plants will go into earlier retirement than in the base case. This is an unfortunate reality of a competitive energy market. However, further studies should be conducted to look at PJMs capacity adequacy in the context of these retirements.

The net benefit of 30% renewable penetration was found to be $14.8-$16.1 billion per year accounting for the additional cycling of the thermal generators (GE Energy Consulting). Including the cost of transmission expansion and upgrades, this is equivalent to a production cost savings of $49.5-$56.8 per MWh of renewable energy. Note that these scenarios included solar in the renewable penetration mix. However, the Synapse study validated similar savings looking at only penetration of wind up to 65GW (~22%) in 2026 (Synapse Energy Economics).

Summary of System Challenges for Wind in PJM
Several challenges and key insights are identified from reviewing the analyses of the impact of higher levels of wind energy penetration into PJM.

- The utilization of regulation reserves are required for the System Operator to adapt to short-term wind variability
- The volume of regulation reserves necessary is a function of the system wind generation variability
• While ramping can be addressed with the flexibility of the current system generators, it imparts a variable O&M cost (base-load cycling) to these generators that is passed through to the energy market.

• Transmission network expansion/upgrade is required, but is achievable at low cost compared to the system benefit and can be sized to minimize wind curtailment. Additionally, higher geographic dispersion of wind plants can greatly reduce transmission investment requirements.

• The capacity market is not designed properly to remunerate wind plants and may face future challenges with forced coal and gas retirement due to revenue loss.
Part 2 – Innovation

A. Areas of Wind Innovation
The wind industry is continuously innovating and striving to improve wind plant competitiveness and to overcome the system integration challenges described in Part 1. Below are six areas of innovation that bring new technical capabilities and contribute value to both the wind plant and the electric power system.

Grid-Scale Storage
Electric power systems operate under the remarkably stringent criteria that supply must meet demand in real time, or else there can be major disruptions to service and potential damage to the components in the power system (Perez-Arriaga, Power System Operation & Management). To maintain this balance, grid frequency is tightly controlled by System Operators and AGC systems. Imbalances are corrected on a cascading timeline, where short disturbances are “regulated” with quick bursts of energy from regulation reserves and longer shortfalls are met by dispatching bulk energy from a large generator.

Grid-Scale Storage is the capability of the electric power system to temporarily store power and then discharge electrical energy at a controlled level and duration. High power, low energy capacity storage systems can provide regulation services by maintaining frequency balance during short-term disturbances on the grid (Denholm, Jorgenson and Hummon). Low power, high energy capacity systems can load-level the grid by shifting bulk energy from times of low demand to times of high demand. The storage and discharge characteristics of the storage technology will dictate which applications are suitable for the system. At “grid-scale”, such capabilities could completely modify the operation of the power system and expand the penetration for generation sources like wind that previously could not be load-leveled or bi-directionally regulated.

One possible use case is the installation of Grid-Scale Storage Systems at a wind plant. These systems could be based on electro-chemical batteries, compressed gases, or pumped water. At the wind plant, the storage system would dynamically respond to conditions in the power system, power market and wind plant. For example, at times that the wind plant was producing power and the market price for electricity was low, the storage system would accept power (Denholm, Jorgenson and Hummon). At times that the electricity prices were high, the storage system would dispatch power. This could be particularly impactful for many wind plants where the prevalent local resource profile is not coincident with the system demand profile. The “time shifting” or “arbitrage” capability of the storage system brings the wind supply into coincidence with demand and levels the load. Similarly, if there were network conditions that would otherwise force a wind plant to curtail output, the storage system could offtake power and deliver when the network was not constrained. On shorter time scales, storage systems on wind plants can moderate imbalances between the committed and actual generation. A wind plant often is required to commit to a certain level of generation over a certain time schedule (e.g., one-hour ahead). If the actual wind conditions do not allow to maintain this level during the scheduled hour, the storage system can discharge energy to “regulate up” the service from the wind plant.

Grid-Scale Storage systems would require intelligent control systems to co-operate with the wind plant and power system. Predictive intelligence of wind resource, plant output and grid offtake conditions can further the benefit of storage by optimizing the control systems scheduling of the charge/discharge
timing and volume. This is particularly important for systems that are providing both energy and regulation services and need to maintain a certain capacity for regulation while also providing a steady energy discharge.

Ambri is an example of an innovator creating Grid-Scale Storage products that are applicable for the wind power industry and could potentially provide both types of storage capabilities at competitive costs. Ambri’s liquid metal battery contains only liquid, non-moving parts that retain energy storage capacity for much longer than traditional solid electro-chemical batteries (LaMonica). Additionally, the liquid technology has a higher current density than other batteries and can scale to grid-level capacities for much lower cost, under $500/kWh.

Review of the technology shows that liquid metal batteries can perform at lower energy cost than solid batteries, flywheels and capacitors (which are scale limited) and lower power costs than pumped hydro and compressed air energy storage (which are geography limited) (Kim, Boysen and Newhouse).

On-Site Manufacturing Systems

Wind plants benefit greatly from economies of scale. Primarily, this is driven by the cubic relationship of wind speed ($U$) to power ($P$) derived from the continuity equation of fluid mechanics (Manwell, McGowan and Rogers):

$$P = \frac{1}{2} \rho A U^3$$

As a wind system expands its reach higher into the atmosphere by scaling to larger hub-heights, there are typically higher wind speeds and thus much greater power potential (Cotrell, Stehly and Johnson). Similarly, wind power output scales directly with swept rotor area ($A$). Thus, the industry trend has been to build wind systems with large rotors and tall towers. The economy of scale gains result in lower cost of energy generation. Wind system scale up increases the energy output with only marginal increases in capex. The “more power per tower” effect has contributed to an overall lowering of the cost of wind energy as shown in Figure 20.

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5 Figure 19 from http://pubs.acs.org/action/showImage?doi=10.1021%2Fcr300205k&iName=master.img-004.jpg&type=master&
However, the capability for wind systems to further scale to larger rotor and hub-height sizes has become constrained by the current manufacturing, transportation and logistics technologies and infrastructure (Cotrell, Stehly and Johnson). In the US, hub-heights have stagnated below 100m with a rotor diameter of 110m or less. NREL has identified several mass, cost and size breakpoints for which the transportation and logistics costs begin to increase rapidly with incremental increases in rotor size, generator capacity and hub-height. For example, as shown in Figure 21, tower heights beyond 100m greatly increase the capital cost of the system because of greater steel requirements in the tower. The steel requirements arise from the base diameter of the tower being constrained to 4.3m, the largest allowable size for overland trucking. Similar transportation constraints have limited the economic utilization of large blades to approximately 53m in length.

On-Site Manufacturing Systems can address the transportation and logistics constraints and remove these economies of scale breakpoints. Further system scale up can both lower the cost of energy
produced in current wind development regions as well as expand wind development into new, lower wind speed regions. For a typical 6.5 m/s wind site, raising hub-height from today’s max hub-heights to 137m can raise annual energy production by 8% (Del Franco). Similarly, such a hub-height increase could theoretically add 2,000 GW of new wind turbine capacity; the majority of which is located in high energy priced markets in the Eastern US (Cotrell, Stehly and Johnson).

Innovators such as Keystone Tower Systems and Green Dynamics are commercializing On-Site Manufacturing Systems for the wind industry to divert transportation constraints and allow continued economies of scale. Keystone utilizes an automated rolling and spiral-welding process to convert flat sheet steel into tubular towers over 140m tall (Keystone Tower Systems). Green Dynamics utilizes a transportable fiberglass sheet and an automated, modular infusion tool to run an on-site blade lamination process (Green Dynamics).

Transmission Power Flow Control
The challenge to incorporating variable, uncertain renewable energy is that the current transmission network and system operation was designed as a mostly passive system to support predictable, dispatched generation supplies (Schlegel, Babcock and Gould). However, wind energy is variable and uncertain (imperfectly predictable) due to the nature of the wind resource. This variability and uncertainty has the potential to exacerbate transmission congestion as the penetration of renewable generation increases. Conversely, there might be a frequency or voltage disruption if the renewable generators slow or stop production suddenly due to ramping.

To mitigate these challenges, System Operators can require additional regulation reserves to supplement energy shortfalls and come online quickly to stabilize system frequency. They can also curtail output of a wind plant if its supply cannot be reliably transmitted due to congestion elsewhere in the system. In both cases, the energy generation from reserves is higher cost and greater emissions than that of the wind plant.

These additional operational requirements of renewables are manageable, but lessen the net system benefits due to the increased demand for RT reserves and inefficiencies in the near-term asset scheduling and curtailment practices. For example, the integration of wind energy in ERCOT is estimated to cost an additional $0.66/MWh due to deployment/operation of reserves, the cost of base-load cycling, and transmission congestion (Ahlstrom, Questioning the Problem). In terms of capital outlay for reserve capacity, it is estimated that PJM spends $3 per each additional MW of wind power capacity (The Brattle Group).

To support variable and uncertain generation sources such as wind energy at minimal cost, the transmission network needs to be sufficiently flexible, responsive, and reliable to reduce areas of transmission congestion and respond quickly to regional wind ramps. Transmission Power Flow Control (PFC) is one way to achieve this. Power flow is determined by the impedance of a transmission line and the difference in voltage at each end (MIT). PFC is the ability to change the way that power flows through the transmission grid using hardware and software to maximize system value. These technologies can change the effective impedance of the network or the sending and receiving voltages to influence the path of electricity through the transmission grid. This enables the ability to hold power

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6 Content for this section was originally created by the thesis author in collaboration with Lotte Schlegel and Josh Gould at ARPA-E. The draft report was made publically available for download.
on a transmission line at a certain level or direction. Electricity follows the path of lowest impedance, and the result of changing the pathways of the grid is to change the way that power flows through the transmission system. Specifically, PFC can be used to remove congestion from regions with large amounts of wind penetration which will minimize curtailment. In addition, a more interconnected and controllable transmission system will facilitate the network benefits of geographic averaging of wind resources.

PFC technologies from numerous groups of innovators are being supported and demonstrated by the ARPA-E GENI program. Smart Wire Grid’s distributed series reactors (DSRs) have been demonstrated to create a variable impedance transmission network that allows power flow to bypass congested lines. A simulated study in the Pacific North West found that with an investment of $58 million (~3000 devices), the variable impedance system created was able to unlock an additional 2.8GW of wind energy by reducing congestion (Smart Wire Grid).

A similar effect can be accomplished by optimally switching transmission lines to change the impedance characteristics of the transmission system. Topology control algorithms (TCAs) can be deployed by System Operators to optimize their switching decisions based on real-time events on the grid. TCA simulations in power flow modeling software have shown a reduction in wind curtailment instances from 33% to 14% by switching lines (Qiu). A simulation of the impact of TCA using historical PJM data demonstrated over $100 million in annual savings from congestion relief (The Brattle Group).

Near-Term Forecasting

By combining near-term wind forecasts with the standard methods used for forecasting the load, System Operators hope to achieve an accurate estimate of how much energy to deliver at each hour for the coming day, how much will be met by wind, and how much will be met from other sources (Lew, Milligan and Jordan). However, wind speeds vary from hour-to-hour and day-to-day and these variations are imperfectly predictable which leads to uncertainty in the wind energy forecasts. Because these other energy sources, typically base-load and mid-range thermal units, require advanced notice to ramp up or down production, poor forecasts can lead to inefficient unit commitment and dispatching, stranded wind energy, and un-necessary cycling of conventional generators which is a less efficient operational method that outputs greater emissions and more wear and tear on the asset.

To date, System Operators are becoming increasingly comfortable with “real-time” wind forecasts updated just prior to the five-minute economic dispatch process (Ahlstrom, Bartlett and Collier). The uncertainty in these forecasts are on the same relative magnitude to uncertainty in the load, as the wind does not change greatly on such short timescales, therefore assuming persistence (the wind speed in the next forecast period is the same as the current operational period) is a relatively accurate and simple method. However, there is great room for improvement for near-term energy forecasts that can reduce uncertainty for the economic unit commitment process, which typically takes place in the day-ahead planning horizon. “Near-term” energy forecasts are the estimations of wind plant output in the intraday to several days ahead horizon. Most markets use the day-ahead to carefully schedule energy and ancillary services (e.g. reserves) with consideration for technical limitations of the generators. Ignoring the impact of wind can lead to a non-optimal DA schedule that must be realized and corrected for in the RT operation.
Several wind integration studies have shown that the system integration costs for wind are largely driven by the need for increased regulation reserves to mitigate variability and uncertainty. The near-term forecast error is the primary source of this operational uncertainty (Lew, Milligan and Jordan). Forecasts below actual wind output result in more thermal units being committed for the next day than actually required, which will be dispatched below their optimal efficiency. Forecasts above actual wind output result in too few thermal units being committed for the next day, and to meet the shortfall quick-starting peaking units are dispatched at much higher generation cost to the system. Large forecasts errors in either direction can result in more severe actions such as curtailing generation or shedding load.

Reducing Near-Term Forecast error can greatly reduce these system inefficiencies, and thus costs. State of the art day-ahead wind forecasts typically have mean absolute errors (MAE) between 15%-20% for an individual wind plant (Lew, Milligan and Jordan). Comparatively, the DA load forecast errors are 1%-3%. One of the more sophisticated wind forecasters, 3Tier, reports an MAE between 12%-16%. NREL ran scenarios to measure operational cost saving by reducing state of the art forecasting errors. Operational costs are the measure of a power systems fuel costs as well as the unit start up, operation and maintenance costs. For the WECC power system, as shown in Figure 22, multi-hundred million dollar savings could be realized by reducing forecast error in scenarios with high wind penetration.

![Figure 22 - Power System Operating Savings from Reducing Near-Term Forecast Error (Lew, Milligan and Jordan)](image)

A partnership between NCAR and Xcel Power is demonstrating the benefits of advanced Near-Term Forecasting technologies (Bullis). Taking a big data and machine learning approach, NCAR collects SCADA information from every wind turbine in Xcel Power’s operation which feeds into a high-resolution weather model and then combined with five additional weather forecasts. Learning algorithms weight and select which forecast is best for each wind plant. The NCAR forecast gives rolling predictions for wind power output, for each plant, in 15-minute intervals for up to 1 week ahead.

Long-Term Forecasting
The development of a wind plant requires rigorous analysis of the selected site’s wind resource, environmental sensitivities, and network interconnection effects to produce a long-term forecast of the expected energy output. In the early stages of development, these forecasts are essential for
determining the economic feasibility of the site by determining the net capacity factor (or annual energy production), selecting suitable wind turbines and contracting with vendors, forming offtake agreements (such as PPAs), and securing project finance from lenders. In post-construction stages of the wind plant, long-term forecasts are used for asset management decisions that can be key to the projects economic performance, such as whether and when to refinance, repower (upgrade the wind turbine systems), or decommission the project.

As with Near-Term Forecasts, longer-term predictions are subject to errors in the forecast because of wind resource variability, and the forecast uncertainty also manifests in economic inefficiencies. For example, a 0.1 m/s underestimate of average annual wind speed can result in $2.50/MWh reduction in the PPA contract. PPA contract bidding has become increasingly competitive, and contracts have been won or lost over a $0.25/MWh difference (Navigant Research).

In addition to resource uncertainty, the total project uncertainty in the long-term is complicated by many other operational factors effecting the forecast including downtime for maintenance, curtailment from network and environmental conditions, and underperformance of wind turbines to name a few (Poore, Briggs and Mason). In North America, the wind power industry has set a precedent for producing energy below the predicted levels from pre-construction long-term energy forecasts. From 2001-2009, industry wide predictions were 9% below actual performance, as shown in Figure 23. In more recent years, the gap is approximately 3% but the time frame is too short to fully understand long-term variability.

Figure 23 - 2001-2009 Wind Performance below Predicted Levels (Poore, Briggs and Mason)

The long-term performance errors have resulted in decreased confidence in the industry from critical stakeholder groups, such as the Investors (Poore, Briggs and Mason). Current energy estimates are often discounted by Investors which devalues wind projects across the industry. A critical metric for project finance has become the 1 year P99, meaning the annual energy output level at which there is a 99% expected probability of exceeding – 1% expected probability of falling below (Anderson). Lower valuation of this metric often means a lower debt size, and thus lower leverage for the Project Developers. In an example of a small (25MW) onshore wind farm, a reduction in the P99 forecast by 2%
results in over $2.5 million reduction in debt service, which must be supplemented by equity from Project Developers or other equity investors.

Cardinal Wind is an example of an innovator that seeks to lower the uncertainty of long-term wind energy forecasts, return confidence to the Investor stakeholders and mitigate these economic inefficiencies in project development. They are using machine-learning algorithms trained by a multitude of historic weather data to more accurately forecast the long-term variability of a potential project’s wind resource.

**Predictive Maintenance**

Keeping wind plants well maintained is essential to the economic outcome of the plant, particularly because unexpected downtime can decrease the energy output. However, the operational expenses must be kept in check to keep the cost of energy produced by the plant to a minimum. The operations and maintenance of wind plants is challenging because plants are typically distributed amongst many individual wind turbines installed in very remote locations where they are exposed to a wide variety of environmental conditions and dynamic loading of the turbines’ blades, rotor, drivetrain and structural support elements (Dvorak). For wind plants installed in the last decade, many turbines are coming out of their warranty period and the US annual O&M expenditure is expected to rise to approximately $6 billion in the next decade. Wind Plant Owner/Operators require not only the resources to visit, climb and repair tall wind turbines, but also the awareness of the individual turbines’ performance and insight into potential failures.

Maintenance approaches in large capital-intensive industries can be generalized into reactive maintenance (operate to failure), preventative maintenance (performed on a set schedule), and Predictive Maintenance (performed based on conditional awareness of the system) (WWINDEA). The wind industry had historically relied on the first two approaches for lack of reliable and affordable SCADA-connected condition-monitoring systems. However, a Predictive Maintenance approach can lower O&M expenditure by approximately 50% compared to reactive maintenance, as seen in Error! Reference source not found.7.

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7 Figure 24 from http://wpcore.wpe.s3.amazonaws.com/wp-content/uploads/2013/11/G2-How-OM-costs-chang_opt.jpeg
Recent innovations from turbine vendors and equipment suppliers have allowed for turbine condition monitoring systems to become more common place. A typical turbine can produce 10 or more different streams of data every few seconds from meteorological, temperature, power, and other types of sensors that report both time-series and event-based data through the SCADA system to the wind plant operator’s database and monitoring system (Dies). More specialized sensors are being added to drivetrain components to measure component vibration and particle counts in lubrication to get even further insight to the wear and tear of assets (Dvorak).

Innovators such as Romax (Romax Technology) and Fluitec Wind (Fluitec Wind), are using these advances in condition monitoring systems to take advantage of big data and Predictive Maintenance methodologies. By utilizing data mining, predictive analytics and behavioral targeting, impending wind turbine damage can be identified early and Wind Plant Owner/Operators can optimally schedule maintenance to minimize lost energy output and repair costs.

B. Classifications of Innovation

These six innovation areas are occurring in multiple levels of the wind system architecture – at the wind turbine, the wind plant and the power system. The classification of system architecture discussed in Part 1 can be used to map where these innovations occur. As shown in Figure 25, the technical innovations being analyzed are represented in the system at the location in which the form of their technology embodiments will be integrated. In the value analysis, attributes will be segmented into “plant” for those impacts at the innermost boundaries and “system” for those impacts at the outermost boundaries. In the US, there are several power systems, some of them connected. Although here the entire US geography is represented as one system, this analysis will focus on the PJM Interconnection, as described in Part 1.

![Figure 25 - Hierarchical System Boundaries with Technical Innovation Integrations](image)

Dominant Design

In his book, *Mastering the Dynamics of Innovation*, Utterback defines a dominant design as “the one that wins the allegiance of the marketplace, the one that competitors and innovators must adhere to if they hope to command significant market following” (Utterback). Therefore, recognizing a dominant
design where it exists is an important step prior to interpreting the value of certain innovations and the sustainable business formats that could capture this value. Innovating against a dominant design, rather than in conjunction with it, can be an uphill battle in the marketplace (and often a losing one). This may be even more important in the power industry where barriers to entry are high due to high capital costs and large incumbent market participants.

Central to the wind plant is the wind turbine generator. This thesis takes the view that, over the last several decades of utility-scale wind power, the horizontal-axis, upwind, three-bladed wind turbine architecture as described in Part 1, has evolved into the dominant design for the industry. Evidence for this is presented in Imanol De La Torre’s Master of Science Thesis titled “Technological Evolution of the Wind Power Industry” (De La Torre). Among others, De La Torre uses Abernathy and Utterback’s industry life cycle framework to show that the wind power industry is in the “transitional phase” in which product innovation has slowed greatly and process innovation is more prominent but beginning to slow and move towards the “specific phase” in 2020 where little additional innovation will occur.

Central to the power system is the design of the electrical current carrying infrastructure, the controls for these systems, and the electrical machines that consume the electrical energy. At this level, design dominance is truly apparent and has been established for over a century. In the famous “War of the Electric Currents”, Edison’s direct current (DC) power system concept eventually lost out to Westinghouse’s (and Tesla’s) alternating current (AC) power system (Jonnes). The global industry has maintained an AC generation, transmission, distribution and consumption system ever since. While there has been some resurgence in DC systems, these are largely extensions of the AC network or for micro-grid applications. Overturning the dominant power system would mean leaving hundreds of billions of dollars of current assets behind and therefore, is not likely to happen over a short amount of time.

Henderson and Clark Framework
With the presence of dominant designs within the plant and system boundaries, it is then possible to examine the nature of innovations in each system level. Henderson and Clark present a convenient framework for classifying types of innovations as either reinforcing or overturning a core design concept. A reinforcing innovation would be one that either improves the performance or cost of the system by improving the components in the design (“Incremental Innovation”) or by restructuring or introducing new linkages in the components (“Architectural Innovation”) (Henderson). These types of innovations tend to have small step changes in the performance or cost of the system.
On the contrary, as shown in Figure 26, innovations that overturn the core concept can have much larger improvements in performance or cost, yet these innovations happen less frequently (Henderson). A “Modular Innovation” is one that overturns the core concept by adding additional functionality, while a “Radical Innovation” completely changes the concept with which to achieve the desired functionality.

The core design concept for wind energy generation, at the wind plant level, is the transfer of kinetic energy in the wind to the rotational energy of a turbine powering an electro-magnetic generator to produce sellable electricity. We’ve seen that there is a dominant design for this wind turbine generator. Due to this, the innovations in the wind plant have largely been reinforcing. This can be seen by looking at the performance/cost trends of wind turbines for the last several decades of utility-scale wind power.
Starting from the early years of the utility-scale wind power industry, Figure 27 shows a 14% annual average cost reduction in wind energy as more wind plant capacity is built (Clean Technica). This effect is also evidence of a dominant design being selected for the wind generator and an innovation shift to drive down the cost of that design. This largely has been done by the scaling up of the wind generator hub-height and rotor diameter as shown in Figure 20. Larger wind energy generators capture more energy per capital investment.

The historical evidence of past industry performance, the presence of dominant designs, and the practicality of innovating within a century-old, trillion dollar electric power industry suggest that successful innovations will be in the left quadrants of Henderson and Clark’s model, as shown in Figure 28. Therefore, this thesis will strictly analyze innovations in those quadrants, at both the plant and system level. The technical capabilities and the technologies that deliver them will be segmented below and represent both incremental and architectural innovations.

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8 http://www.economywatch.com/world-industries/energy/electricity-industry.html
Plant Level Innovations

On-Site Manufacturing Systems, such as Keystone Tower Systems’ technology for producing steel towers at the wind plant, are an example of architectural innovation. In the case of Keystone, similar steel handling and welding components are used to produce towers that are currently manufactured in permanent steel welding facilities. The architecture of the welding and steel handling equipment was re-designed to produce a continuous rolling and welding process that takes in flat sheets of steel and outputs conical tower segments. In the current process, these steps are done by discrete pieces of machinery and operators, rather than in one continuous step. Due to the size and labor requirements for the current process, on-site manufacturing is not economical (Keystone Tower Systems). Through architectural innovation, Keystone enables an economic process to produce much larger steel towers than conventional methods, which improves the cost-performance of the wind plant.

Long-Term Forecasting and Predictive Maintenance are both examples of incremental innovations at the wind plant. These innovations amount to better intelligence to be used in an existing decision making system. For example, Wind Plant Owner/Operators currently use a maintenance system, which might be as simple as wait for a failure to be reported, identify the failure, and fix the failure (WWINDEA). With Predictive Maintenance, the “wait for a failure to be reported” component of the system would be augmented by a prediction of when a failure would occur before it actually occurs. The downstream elements of the maintenance system remain largely unchanged, but the system performs with better cost-performance. Likewise, Long-Term Forecasting augments any number of decision making systems that Project Developers and Investors use to evaluate a wind plant project. With better information on long-term performance, better results are obtained from the decision making systems.
System Level Innovations

Grid-Scale Storage technology is an example of architectural innovation. This technology is analyzed at the interface of the wind plant and the power system interconnection, such as a substation. Grid-Scale Storage might be considered a modular innovation in the context of the wind plant alone, as new components are being added to achieve an additional functionality. However, from the system perspective, generation plants are typically dispatchable, meaning there is some store of energy that can be converted to electrical energy for delivery at the request of the System Operator. In thermal generation plants, the storage capability is achieved by the fuel being used in the thermal generator (i.e. coal or natural gas). Grid-Scale Storage technologies like Ambri allow wind plants to generate electricity and then store as electro-chemical energy for later dispatch. In this sense, the storage system amounts to an architectural reconfiguration of linkages between the wind plant and then power system.

Transmission PFC is an incremental innovation at the system level. PFC emerges as a new capability for the existing transmission network infrastructure. Within the same system architecture, coordinated control of substation hardware can modify the voltage, phase and impedance of electricity to direct the flow of power (Schlegel, Babcock and Gould). For example, TCAs can be used in existing System Operator software to input data from sensors in the transmission network, run power flow simulations, and then report to the System Operator how to switch transmission breakers on or off to route power around congested lines. All of the transmission, control and sensor elements are embedded in the current system, and the new layer of optimization that is added is an incremental innovation for the system.

Lastly, Near-Term Forecasting is also an incremental innovation at the system level. This is analogous to the examples of Long-Term Forecasting and Predictive Maintenance improving decision support systems at the plant level. Near-Term Forecasting can give System Operators predictive awareness of the wind plants in the system to better inform their security-constrained unit commitment and economic dispatch systems (Ahlstrom, Bartlett and Collier). Higher accuracy of the available capacity of each wind plant achieves greater economic efficiency in these scheduling and dispatch systems. Near-Term Forecasting can also be integrated at the plant level to give wind farm operators predictive awareness for row, sector and individual turbine optimization. These values will also be considered in later analysis, but in general the forecasting system will be in place at the system level to aggregate data from a larger geography. The forecast information may then be distributed to the individual Wind Plant Owner/Operators.
Part 3 – Analytical Framework

A. Intro to Analysis
This analysis uses a value-based approach to better understand the dynamics of technology adoption in the wind industry amidst the larger context of the electric power industry. The technical innovations presented in Part 2 will serve as representative candidates for the purposes of applying the analytical framework described herein. This framework not only analyzes technical innovations in regards to improving the competitiveness of a single wind plant, but in addition, also considers the system effects of incorporating more wind plants into the electrical power system. To begin, it is helpful to first define the analysis metrics that will be discussed in the following sections.

- **Attribute** – A qualifying characteristic
- **Benefit (Beneficial Attribute)** – An attribute that is advantageous or profitable (e.g. “increase energy generation”)
- **Value** – The measure of benefit gained, lost or exchanged (has quantity and direction)
- **Value Creation** – The assignment of value created by the technology for a given attribute
- **Value Capture** – The assignment of value received by a stakeholder for a given attribute
- **Value Contribution** – The total value created by a technology and captured by a stakeholder

B. Value-Based Approach
Adoption of new technology in the electric power industry is a complex, ill-defined process that is engaged by a diverse and large set of stakeholders. Amongst the industry stakeholders, there are often multiple decision makers, multiple flows of value exchange, and often misalignment between the economic buyers and the primary beneficiaries of the technology. The benefits of a new technology in a complex system, such as the electric power industry, are difficult to measure using a singular metric. An often used metric for comparing energy technologies is the impact of the technology’s adoption on the plant’s levelized cost of electricity (LCOE) in $/kWh. This metric represents the economic cost of electricity generation for which there is a 0% net present value on the capital and operational cash flows. Similarly, an often used performance metric for an electric power system is the average cost of electricity in $/kWh. This is the annually averaged cost of producing wholesale electricity in a given power system. However, neither of these economic metrics are representative of value – they are singularly focused on the cost impact to the plant or the price impact to the Electricity Consumer. Calculating these metrics does not provide information about how other system stakeholders will be affected. Additionally, these singular metrics obscure the beneficial attributes which are the ingredients for the net economic effect. While the over-riding decision principles are to reduce costs incurred, often it is the beneficial attributes which stakeholders relate to and incorporate as inputs into their value judgment and decision making processes.

Using a simple example, if a new technology increases energy generation, but also increases O&M costs a few years into operation, the LCOE metric alone does not provide sufficient information for all stakeholders to judge the value of that technology. While the Project Developer will improve his

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9 These definitions are largely adapted from the basic definitions of the course ESD.34 – System Architecture taught at MIT
competitiveness in attracting PPAs, the Wind Plant Owner/Operator will increase his O&M expenses. The technology will thus be valued differently depending on the business models and decision making structures of the stakeholders.

In this context, evaluating the impact of a particular technology’s proliferation is challenged by the lack of an analytical framework to anticipate both the value created by adopting the technology in addition to the value captured by the industry stakeholders. Such an analytical framework must consider multiple beneficial attributes from both the perspective of the wind plant as an economic participant in the electric power industry, as well as from the perspective of the electric power system as a whole which includes many market and non-market oriented stakeholders. Additionally, the framework must address the assignment and valuation of benefits imparted by technologies and utilized by stakeholders. Furthermore, the dynamics of the value exchanges amongst the industry stakeholders needs to be understood and quantified to weigh the importance of these stakeholders and focus the technology adoption strategy on a subset of the stakeholders with the highest relative influence.

To meet these requirements, and evaluate the potential impact of adopting the six technologies described in Part 2, a value creation-value capture analytical framework is proposed and utilized in this thesis. An illustration of the proposed framework is represented in Figure 29, and each component is described in the following sections.

![Value Creation - Value Capture Framework](image)

### C. The Value Axis

Central to the framework is a binary axis of beneficial attributes for a wind energy generator power plant (“plant” or “wind plant” – on the left) and for the entire electrical power system (“system” – on the right).

The goal of the wind plant is to produce sellable electricity for a profit. Profit is defined as the margin between the sale price for a quantity of electricity and the plant’s expenses for generating that quantity.
of electricity. The sale price can be defined through a PPA with an LSE or by the market pricing in the wholesale electricity market. The plant’s generation expenses are represented by LCOE. The plant value axis therefore contains a discrete set of beneficial attributes which are the decomposition of the cost based metric LCOE in addition to attributes that reflect sale price or salability. The LCOE ingredient attributes are explicitly identified and assigned a direction that implies a reduction in LCOE. For example, “Increased Energy Generation” would reduce LCOE, with all other attributes remaining constant. Similarly “Reduce O&M Expenses” would also reduce LCOE. In addition to these LCOE reducing attributes, market facing attributes are included in scenarios in which the wind plant is selling power into wholesale electricity markets rather than through PPAs.

The goal of the electric power system is to instantaneously deliver reliable, low-cost electric power with varying demand levels to a wide variety of Electricity Consumers. The system axis attempts to reflect these requirements with a discrete set of beneficial attributes which will reduce the integration costs for wind energy into the electric power system as well as increase the reliability of the system. A core assumption made here is that the overall reduction of wind integration costs allows for an increased penetration of wind energy into the energy generation mix of the power system. Several power system integration studies have shown that an increase in wind penetration results in a decrease in the average cost of electricity because wind generators operate at near-zero variable cost and displace higher variable cost generators (Bird). Therefore the increase in benefit of any of the system attributes are expected to lead to a decrease in electricity costs. For example, “Reduce Regulation Reserves” would reduce costs because fewer thermal generating unit reserves would need to be committed and scheduled by the System Operator. In addition to these system cost-reducing attributes, “Increase System Capacity” serves as a proxy metric for system reliability as adding additional firm capacity will improve the system’s ability to meet peak demand. Other attributes are added for scenario analysis in which additional requirements are demanded of the system. For example, “Reduce Risk of Price Shock” becomes an important beneficial attribute when protecting consumers from price volatility becomes a system requirement. Furthermore, “Increase Carbon Offset from Base-Load” is a beneficial attribute in a scenario where the power system is held accountable for carbon emissions.

D. The Technology Domain

Lying above the value axis is the “Technology Domain”. Here is where a discrete set of technologies are measured against the beneficial attributes along the value axis. The potential for value creation is recorded in this domain. Several analytical techniques to quantify the value are explored and are described in a later section. The technologies are defined generally according to the primary technical capability they provide. For example, the analysis does not evaluate Ambri’s liquid metal battery technology, per se, but rather the Grid-Scale Storage capability that the technology provides to the plant and system. Additional technologies and combinations of technologies can be added to the domain and equally compared against the set of attributes along the value axis. The primary analysis for this thesis will focus only on the six technologies stand-alone, as later discussion will address the business strategy of commercializing the most promising technologies from the perspective of a new firm – whose resources are limited to only a single technology to be commercialized.

E. The Stakeholder Domain

Lying below the value axis is the “Stakeholder Domain”. The framework uses this domain to measure the importance of the beneficial attributes on the value axis to each of a discrete set of stakeholders
included in the wind plant and system stakeholder network described in Part 1. The potential for value capture is recorded in this domain. Two approaches to quantify the value are explored, one assuming no dynamic network effects of the stakeholders and the other using a stakeholder value network methodology to capture the dynamic effects. These will be described in more detail in a later section.

F. The X-Matrix

The framework described above can be embodied in a four quadrant matrix referred to as an “X-matrix”. The X-matrix is a tool used for enterprise design and strategy that helps align stakeholder values and strategic goals (Donnelly). The ability of the format to capture multiple attributes and multiple stakeholders makes the X-matrix an applicable tool when evaluating the value creation – value capture potential of new technologies for wind energy.

As shown in Figure 30, the discrete set of plant beneficial attributes [PA] are listed on the left side of the matrix while the discrete set of system beneficial attributes [SA] are listed on the right. This is the matrix representation of the value axis from Figure 29. Similarly, above the value axis are the set of technologies [T] and below are the set of stakeholders [S] which represent the Technology Domain and Stakeholder Domain.

<table>
<thead>
<tr>
<th>[PA, T]</th>
<th>Grid Scale Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Site Mfg Systems</td>
<td></td>
</tr>
<tr>
<td>Transmission PFC</td>
<td></td>
</tr>
<tr>
<td>NT Forecasting</td>
<td></td>
</tr>
<tr>
<td>LT Forecasting</td>
<td></td>
</tr>
<tr>
<td>Predictive Maintenance</td>
<td></td>
</tr>
<tr>
<td>System Capability</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value to Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce O&amp;M Expenses</td>
</tr>
<tr>
<td>Reduce Maintenance Downtime</td>
</tr>
<tr>
<td>Reduce Curtailment Loss</td>
</tr>
<tr>
<td>Reduce Development &amp; Construction Costs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology &amp; Stakeholder X-Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value to System</td>
</tr>
<tr>
<td>Decrease Need for Regulation Reserves</td>
</tr>
<tr>
<td>Reduce Need for Contingency Reserves</td>
</tr>
<tr>
<td>Reduce Need for Transmission</td>
</tr>
<tr>
<td>Reduce Baseload Cycling</td>
</tr>
<tr>
<td>Increase Total System Capacity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPC</td>
</tr>
<tr>
<td>Fed Gov/Reg</td>
</tr>
<tr>
<td>IF</td>
</tr>
<tr>
<td>Investors</td>
</tr>
<tr>
<td>Land Owner</td>
</tr>
<tr>
<td>Loc Comm</td>
</tr>
<tr>
<td>Loc Gov/Reg</td>
</tr>
<tr>
<td>LSE</td>
</tr>
<tr>
<td>NGO</td>
</tr>
<tr>
<td>Supp/OEM</td>
</tr>
<tr>
<td>System Operator</td>
</tr>
<tr>
<td>Wind Plant O/O</td>
</tr>
</tbody>
</table>

Figure 30 - The X-Matrix
In the Technology Domain for each matrix cell \((PA_i, T_j)\), the analysis proceeds cell by cell answering the following question:

**If the capability described by \(T_j\) were to exist, then what value can be assigned to \(PA_i\)?**

If value can be interpreted from the perspective of the wind plant, it is assigned to that cell. Similarly, for each matrix cell \((SA_i, T_j)\), if a value can be interpreted from the perspective of the electric power system it is assigned to that cell.

In the Stakeholder Domain for each matrix cell \((PA_i, S_j)\), the analysis proceeds cell by cell answering the following question:

**If the benefit described by \(PA_i\) were to exist, then what value can be assigned to \(S_j\)?**

If value can be interpreted from the perspective of the wind plant, it is assigned to that cell. Similarly, for each matrix cell \((SA_i, S_j)\), if a value can be interpreted from the perspective of the electric power system it is assigned to that cell.

It is important to note, that when comparing the two analysis questions, the dependent variable (the “If” question) is shifted between the Technology Domain and the Stakeholder Domain, however the notation of the matrix cells remains constant. This contradiction will be resolved in the next and final element of the framework.

**G. The Value Creation-Value Capture Matrix**

A comparison matrix is then calculated to measure the strength of the value creation potential from the Technology Domain to the value capture potential from the Stakeholder Domain. This matrix will provide the value creation-value capture metric which will be called the “value contribution”. The first step of this calculation is to find the inverse of both matrices in the Stakeholder Domain. This can be done using spreadsheet software and the TRANSPOSE function. An example of this calculation is shown in Figure 31 for the plant matrix in the Stakeholder Domain. This matrix inversion corrects for the dependency contradiction with the two analysis questions described above.
The final step is to compute the matrix multiplication product of the Technology Domain matrices and the Inverse Stakeholder Domain matrices. This can be done using the MMULT function in spreadsheet software.

Figure 31 - Inverse Stakeholder Matrix for Plant: TRANSPOSE(A1:E12) = (A1:L5)

Figure 32 - Matrix Multiplication of Technology Domain and Inverse Stakeholder Domain for Plant shown
The multiplicative rule serves a useful tool in this analysis as it captures both the direction of the value flow as well as the value attrition when imperfect value creation and value capture metrics are paired. For example, if Technology A increases the need for transmission (rather than reduces the need) it will be assigned a negative value in that cell. If Stakeholder B loses value when additional transmission is not built, a negative value is assigned to that cell. Under the multiplicative rule, the product of these cells assigns a positive value contribution from Technology A to Stakeholder B. Furthermore, if Technology A only slightly increased the need for transmission and was assigned a -0.5 value, and Stakeholder B only benefited slightly from increasing transmission and was assigned a -0.5 the value contribution from Technology A to Stakeholder B would be 0.25. Therefore, direction correctness, as well as value attrition, is preserved even though a certain direction was implied in the beneficial attributes on the value axis.

H. Analytical Techniques

Within this framework, different value assignment techniques can be used to estimate the value creation potential in the Technology Domain and value capture potential in the Stakeholder Domain, and thus fill in the cells of the X-matrix when answering the analysis questions posed above. This analysis will employ several techniques which are described below. In addition multiple analysis scenarios are considered which change the core assumptions for which beneficial attributes to include on the value axis and which stakeholders to include in the Stakeholder Domain. During the course of the analysis, several X-matrices and Value Creation-Value Capture matrices are constructed and the results from these different analytical techniques and scenario tests are summarized and presented in Part 4.

Pugh Method

The Pugh method uses a decision matrix, generally composed of a tertiary metric (-1, 0, 1) to score multi-dimensional options for a set of alternatives and then rank the alternatives (Rhodes and Ross). The scores for each option are generated by considering the delta between the alternative and a baseline assumption. If the alternative is better than baseline it receives a 1, a 0 if there is no change, and a -1 if worse than baseline. The sum of the scores across all attributes are used to rank the alternatives and select the dominant score. Generally the scoring for each option is not weighted so that each option is considered with equal importance. For all quadrants of the X-matrix in this analysis, the tertiary scoring will be used to indicate direction of value flow if it exists where 1 is receiving value and -1 is losing value.
No change to value will be scored as 0. Summing the scores can indicate which, if any, of the technologies or stakeholders are dominant value creators or value capturers.

To carry out Pugh analysis an assumption for the reference baseline must be made. This analysis will use the PJM Interconnection as the reference power system and use the current performance, integration and operation characteristics of wind power plants in that system as the reference plant. Specifically, for the baseline:

- The technical capabilities for Grid-Scale Storage, On-Site Manufacturing Systems, and Transmission Power Flow Control do not exist
- The technical capabilities for Near-Term Forecasting, Long-Term Forecasting and Predictive Maintenance exist but require large improvements to be adopted at scale
- There is very little penetration of wind energy but large potential for new capacity growth
- The plant competes for long-term power purchase agreements backed by renewable portfolio standards and subsidy-supported outside financing.
- Any improvements to the cost structure or the energy pricing increases the wind plants competitiveness as there is an unsaturated demand for new power generation in the system.
- The system integration costs scale with the increased penetration of wind energy, specifically the need for regulation reserves and transmission as well as the increased occurrence of base-load cycling.

**Stakeholder Value Network**

The Pugh method assumes that all stakeholders receive value independently of one another and disregards any value exchange amongst the stakeholder set. A more rigorous analysis is required to demonstrate the dynamic relationship between stakeholders and value flow. A stakeholder value network (SVN), as described in the methodology proposed by Feng et al., is “a multi-relation network consisting of a focal organization, focal organization’s stakeholders, and the tangible and intangible value exchanges between the focal organization and its stakeholders, as well as between the stakeholders themselves” (Feng, Crawley and de Weck). This method starts by selecting a focal organization that is best representative of the system, either a primary beneficiary of the system or a primary decision maker. Then a stakeholder map is constructed that includes all of the other relevant stakeholders to the focal organization and a qualitative value network is drawn by mapping the needs of each stakeholder as value exchanges, or flows, in the network. Figure 34 depicts an example in which Stakeholder A, the Electricity Consumer, needs electricity services delivered to their factory from Stakeholder B, the LSE. In exchange, the LSE receives payment ($) for service from the Electricity Consumer.
For this analysis, two main SVNs are constructed, corresponding with each side of the value axis. For the plant SVN, the Project Developer is chosen as the focal organization. As described in Part 1, the Project Developer is the hub for any new wind plant project. They lead the project definition, design, and implementation and bring together a diverse set of stakeholders to accomplish all the necessary project tasks. It could be argued that the Wind Plant Owner/Operator, whom receives revenues from electricity sales, is the primary beneficiary of the plant. However, as the focus of this analysis is on the implementation of new technologies, the Project Developer – who owns the early stage design decisions – will have greater influence on the technology choices as well as design of options to allow future incorporation of technology into the wind plant post-commissioning. Therefore, the Project Developer is chosen as the focal organization for the plant SVN given their role as the primary decision maker. As we will see in the construction of the plant SVN, the Project Developer and Wind Plant Owner/Operator are tightly coupled with a bilateral value exchange. Therefore, it is not expected that the choice of Project Developer over Wind Plant Owner/Operator will have much impact on the results of the eventual scoring of the plant SVN, as any value exchanges will pass through to either stakeholder via similar pathways.

For the system SVN, two alternatives can be selected for the focal organization. It can be argued that the electrical power system exists to serve the Electricity Consumers (i.e. customers). Therefore the system SVN could be modeled with the Electricity Consumer as the focal organization in their role as the primary beneficiary. Alternatively, the System Operator plays a central role as the operator and collaborator of the power system and its assets, market participants, and other stakeholders. They are a critical decision maker in regards to the operation of the system and planning for future changes to the system. Therefore the system SVN could also be modeled with the System Operator as the focal organization in their role as the primary decision maker. For this analysis, both alternative system SVN are constructed and analyzed. It can be seen in the construction of these SVN that the structure of each are distinct as the Electricity Consumer and System Operator are not tightly coupled through a bilateral value exchange.

It is important to note that the focal organization is removed from the Stakeholder Domain for the X-matrix and Value Creation-Value Capture analysis. The SVN methodology described in this section measures value relative to the focal organization, and provides insight into the value captured by the most influential stakeholders in the focal organizations network. For this reason, the stakeholder set will change depending on the focal organization chosen.
Benefit and Supply Ranking

To quantify the value exchanges between stakeholders, each need is scored using metrics derived from two additional analysis questions:

1) How much benefit will the fulfillment of the need bring to the recipient?

2) How important is the supply source in meeting the need?

To answer the first question, a simple “Must Have”, “Should Have”, and “Might Have” benefit ranking can be made – derived from the Kano model for product development and customer satisfaction (Cameron). The Kano model maps customer satisfaction (in this case stakeholder satisfaction) with a product’s performance in meeting a customer requirement (in this case meeting a stakeholder need from the value exchange map). A “Must Have” character is absolutely essential and the absence of meeting the need is unacceptable. A “Should Have” character is satisfied by meeting the need, yet the appetite for continuing to meet the need will not be satiated (i.e. more is better). A “Might Have” character is satisfied by meeting the need, but the absence of meeting the need would still be acceptable. These characteristic curves are plotted in Figure 36.

In the previous example, the Electricity Consumer “Must Have” service to keep their factory in operation. If this need was not met, the results would be unacceptable because the factory would not operate. However, having more electricity service than needed does not improve the Electricity Consumer’s satisfaction. In contrast, the LSE “Should Have” payment ($). While not having payment is unacceptable, having more payment is clearly better, and there is no limiting boundary on performance and satisfaction. The benefit mapping is shown in Figure 35.

To answer the second question, a simple “High”, “Medium” and “Low” supply ranking is utilized to judge the supply constraints (Cameron). A “High” supply ranking would indicate a single-source for meeting the need. A “Medium” supply ranking would indicate more than one source, but restricted to only a few sources. Finally, a “Low” supply ranking indicates that the sources are plentiful.
To complete the analysis for the previous example, there are a restricted number of LSE options for the Electricity Consumer while there are a plentiful number of Electricity Consumers in the LSE’s territory. The supply mapping is shown in Figure 37.

![Figure 37 - Value Exchange Map with Benefit and Supply Ranking](image)

**Constructing SVN**

Using the benefit and supply ranking scheme, a complete SVN is built for both the plant and the system using the stakeholder set described in Part 1 (with alternative focal organizations for the system). Figure 38 to Figure 40 show the gradual construction of the plant SVN with the Project Developer as the focal organization, starting with the “Must Have” benefits and then followed by adding the “Should Have” and “Might Have”. Stakeholders are also labeled as either market or non-market participants to identify opportunities for economic leverage versus political leverage.

It is important to note the large amount of “Must Have” needs of the Project Developer, several with single source supplies from non-market stakeholders. This indicates the tenuous nature of project development with many variables that can halt progress if a single need is not met.
Figure 38 - Plant SVN - Must Have Benefit Only

Figure 39 - Plant SVN - Must Have & Should Have Benefits
Figure 40 - Plant SVN - All Benefits

Figure 41 and Figure 42 show the final construction of the system SVN with both the Electricity Consumer and the System Operator as the focal organization.

Figure 41 - System SVN of Electricity Consumer - All Benefits
Measuring the Value Exchange

The benefit and supply rankings are then combined into a single numeric score for each value exchange between stakeholders using the scoring matrix shown below (Cameron). The principle of this weighting scheme is that the benefit ranking increases non-linearly while the supply ranking increases linearly, therefore weighing the benefit higher than the supply.

The SVN structure is then analyzed to look for discrete pathways using the methodology described by Feng et al. to measure the “path score” - that is loops of value exchanges that originate from and return to the focal organization (Feng, Crawley and de Weck). These paths can contain at least two and up to the complete set of stakeholders depending on the SVN structure. In this analysis, a path counting rule is imposed to include at most one of each stakeholder. This disqualifies paths with iterative loops that pass value back and forth between the same stakeholders before returning to the focal organization. Therefore, this is a first order analysis of value flow and ignores second order and later effects. For each
path, the value of the exchanges are multiplied, and the final exchange to the focal organization is squared to emphasize the desired impact of the loop. The multiplicative rule is again useful here because longer pathways will return lower scores, reflecting the attrition of value in managing long chains of stakeholders.

For example, a value exchange path is selected from the plant SVN and shown in Figure 44.

![Figure 44 - Example Value Exchange Path](image)

Using the benefit and supply ranking the quantified value exchange is shown in Figure 45. The calculation of the path score is as follows:

\[ 0.2 \times 0.2 \times 1^2 = 0.04 \]

**Weighted Stakeholder Occurrence (WSO)**

The objective for the SVN analysis is to utilize a more rigorous approach to represent the dynamic nature of the stakeholders in the X-matrix and Value Creation-Value Capture matrix. The SVN construction and quantification method described above allows us to identify and estimate the flows of value amongst the stakeholders. We can then use this knowledge to weight each stakeholder relative to their contribution towards the dynamic exchanges of value to the focal organization. The weighted stakeholder occurrence (WSO) method, also described by Feng et al., quantifies each stakeholder in the network based on the aggregate of the pathways in which they are included (Feng, Crawley and de Weck). The WSO metric for each stakeholder is defined by:

\[
WSO = \frac{\text{Sum of the Value Paths Containing a Specific Stakeholder}}{\text{Sum of All the Value Paths for the Focal Organization}}
\]

The WSO values are calculated for each stakeholder for each of the three SVNs. These are fractional, dimensionless values and will be used to weight the scores reported from the Pugh method analysis in the Stakeholder Domain. This is done by multiplying the WSO value for the stakeholder to the Pugh scoring. Figure 46 shows the representative results from WSO calculated for the stakeholder set for the plant SVN.
Multi-Attribute Utility Method

The SVN method expands upon the Pugh analysis with greater detail regarding the dynamics of value flow in a diverse set of stakeholders in the Stakeholder Domain. A similar application of a more rigorous analytical tool for the Technology Domain is required. The method must allow distinction to be made between the different technical capabilities and how much value they create for a given beneficial attribute. While the Pugh method reveals positive, negative and no change in direction, one would also like to know if, for any set of technologies that provide value to the same beneficial attribute, one technology provides more value in that attribute than the other. One would also like to have the scale of this distinction be such that individual scores for a technology in each of the beneficial attributes can be aggregated into a combined score (sum of scores) representing the technologies ability to satisfy multiple attributes and allowing for a comparison to be made to other technologies. One method, among many, that allows for this is the multi-attribute utility method (MAU) (Rhodes and Ross). The core of MAU is the creation of “utility functions” which are curves that represent how much the beneficial attributes are worth to a decision maker (i.e. how much “utility” is derived from the attribute). Use of MAU in this analysis will also assume a single stakeholder as the primary decision maker and will use utility functions to weight the value creation potential of the technical capabilities.

The choice of the primary decision maker will influence the formation of the utility function. As discussed in the SVN creation, the Project Developer is chosen as the primary decision maker for the Plant and the System Operator as the primary decision maker for the System. The Electricity Consumer was also used as a central role in the SVN. However, in considering utility functions for the list of attributes for the system (e.g. “Reduce Need for Contingency Reserves”, “Reduce Base-Load Cycling”, etc.), it becomes clear that the Electricity Consumer is a poor choice for the primary decision maker role.
While the Electricity Consumer may be the primary beneficiary of the system, they are generally exposed to only two attributes; price and reliability of service. It would take a very educated Consumer to understand the ingredients of these two attributes, and for this analysis, it is the ingredients that are the focus and not the net economic result. Therefore, the Project Developer is used as the basis for utility functions for the plant attributes, and the System Operator as the basis for utility functions for the system attributes.

The formation of the utility function follows “utility theory” in which a dimensionless metric is created between 0 and 1, where 0 is the least desirable value of the attribute and 1 is the most desirable from the perspective of the decision maker (Rhodes and Ross). Similar to the Pugh method, a baseline must be understood as a reference to judge an increase in utility. We will use the same baseline described above for Pugh. In MAU scoring, the negative direction of value is lost. A score of 0 implies that the technology is no greater than, or is perhaps worse than, the baseline. A score of 1 implies that the technology has completely met the utility of the decision maker, and any additional utility added beyond that is not scored higher.

Two common ways of creating the utility functions for the attribute set are to sketch the shape of the function through intuition, or to interview the decision makers to either gain additional intuition or actual reference points to base the function on (Rhodes and Ross). For this analysis, utility curves are sketched based on the intuition of the author after seven years in the wind energy industry and numerous informal interviews with both Project Developers and System Operators. The utility functions can be categorized into three main categories: linear, diminishing returns, and threshold functions.

![Utility Function Categories](Rhodes and Ross)
The plant (green) and system (red) beneficial attributes can then be sorted into these three utility function categories based on the primary decision maker’s utility response to the attribute. Table 2 shows the segmented attributes by utility type.

<table>
<thead>
<tr>
<th>Linear Attributes</th>
<th>Diminishing Returns Attributes</th>
<th>Threshold Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase Energy Generation</td>
<td>Reduce O&amp;M Expenses</td>
<td>Increase Penetration in High Value Market</td>
</tr>
<tr>
<td>Increase Firm Capacity Rating</td>
<td>Reduce Maintenance Downtime</td>
<td>Increase Coincident Supply &amp; Demand</td>
</tr>
<tr>
<td>Increase Total System Capacity</td>
<td>Reduce Curtailment Loss</td>
<td></td>
</tr>
<tr>
<td>Increase Carbon Offset from Base-Load</td>
<td>Reduce Development &amp; Construction Costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce Need for Additional Regulation Reserves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce Need for Additional Contingency Reserves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce Need for Additional Transmission</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce Base-Load Cycling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce Risk of Price Shock</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2 - Utility Function Categories*

The utility for linear attributes increases less rapidly than for the diminishing returns attributes, but maintains steady growth (i.e. “more is better”). For example, a benchmark for the wind industry is a 30% net energy capacity factor for the wind plant. For energy generation, the utility value was judged by the increase of net capacity factor from 30% to 50% on a linear scale.

*Figure 48 - NCF Linear Utility*
The diminishing returns attributes are expected to follow the 80-20 rule, in which 80% of the utility is gained by the reduction (or increased efficiency) of the attribute by 20%. For example, a reduction in a base-load cycling by 20% would achieve 80% of the utility score.

![Cost/Loss Reduction](image)

*Figure 49 - Cost/Loss Reduction Diminishing Utility*

The threshold attributes are bit more intuitively challenging as they have some slow growth ramp time before increasing to near maximum utility and then produce diminishing returns. For example, an increase in high value market penetration in the 10-20% range has large utility gains, with only marginal gains above and below this range.

![Market Penetration](image)

*Figure 50 – High Value Market Penetration Threshold Utility*

**Weighting the Technology Domain**

Once the utility functions are defined, each cell in the Technology Domain that was scored during the Pugh analysis is then multiplied by the utility score ranging from 0 to 1. Previous negative scores from Pugh will be set to 0.

**Scenario Test**

In the final consideration for the analysis, the effects of possible future energy and policy scenarios are explored. The analysis described is performed in the context of each of four scenarios based on potential disruptions to the electric power and wind industry. Each scenario poses different goals for the plant and system, and thus different beneficial attributes to compare technologies. Similarly, each scenario creates different stakeholder needs and value exchanges. Therefore, the attribute set, and SVN are revised for each scenario and iterations of the X-matrix and Value Creation-Value Capture matrix are performed for each.
**Scenario 1 - Baseline**

The Baseline scenario is the present wind energy policy and electricity market conditions in the PJM Interconnection. The key factors that influence the analysis are:

- Active Production Tax Credit (PTC)
- Active Renewable Portfolio Standards (RPS)
- Wind energy and RECs are purchased through a bilateral contract with an LSE under a long-term PPA

Under these conditions, the wind plant’s goal is to lower capital and operational costs to compete for power purchase agreements that provide it the maximum return on investment. The plant measures value by the following beneficial attributes:

- Increase Energy Generation
- Reduce O&M Expenses
- Reduce Maintenance Downtime
- Reduce Curtailment Loss
- Reduce Development & Construction Costs

Without additional policy, the system goals are to deliver electricity reliably and at lowest cost to its consumers. Therefore the attributes by which it measures value relate to mitigating the integration costs of wind plants connecting to the system. It measures value by the following beneficial attributes:

- Reduce Need for Regulation Reserves
- Reduce Need for Contingency Reserves
- Reduce Need for Transmission
- Reduce Base-Load Cycling
- Increase Total System Capacity

The plant and system SVN’s are modeled under these assumptions as shown previously in Figure 38 to Figure 42 under the description of SVN methodology.

**Scenario 2 – “Sunset” of PTC and RPS**

The Sunset scenario models the removal of two historically key policy drivers for wind energy growth in the US, the PTC and the RPS. The extinction of the PTC is actually a scenario that is quite imminent and the historic RPS goals have largely been met. This scenario examines the worst case where neither PTC nor RPS are in place to see the effect of value contribution by the technologies under a new set of attributes and SVN’s. The key factors that will influence these are:

- Expired PTC – an therefore no more tax equity investors
- Expired RPS - and therefore no more REC market
- LSEs have lower incentive to purchase electricity from wind plants under long-term PPAs
- Wind plant’s sell their electricity on the wholesale electricity market, similar to many other power plants

Under these conditions, the wind plant’s goal is to both lower their capital and operational costs (similar to baseline scenario) but also increase their market performance to compete for electricity sales on the
wholesale market. In addition to the baseline attributes, the plant will also measure value by the following beneficial attributes:

- Increase Penetration in High Value Markets – allows sales into higher priced energy markets
- Increase Coincident Supply & Demand – allows sales at peak pricing hours
- Increase Firm Capacity Rating – allows higher return in the forward capacity market

The system goals and attributes remain the same as for the baseline scenario as no additional requirements are being placed on the system from their users. The operational and planning goals are to control the cost and reliability of the system as more wind is added.

New SVN attributes are constructed for this scenario, primarily shifting value exchanges between the Wind Plant Owner/Operator, the LSE and the System Operator, as the bilateral exchange between Wind Plant Owner/Operator and LSE are no longer in place and the wind plant must participate in the market coordinated by the System Operator. In addition, there is no exchange of PTC or RECs.

![Figure 51 - Plant SVN - Sunset Scenario](image-url)
Scenario 3 – High Natural Gas Pricing “HNG”

The third scenario builds from the assumptions in the Sunset scenario, but also anticipates natural gas supply disruptions and price shocks. These high natural gas “HNG” pricing events can be caused by supply restrictions in areas with heavy usage of natural gas for residential heating in addition to base-load electricity generation (Puko). However, there is also future uncertainty of the resource supply and
the effect of global export on the supply and demand pricing for natural gas. The EIA, and other energy economists, have predicted that the US will experience higher, and sometimes volatile, future natural gas pricing. In any case, for a robust analysis of the value contribution to stakeholders, it is an interesting scenario to consider the additional system requirements under a new core assumption:

- The system, in addition to providing reliable, low-cost service, will also be required to protect consumers from price volatility

In this scenario, the plant attributes remain the same but an additional system attribute is added to measure value:

- Reduce Risk of Price Shock

The SVNs are adapted from the previous scenario to increase the supply ranking of energy services from the Wind Plant Owner/Operator, increase the benefit and supply ranking of energy security to the Federal Government/Regulators, and increase the benefit ranking of price protection to the Electricity Consumer.

Figure 54 - Plant SVN - HNG Scenario
Scenario 4 – Carbon Market “Carb”

In the final scenario, a future where a market exists for offsetting carbon emissions from the electric power industry is considered. The EPA’s recent Clean Power Plan proposal lays a framework by which individual states must reduce the emissions of their energy generation to 30% of 2005 levels (Spees). One potential mechanism to achieve this would be a carbon credit trading mechanism for which zero-
carbon electricity sources such as wind could monetize carbon offsets in a liquid market. The following assumptions are used for this scenario analysis to understand the effect of a carbon market:

- No PTC or RPS exists
- Carbon offset credits, COs, replace RECs
- Bilateral, long-term PPAs with wind plants are sought to lock in carbon offsets
- The state governments are tasked with ensuring their electricity consumers’ need for climate protection is met

The same plant attributes are used as in the baseline scenario, as the plant is again focused on competing for long-term contracts with guaranteed offtake agreements, and thus is more focused on reducing costs. However, in place of Reduce Base-Load Cycling, the system is now more concerned with offsetting thermal base-load generation. A new attribute is added:

- Increase Carbon Offset of Base-Load

SVNs are constructed that remove the value exchanges for PTC and RECs and add the value exchanges for COs, Lower Carbon and Climate Protection.

---

**Figure 57 - Plant SVN - Carb Scenario**
I. Analyzing Results

The analysis described above results in four scenarios, with two alternative SVNs and using three different analysis methods. That is, there are six different X-matrices and Value Creation-Value Capture matrices produced for each of four scenarios, for a total of 24 sets of matrices.
The scoring for individual technologies in the X-matrix is the sum of each cell along the value axis. This is done for both the plant side of the axis and the system side, as well as a combined sum. For the MAU method, the individual cells are multiplied by the utility factor before being summed (a weighted sum approach). This same sum of scores approach is used for each stakeholder in the X-matrix. Under the WSO method, the individual cells are multiplied by the WSO factor before being summed.

The scoring for individual technologies in the Value Creation-Value Capture matrix is the sum of the scores in the individual cells for each of the stakeholders. This is done for both the plant side of the axis and the system side. Upon inspection, the results from the alternative system SVN are similar and are averaged for simplicity of interpreting the results.

To visualize these results, stacked bar charts and trade space scatter plots for each analysis method are built that include the results from all scenarios. The metrics for these plots are the summed value contribution scores of the Value Creation – Value Capture matrix as a percentage of the total possible score (i.e. a perfect score) for each technology in that analysis. For the Pugh analysis, the perfect score is given by the number of attributes analyzed multiplied by the number of stakeholders analyzed. For the Pugh with WSO and MAU with WSO analyses, the perfect score is equal to the number of attributes analyzed (as the stakeholder effect is normalized on a 0 to 1 scale).
Part 4 – Results

Results from utilizing the analytical framework presented in Part 3 can help direct technology selection and implementation decisions. The optimal technology will improve a wind plant’s competitiveness by lowering the cost of energy allowing greater opportunities for the plant to secure investor capital, offtake commitments, and/or higher infra-marginal rent in the electricity markets. In addition, the optimal technology will increase wind energy integration by lowering system integration costs and thus lower the average system cost of electricity. Furthermore, the optimal technology will be robust across multiple possible future scenarios, to ensure future value contribution despite policy and market uncertainty.

The analytical techniques discussed in Part 3 are used to estimate the potential for value creation and value capture and thus calculate the value contribution. These techniques help to quantify a qualitative assessment of the Technology and Stakeholder Domains for numerous beneficial attributes. While the results of this type of analysis can help identify those technologies that will most likely meet the plant and system objectives, further analytical work should be performed to truly quantify the value for each cell in the X-matrix.

For the results of this analysis, several stacked bar plots and trade space plots are presented which depict the value contribution to both the system and the plant. An alternative notation is used to represent the technologies in these plots, which is shown in Table 3. The technologies at the frontier of the trade plots represent the technologies that create and deliver the most value for wind energy. Dominance at the “value frontier” of these plots for the multiple scenarios analyzed will dictate the optimal technology choice. Grid-scale Storage, On-Site Manufacturing Systems and Predictive Maintenance are chosen as the most optimal technologies. In Part 5, the implementation of these technologies will be considered and the results from the Value Creation-Value Capture matrices will be utilized to inform commercialization strategy and business model design.

<table>
<thead>
<tr>
<th>Grid-Scale Storage</th>
<th>Long-Term Forecasting</th>
<th>Near-Term Forecasting</th>
<th>On-Site Manufacturing Systems</th>
<th>Transmission Power Flow Control</th>
<th>Predictive Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSS</td>
<td>LTF</td>
<td>NTF</td>
<td>OSMS</td>
<td>PFC</td>
<td>PdM</td>
</tr>
</tbody>
</table>

Table 3 - Key for Trade Plots

A. Matrix Results

The following figures show an example set of results of the 24 X-matrices and Value Creation-Value Capture matrices generated. Figures for the Baseline scenario using the Project Developer and Electricity Consumer SVNs are shown here. The complete set of matrices are included in the Appendix A.

Figure 60 is for the Pugh method. No weighting occurs in this analysis, and the stakeholder set does not include the focal organizations. The yellow highlights show the highest value sums per stakeholder or technology. Entries of “0” are hidden from view. The conditional formatting in the Value Creation-Value Capture matrix shows the value contribution per stakeholder – where the green shading is the highest contribution. These color-coded formats and highlights can be used as a visual check to see the effect of the scenario assumptions and analytical methods on the value scoring in the Technology and Stakeholder Domains and the value contribution in the Value Creation-Value Capture matrix. More
importantly, the value contribution of each of the technologies plotted amongst the stakeholder set is an important qualitative device to understand which stakeholders are benefiting most from each technology and thus will be critical when considering the commercialization strategy and business model design – as discussed in Part 5.

<table>
<thead>
<tr>
<th>Increase Energy Generation</th>
<th>Reduce O&amp;M Expenses</th>
<th>Reduce Maintenance Downtime</th>
<th>Reduce-Certainment Loss</th>
<th>Reduce Development &amp; Construction Costs</th>
<th>Value to Plant</th>
<th>Technology &amp; Stakeholder X Matrix</th>
<th>Value to System</th>
<th>Reduce Regulation Reserves</th>
<th>Reduce Contingency Reserve</th>
<th>Reduce Need for Transmission</th>
<th>Reduce Base Load Cycling</th>
<th>Increase Total System Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>Grid-Scale Storage</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>On-Site Mfg Systems</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Transmission PFC</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>NT Forecasting</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>LT Forecasting</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Predictive Maintenance</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

**Figure 60 - Pugh Method Results under the Baseline Scenario with Electricity Consumer SVN**

Figure 61 shows the same Baseline scenario with Project Developer and Electricity Consumer SVN weighted using the WSO method in addition to the Pugh analysis.
Figure 61 – Pugh & WSO Method Results under the Baseline Scenario with Electricity Consumer SVN

Figure 62 shows the same Baseline scenario with Project Developer and Electricity Consumer SVN weighted using the WSO method in addition to the MAU method.
B. Stacked Bar Plots

To better visualize the results in the matrices, bar plots in Figure 63 to Figure 65 show system value contribution as an addition to plant value contribution for the Baseline scenario. Results from the Sunset, HNG and Carb scenarios are shown as positive ("future upside") and negative ("future downside") error bars to show the range of values for all scenarios.
Figure 63 - Bar Plot for Pugh Method

Figure 64 - Bar Plot for Pugh & WSO Method
C. Trade Plots

To more effectively analyze the matrix results and make trade-off decisions, several trade plots are constructed. Figure 66 to Figure 69 show the results from the Pugh method for all four scenarios. The complete set of trade plots is in Appendix B. Note that some scenarios in the Pugh and Pugh & WSO methods generated negative results which are not shown on the plots. The dotted diagonal line bisecting the trade plots represents the binary value axis. Technologies near the diagonal have a relatively even value contribution to both system and plant, while above or below the line the value contribution is biased towards either system (above) or plant (below).

The solid line drawn in the trade plot represents the highest value contribution on each side of the axis – similar to a trade-off frontier in trade space analysis (Connors). Technologies are chosen if they are consistently near this value frontier for each of the scenarios examined and in each of the analysis methods.
Figure 66 - Trade Plot for Pugh Method for Baseline Scenario – Negative GSS Score Not Shown

Figure 67 - Trade Plot for Pugh Method for Sunset Scenario
D. Discussion of Results

Near-Term Forecasting

NTF contributes value fairly evenly to both the plant and system in most of the scenarios. Under the Pugh analyses (Pugh and Pugh & WSO methods), NTF tied for highest plant contribution but with
significant future downside. The system contribution was also quite high but with a balanced future upside and downside across the scenarios. However, under the MAU analysis, NTF contributed a much smaller amount of value. While NTF was at the value frontier for most scenarios in Pugh, it was not on the frontier for MAU. This suggests that advancements in NTF, while contributing value to both the plant and system stakeholders, will have small gains and diminishing returns for those stakeholders.

**Transmission Power Flow Control**

PFC also contributes value fairly evenly to both the plant and system across the different scenarios. Under the Pugh analyses, the value contribution is in the middle of the pack of the technologies analyzed, but has mostly future upside, especially at the system level. The addition of the WSO analysis exposes less system value which suggests that PFC value creation is more difficult to capture in the system SVNs. The MAU analysis exposes more future downside for both the plant and system and removes the upside, meaning that PFC might not be a great hedge for future policy and market changes. PFC is not at the value frontier very often.

**Predictive Maintenance**

PdM consistently contributes value to the plant, and only to the plant. PdM is the highest scoring for plant value contribution in all of the analysis methods. While there is future downside, exposed by the addition of the WSO method and MAU method, the targeted value contribution simplifies the stakeholder management for technology adoption. PdM is on the value frontier for most scenarios and analyses and thus is chosen for further commercialization discussion.

**Long-Term Forecasting**

LTF similarly only contributes value to the plant. The Pugh methods show middle of the pack plant value with some future upside, but the MAU exposes less plant value, suggesting diminishing returns with further technical improvements. LTF is never at the value frontier.

**On-Site Manufacturing Systems**

OSMS has a very high total value contribution with a lot of future upside for both the plant and the system. While Pugh methods show small plant value, the MAU exposes higher plant contribution. This suggests that the gains from OSMS are large and mostly linear. OSMS is often at the value frontier and thus is chosen for further commercialization discussion.

**Grid-Scale Storage**

GSS has the highest system value contribution. The Pugh methods show negative plant value contribution, but with a lot of future upside for both the system and plant. While the main contribution is to the system stakeholders, the MAU method exposes a lot of future downside for the system, but a lot of future upside for the plant. This suggests that targeting adoption by plant stakeholders now will be difficult, but may be adopted more easily as a hedge if some future scenarios seem likely. GSS is often at the value frontier and thus is chosen for further commercialization discussion.

**Architectural vs. Incremental Innovations**

The analysis results for the six technologies indicate a certain technical direction for the industry. NTF, LTF, PFC and PdM are similar in that they were classified as incremental innovations under the Henderson and Clark framework discussed in Part 2. These four technologies are primarily information technologies that interpret data from the current or expected infrastructure to suggest operational and
efficiency improvements. Whereas GSS and OSMS are architectural innovations that prompt the creation of new infrastructure and linkages. It is this latter innovation category that ranks higher in the system value contribution. This suggests that the wind industry still has “headroom” for first-order architecture improvements, relative to second-order efficiency improvements, to ease the system integration for larger amounts of wind power. These architectural innovations may be more complex in terms of commercialization overhead, but the system value derived is large and non-diminishing.

In comparison, the incremental improvements from information technologies contribute more value to the plant – quite a lot of value in the case of PdM. These technologies may be easier to adopt due to less technical integration complexity and can improve the wind plant’s competitiveness. However, when analyzing these technologies, it is clear that they contribute less value under the MAU analysis, which suggests that incremental innovations have diminishing returns. These results resonate with the Henderson and Clark theoretical framework presented in Figure 26.

Plant vs. System Biased
Comparison of the trade plots across each of the four scenarios reveals patterns in how the technologies behave. PFC and NTF; LTF and PdM; and OSMS and GSS seem to behave as similar pairs in how value is split between the plant and the system and how these contributions change in different scenarios. From an energy planner’s perspective, this is an important insight when considering a portfolio strategy for a robust combination of technologies to contribute high value despite the future scenario. For example, using the Pugh method, OSMS and GSS tend to be “system-biased” meaning they contribute more value to the system than to the plant, while LTF and PdM are “plant-biased”, and NTF and PFC contribute fairly evenly to both the plant and the system.

Pugh Method
The Pugh method reveals positive, negative and no change in value contribution direction, but does not discriminate the magnitudes of these contributions. Therefore, a positive is equal to a negative in terms of contribution. This creates interesting effects, such as with the OSMS analysis in which plant value is negated and only system value comes through – whereas intuitively one would think the technology contributes more to the plant. Therefore, it is critical to not use the Pugh results at their stated value, but to compare against the results that incorporate the MAU method.

WSO Method
The WSO method exposes value attrition from the complexity of the stakeholder network dynamics. For each scenario, comparing the Pugh method alone to the Pugh with WSO method indicates that the structure of the matrices remain consistent, but the magnitudes of value in the Stakeholder Domain change based on the WSO weighting. The resulting Value Creation-Value Capture matrices thus show an amended ranking of the technologies based on the difficulty of value capture in the corresponding SVNs. For example, with the addition of WSO methodology, OSMS begins to migrate towards the diagonal and becomes less system-biased (meaning value is not being completely captured in the system SVNs) while GSS migrates further towards system-bias (meaning value is not being completely captured in the plant SVNs).

MAU Method
With the addition of the MAU method, again the structure of the matrices remains consistent, but the magnitudes of value in the Technology Domain change based on the MAU weighting. The resulting
Value Creation-Value Capture matrices show a more pronounced shift in the technology value rankings, with a higher plant scoring for GSS and OSMS, which previously had negative scores incorporated from Pugh. It is important to note that the scaling for the MAU method is non-negative, which obscures any negative value contribution to stakeholders. This is pertinent, for example, in the case of GSS where the addition of new equipment can increase O&M complexity and development timelines and negatively impact some stakeholders such as the Wind Plant O/Os and Supp/OEMs.

Further Work
Ideally, the analytical method used for estimating value creation in the Technology Domain should be able to distinguish both value creation and value destruction, as well as the magnitude for each. This analysis used two methods that accomplished one but not both of these requirements. Pugh captures direction and MAU captures magnitude, but this leaves the reader to compare the methods to truly understand the value contribution results.

Additionally, while the MAU method allows for the most powerful segmentation of value contribution amongst the technologies, the results should be verified with further application of the technique. Greater rigor should be exercised in the forming of the utility functions. A likely improvement would be to collect more data from Project Developers and System Operators on the perception of utility for each of the benefit attributes through interviews and surveys. In addition, iterations of the analysis with different primary decision makers forming the utility functions should be performed for a more robust conclusion.
Part 5 – Commercialization

Interpreting the results in Part 4 gives insight into the robustness of a technology to contribute value in multiple scenarios. Additionally, it gives insight into which commercialization strategies might be most appropriate. For example, if the technology contributes value consistently to the system but not to the plant, the target market can be narrowed to include the system stakeholders. Further inspection of the Value Creation – Value Capture matrices identifies where exactly the value contributions are. These will better inform strategy for bringing the technologies to market and focus the attention to the most influential stakeholders while flagging where the technology adoption resistance will be.

In this section a commercialization analysis is performed to further understand how the value created by the selected technologies can be captured by industry stakeholders. Results from Part 4 indicate that the technology candidates that contribute the highest value to both the system and plant are Grid-Scale Storage (GSS), On-Site Manufacturing Systems (OSMS) and Predictive Maintenance (PdM). Each of these will be analyzed to consider stakeholder adoption, supply chain integration, and technical integration challenges. These will be used to inform a commercialization strategy that suits each technology.

A. Stakeholder Adoption

Stakeholder Analysis

Inspecting the Value Creation – Value Capture matrices indicate how value is contributed to each stakeholder from each technology. These results can be used to create a prioritized stakeholder list in terms of value contribution for each scenario considered. It is important to also consider the focal organizations in the SVNs which were removed from the matrix analyses. For commercialization considerations, Electricity Consumers impart little influence for the adoption of a new technology, and thus are removed from this commercialization analysis. Therefore, only Project Developers and System Operators will be considered in addition to the highest ranked stakeholders in the matrices. It is assumed that the value contribution to these focal organization stakeholders remains relatively high and unchanging across the four different scenarios.

From this stakeholder analysis, it can be determined that the stakeholders that receive the most value, and are thus important for commercialization considerations, are common for both GSS and OSMS but PdM has a much narrower list. For GSS and OSMS, the key stakeholders are the LSE, Wind Plant O/O, Supp/OEM and Fed Gov/Reg in addition to the Project Developer and System Operator. For PdM, the key stakeholders are the Wind Plant O/O, Supp/OEM and the Project Developer.

Concentrated value contributions to market biased participants allows for easier technology adoption compared to more dispersed value contributions that include non-market biased participants. In this analysis, the value contributions for GSS and OSMS are spread mostly amongst market-biased participants with the exception of Fed Gov/Reg and the System Operator. GSS has a very concentrated value contribution to LSE, which will be an important consideration for the commercialization of this technology. OSMS and GSS contribute a relatively similar amount of value across the Wind Plant O/O, Supp/OEM and Fed Gov/Reg. PdM has a near equal value contribution to the Wind Plant O/O and the Supp/OEM.

Understanding how the future scenarios might move the value contributions is important in considering the stakeholder value propositions. Often stakeholders see technology adoption as a hedging strategy for future change. For GSS and OSMS, it can be seen that the Wind Plant O/O and Supp/OEM see a large
future upside in value contribution in the Sunset and HNG scenarios, and additionally, Fed Gov/Reg sees some upside in the Carb scenario. However, for GSS, the LSE sees mostly future downside from HNG and Sunset scenarios, while for OSMS, it has some upside for the Carb scenario. For PdM, the Wind Plant O/O and Supp/OEM see mostly future upside, with the Wind Plant O/O seeing more upside than Supp/OEM.

Stakeholder Business Models

To understand how the value contributions will be interpreted by the stakeholders it is first necessary to review their business models. This will then help to inform what the value propositions are for each technology to each stakeholder.

The Project Developer is closely aligned with the interests of the Wind Plant O/O that will be the eventual beneficiary of a wind plant. Project Developers have multiple business models, and in this analysis it is assumed that the Project Developer is developing the majority of the project and then selling their equity stake to a Wind Plant O/O.

The Wind Plant O/O, as described in Part 1, is an IPP that collects revenue from the bundled sale of RECs and energy under a long-term PPA with a LSE. The energy is priced per kWh at the levelized cost of energy plus a margin representing the return on investment. This model is applicable in the Baseline and Carbon scenario. However, under the Sunset and HNG scenario, a wholesale market business model is assumed where the IPP bids only energy into the market and receives the clearing LMPs.

The Supp/OEM are business-to-business vendors of equipment and services to Project Developers and Wind Plant O/O. They sell high value products with longer lead times and often under long-term supply or service agreements. For example, a turbine supply agreement with a Project Developer might be for multiple years’ worth of turbine equipment to equip multiple projects.

LSEs in a deregulated market can own generation assets or purchase electricity from other generators through a wholesale electricity market or through bilateral energy contracts (such as PPAs). In this analysis, it is assumed that LSEs source most of their electricity needs from the wholesale market and benefit from lower system average costs of electricity. LSEs are the market agents that sell and maintain electricity services to both wholesale and retail consumers. LSEs may also own the transmission and distribution assets used to transmit electricity to the consumers and would receive revenue from these asset investments as well.

The Fed Gov/Reg and System Operator are both non-market biased stakeholders. System Operators are independent, non-profit organizations that follow Federal mandates to operate the electric power system and markets. The Federal Gov/Reg serves the benefit of the tax-paying population and represents the best interests of Electricity Consumers.

Value Proposition to Stakeholders

Given the business models of and value contributions to the selected stakeholders, distinct value propositions for each technology can be defined. Table 4 lists examples of value propositions to each of the key stakeholders for GSS, OSMS and PdM.
<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>GSS Value Propositions</th>
<th>OSMS Value Propositions</th>
<th>PdM Value Propositions</th>
</tr>
</thead>
</table>
| Project Developer | • Increase the project’s net energy by mitigating curtailment loss  
• In the case of market participation, increase the coincidence of supply and demand. | • Increase the project’s capacity factor  
• Expand development area by enabling lower wind speed sites  
• Increase penetration into higher value markets where low wind speed sites are close to load centers. | • Reduce project’s lifetime O&M costs, thus lowering expected LCOE  
• Increase competitiveness for PPAs |
| Wind Plant O/O | • Increase the project’s net energy by mitigating curtailment loss  
• In the case of market participation, increase the coincidence of supply and demand. | • Increase the project’s capacity factor  
• Enable new markets for larger turbine equipment.  
• Improve performance of existing products. | • Reduce generator downtime  
• Reduce post-warranty O&M costs |
| Supp/OEM | • Improve the competitiveness of wind energy in wholesale markets thus expanding the total market for wind plant equipment.  
• Improve performance of existing products. | • Enable new markets for larger turbine equipment.  
• Improve performance of existing products. | • Preempt in-warranty service to reduce warranty claims and service costs  
• Improve product reliability and thus increase equipment sales |
| LSE | • Reduce wind plants’ effect on LSE assets – lower maintenance costs from cycling  
• Reduce cost of electricity sourced from the wholesale market  
• Increase RPS or carbon emission compliance | • Lower cost of PPA contracts  
• Increase RPS or carbon emission compliance | • N/A |
| System Operator | • Increase “dispatchability” of wind plants for greater control  
• Reduce reserve requirements | • Increase regional dispersion of wind plants for lower system uncertainty  
• Reduce reserve requirements | • N/A |
| Fed Gov/Reg | • Lower the system average cost of electricity  
• Improve carbon emission compliance and energy security | • Lower the system average cost of electricity  
• Improve carbon emission compliance and energy security | • N/A |

*Table 4 – GSS, OSMS and PdM Value Propositions*
Further analytical work for each GSS, OSMS and PdM technology should be performed to quantify these value propositions using metrics that correspond to the stakeholder business models so that they can easily be interpreted in the stakeholder organizations’ analysis of the technology. For example, under the Baseline scenario, the internal rate of return (IRR) on a wind project is an important decision criteria for Project Developers. Knowing how the value contribution will effect IRR is thus an example of a quantified value proposition.

B. Supply Chain Integration

Grid-Scale Storage Supply Chain
GSS is a nascent market with no established business models, supply chain or industry standards. A small number of manufacturers and system integrators exist, but largely focus on behind-the-meter and distributed applications (Wesof, The Energy Collective). While several grid-scale pilot projects are in operation, they are only just starting to produce reports that would serve as the basis for best practices and standards for installation and operation. With state-level mandates set by Local Regulators, California is driving this market into the early phases of commercialization (Wesof, Greentech Media). Several California LSE’s have issued requests for quotes for quotes for large amounts battery storage. However, LSEs have not had to assign value to energy storage systems before and are just starting to understand how to interpret the technology and value propositions. This means that the new GSS vendors will need to expend significant effort to educate the market and build the supply chain.

On-Site Manufacturing System Supply Chain
In contrast, the equipment produced by OSMS have a very established supply chain, industry standards and business models. The equipment and service supply is concentrated to a small number of wind turbine OEMs in which the top three firm control 70% of the US market (US DOE). These OEMs sell complete wind turbine generator systems that include the tower, blades, drive-train, and nacelle components. Some of these components are manufactured through contract by outside manufacturing firms, while many of them are produced internally. Towers are one component that tend to be largely outsourced by the OEM, while blades are largely built internally. Regardless, the turbines are sold as complete systems to the end users and are not purchased piece-meal from the various manufacturing sources. More importantly, the turbine OEMs dictate the design and manufacturing specifications of the components used in their turbine systems for which any outside manufacturing firm must comply to. Due to the supplier power in the supply chain, and the importance of equipment warranty, Project Developers generally abide to this turbine sales process and source the complete turbine systems for a project from a single OEM.

The turbine OEMs often participate in the coordination of the turbine delivery to the project site, with the addition of the EPC coordinating the logistics on the receiving end. Once on site, the EPC performs the necessary constructions and installations tasks for commissioning the turbine system.

For OSMS, it is critical that the technology and business format allow for a tight integration into the sales, delivery and installation portion of the existing supply chain between the turbine Supp/OEM, the EPC and the Project Developer.

Predictive Maintenance Supply Chain
PdM will experience the same mature supply chain as OSMS in regards to a concentrated market of turbine OEMs. This may help limit the number of platforms that the PdM product will need to operate
with. However, the Supp/OEM power is strong and there might be resistance to allowing a third-party integration into the OEMs proprietary data and monitoring interfaces – depending upon the extent of the technical integration required.

PdM has two potential markets; new construction turbines and existing assets. The former may prove difficult as new turbine equipment generally comes with a standard service and warranty contract between the Wind Plant O/O and the Supp/OEM. Following the standard contract, additional extended warranty contracts are often available. During the contract period, the Supp/OEM is generally responsible for in-warranty turbine service and repairs, and additional hedging against O&M costs may not provide additional value to the Wind Plant O/O. Also, depending upon the extent of the technical integration required, third-party modifications or additions to the OEM equipment may invalidate the service and warranty contract and thus draw resistance from each party. However, the Supp/OEM may reduce their in-warranty service overhead and variable costs if they implement the technology in their turbine platform.

Existing turbine assets might be an easier target if the assets are out-of-warranty and the Wind Plant O/O is not hedged against large potential O&M expenses. Approximately half of all wind turbine installations are now out of warranty with the Wind Plant O/O responsible for the O&M expenses (North American Windpower).

C. Technical Integration

Grid-Scale Storage Technical Integration
One of the difficulties with GSS integration is that the GSS system will need to be customized to different voltage levels utilized at plant substations as well as different levels of power capacity depending on the size of the wind plant. This customization means that modularization of the technology and efficient installation processes will be necessary to keep integration costs to a minimum.

In addition, some level of sophisticated control may be necessary to fully achieve the benefits of GSS. The GSS system should have an intelligent control system to optimize the storage and discharge cycles within the constraints of the expected transmission network conditions, market pricing, and plant generation. Also, the GSS system will need to interface with the System Operator dispatch for participation in the real-time energy and ancillary markets.

The additional technical integration and installation work for GSS may be burdensome on Project Developers that are inexperienced with the development tasks for this new technology and may already be at resource capacity for developing the rest of the wind plant. Alternatives to giving Project Developers the responsibility to develop GSS at the plant should be considered to ease adoption of the technology.

On-Site Manufacturing System Technical Integration
The primary technical challenge for integrating OSMS are the large scale operations that must be setup, operated and supplied at each project site. Many wind plant locations are in difficult to access areas with poor infrastructure that can be quite distant from many of the amenities typically co-located with manufacturing facilities (e.g. railroad track). OSMS will consume a large overhead cost to ship in equipment and prepare the site. OSMS will also require well-coordinated and reliable supply lines for production materials. Electric power, heat, and temperature controlled facilities will be required for
certain OSMS processes, which means that generators and fuel must be brought into the site, or, the substation interconnection must be established in advance.

This scale of operations requires superb logistics coordination skills and tight integration of OSMS with Project Developers and EPCs development and construction schedules. Additionally, OSMS technology has high capital costs and it is unlikely that a firm will operate a multitude of these systems. Therefore, a single OSMS facility must be shared across multiple projects, which adds to the scheduling challenges. Similar to GSS, these additional development tasks may prove too burdensome for Project Developers to adopt OSMS if not addressed properly in the business format.

**Predictive Maintenance Technical Integration**

PdM technology is likely to be embedded in a software system that integrates at the Wind Plant O/O-controlled SCADA system. The integration challenge depends on the location and ownership of the plant data input and SCADA interface. The challenge is mostly in regards to interfacing with proprietary systems and the service and warranty contract implications of adding to or modifying these systems.

In the simpler case, the SCADA data feed is from pre-established condition monitoring systems and sensors at the plant and the SCADA interface is open to the Wind Plant O/O. The PdM software would access the SCADA’s historical archive and live data feed for event-based and time-series data and apply predictive intelligence algorithms to determine when a likely service or failure event should be expected.

In the more complex case, either the condition monitoring systems and sensors are not established, or, the SCADA interface is proprietary and not open to PdM software. In either case, challenges exist to gain the proper knowledge and agreements from these technologies’ proprietors – often the turbine OEMs. Connecting sensors and monitoring systems at the wind plant without the knowledge of the engineering specifications for the equipment is challenging and risky. Similarly, integrating software to a proprietary SCADA interface is also challenging without the knowledge of what encryption, reporting standards or data formats are being used. In any case, such integration may invalidate service and warranty contracts because of the potential for modifying the systems in an unintended manner.
D. Summary of Commercialization Analysis

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<td>• Mature, concentrated supply chain with concern regarding service and warranty terms</td>
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<td><strong>Technical Integration</strong></td>
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<td>• Customization of system integration required</td>
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<td>• Additional technology for GSS control system required</td>
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<td>• Open interface installations might be easier first target market</td>
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Table 5 - Summary of Commercialization Analysis

E. Commercialization Strategy

Grid-Scale Storage Strategy
Given the nascent market and supply chain, GSS technology firms should consider forming or partnering with a system integration/operation firm to drive the commercialization efforts, while the GSS firm focuses resources on building out the supply chain and modularizing the systems. The GSS system integrator/operator should lead the education of the LSE market and standard setting for GSS systems integration to substations. Early adoption and education of LSEs will be critical for GSS system
integration into substation equipment. LSEs typically are not early adopters of new technology, so business formats should be tailored to minimize the impact on LSEs business-as-usual scenario. With the LSEs in favor of GSS, future lobbying of System Operators could increase demand for GSS systems to be located at wind plants as a requirement for interconnection.

The GSS system integrator/operator can also be technology “agnostic” in the early phase of commercialization and source supplementary technology required for the GSS control system and System Operator dispatch. This is likely necessary as the complete supply chain is not established or controlled by a single entity. One potential business model is for the GSS firm to lease systems to the GSS system integrator/operator who would install and operate the system on the market by purchasing electricity from wind plants at low prices and selling at higher prices during peak demand – known as electricity arbitrage. Profit gained in the markets can be used to pay-off the equipment lease. Whereas, the GSS firm can collect steady lease revenue while producing a larger volume of GSS systems to bring down manufacturing costs. Additionally, these GSS system integrator/operators can provide ancillary services on the market, such as regulation and capacity, to the benefit of Wind Plant O/Os and LSEs.

On-Site Manufacturing System Strategy
OSMS technology firms should identify Project Developers with the most project portfolio exposure to PTC/RPS expiration and low-wind speed areas and form strategic partnerships with the EPC firms that these Project Developers contract for project execution. In the value analysis, the EPC saw no value contribution from OSMS, so partnership may require larger revenue contracts or equity/profit sharing to incentivize participation in an entrepreneurial venture. The EPC should be contracted to coordinate the project logistics, to prepare the site in advance for OSMS, and manage the supply lines and operations for the OSMS firm. OSMS firms should assume a contract-manufacturing business model, similar to the existing models in the turbine supply chain. The OSMS firm should maintain the production and quality responsibilities for the manufactured equipment, similar to other contract manufacturers, and interface with the EPC for installation of that equipment.

The OSMS technology firms should engage in business development efforts to bring both turbine Supp/OEMs and Project Developers together (similar to a two-sided market), to validate the economics of OSMS and identify target projects to schedule manufacturing. In addition, the OSMS firm should develop the relationships with turbine Supp/OEMs to bid into supply contracts and gain penetration and visibility into their sales pipeline to ease future capacity planning and logistics.

Predictive Maintenance
The commercial strategy for the PdM technology firm should consider the network and learning effects of the expanded deployment of the PdM technology. As more PdM systems are installed, the learning algorithms are exposed to larger sets of data with more operating environments and across different turbine technology platforms. This operational experience allows algorithms to be refined and improved for better predictive performance. Additionally, as more PdM systems are installed, more knowledge is gained regarding the integration to different, and sometimes proprietary, SCADA systems and data feeds from plant sensors and condition monitoring systems. This knowledge reduces the sales cycle for subsequent projects and improves the integration time and performance which may be a competitive advantage.
The target market for early adoption is likely to be the Wind Plant O/Os with out-of-warranty turbines that have less complex interfaces for integration. However, this will be an attractive market for other PdM firms as well. To gain larger share in this target market, a competitive, and perhaps even loss-leading, strategy should be used to ensure gains from the network effects described above.

Moving beyond the target market, the PdM firm may consider technology licensing agreements with the turbine OEMs who stand to benefit from having better intelligence about their in-warranty operating fleet – as these are service liabilities. Technology improvements and integration experience gained in the target market can be very valuable in managing the strong market power that the turbine OEMs have. For example, if the PdM firm was able to capture a significant share of the out-of-warranty market from Wind Plant O/Os, they will be in a better market position to negotiate licensing agreements with the turbine OEMs. Ideally, the license is not exclusive, and business can be sought from multiple turbine OEMs for an expanded market.
Conclusion

The conceptual framework proposed in this thesis is intended for measuring value contribution from multiple technologies to multiple stakeholders across multiple attributes. This type of analysis is well suited for exploring technology adoption in the complex electric power industry.

Of the six wind energy technical innovations analyzed in the value creation – value capture framework, Grid-Scale Storage, On-Site Manufacturing Systems and Predictive Maintenance promise to contribute the greatest value to industry stakeholders and thus are the most likely to improve the competitiveness of the wind industry. Distinct commercialization strategies were formed for each of these three technologies based upon the characteristics of the value contribution to stakeholders in addition to considering the current status of the technology supply chain and integration requirements. While Grid-Scale Storage and On-Site Manufacturing Systems have similar stakeholder sets, the immature supply chain of Grid-Scale Storage and higher technical complexity of system integration suggest a much different commercialization strategy than that for On-Site Manufacturing Systems which have a mature supply chain and higher logistical complexity. Predictive Maintenance has a more focused stakeholder set and the commercialization strategy is directed towards overcoming technical integration challenges and managing OEM market power.

In exploring this framework, it was apparent that a combined application of the multi-attribute utility method with the weighted stakeholder occurrence method, based on stakeholder value networks, was the most effective in distinguishing which technologies contributed the most value and to whom. However, a value estimation method that can better discern both magnitude and direction of technology value creation is still necessary for a more complete analysis. Trade plots were an effective tool for visualizing where technologies contributed value to the wind plant versus the electric power system across multiple possible future scenarios. Utilizing the “value frontier” of these plots allowed for a simple method to select optimal technologies.
References


Dies, Rob. Supervisor Technical Division at Iberdrola Renewables Chris Babcock. 13 June 2014.


Appendix A – Matrix Results

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System Capability

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System Stakeholder

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- IE
- Investors
- Land Owner
- Loc Comm
- Loc Gov/Reg
- NGO
- Supp/OEM
- Consumer
- Wind Plant C/O

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Figure 70 - Pugh Method Results under the Baseline Scenario with System Operator SVN
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**Figure 71 - Pugh & WSO Method Results under the Baseline Scenario with System Operator SVN**
### Figure 72 - MAU & WSO Method Results under the Baseline Scenario with System Operator SVN

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Figure 73 - Pugh Method Results under the Sunset Scenario with Electricity Consumer SVN
Figure 74 - Pugh Method Results under the Sunset Scenario with System Operator SVN
Figure 75 - Pugh & WSO Method Results under the Sunset Scenario with Electricity Consumer SVN
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Figure 76 - Pugh & WSO Method Results under the Sunset Scenario with System Operator SVN
Figure 77 - MAU & WSO Method Results under the Sunset Scenario with Electricity Consumer SVN
<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>PFC</th>
<th>Fed Gov/Reg</th>
<th>EPC</th>
<th>Loc Gov/Reg</th>
<th>LSE</th>
<th>MSE</th>
<th>Sup/OSM</th>
<th>System Operator</th>
<th>Wind Plant O/O</th>
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<td>0.22</td>
<td>0.01</td>
<td>0.09</td>
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Figure 7B - MAU & WSO Method Results under the Sunset Scenario with System Operator SVN
Figure 79 - Pugh Method Results under the HNG Scenario with Electricity Consumer SVN
Figure 80 - Pugh Method Results under the HNG Scenario with System Operator SVN
- Figure B1 - Pugh & WSO Method Results under the HNG Scenario with Electricity Consumer SVN
<table>
<thead>
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<th>Grid-Scale Storage</th>
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<th>Transmission PCC</th>
<th>NT Forecasting</th>
<th>LT Forecasting</th>
<th>Predictive Maintenance</th>
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**System Capability**

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<th>Technology &amp; Stakeholder X-Matrix</th>
<th>Value to Plant</th>
<th>Value to System</th>
</tr>
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<td>Value to Plant</td>
<td>Value to System</td>
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</tbody>
</table>

**System Stakeholder**

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<tr>
<th>Stakeholder</th>
<th>EPC</th>
<th>Fed Gov/Reg</th>
<th>Land Owner</th>
<th>Loc Gov/Reg</th>
<th>LSE</th>
<th>NGO</th>
<th>Supp/OEM</th>
<th>Plant</th>
</tr>
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<tr>
<td>Value</td>
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<td>0.02</td>
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**Figure 82 - Pugh & WSO Method Results under the HNG Scenario with System Operator SVN**
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**System Capability**

<table>
<thead>
<tr>
<th>Increase Energy Generation</th>
<th>Reduce O&amp;M Expenses</th>
<th>Reduce Maintenance Down Time</th>
<th>Reduce Outage Loss &amp; Down Time</th>
<th>Reduce Development &amp; Construction Costs</th>
<th>Increase Penetration in High Value Market</th>
<th>Increase Cost</th>
<th>Increase Plant Capacity</th>
<th>Value to Plant</th>
</tr>
</thead>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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**System Stakeholders**

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<th></th>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
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<td>0.05</td>
<td>0.05</td>
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<td></td>
</tr>
</tbody>
</table>

| Grid Scale Storage | 0.01 | 0.08 | 0.66 | 0.10 | 0.74 | 1.59 | 0.28 | 0.68 | 0.08 | 0.09 | 0.42 | 2.23 |
| On-Site Mfg Systems | 0.03 | 0.09 | 0.57 | 0.03 | 0.64 | 1.33 | 0.36 | 0.00 | 0.01 | 0.06 | 0.30 | 0.09 |
| Transmission PFC | 0.00 | 0.07 | 0.24 | 0.27 | 0.58 | 0.16 | 0.16 | 0.00 | 0.01 | 0.19 | 0.12 | 0.02 |
| NT Forecasting | 0.00 | 0.01 | 0.14 | 0.15 | 0.30 | 0.08 | 0.19 | 0.30 | 0.02 | 0.16 | 0.79 |
| LT Forecasting | 0.03 | 0.00 | 0.16 | 0.05 | 0.18 | 0.36 | 0.00 | 0.00 | 0.03 | 1.73 | 1.69 | 0.22 |
| Predictive Maintenance | 0.01 | 0.02 | 0.33 | 2.23 | 0.15 | 2.48 | 0.87 | 0.00 | 0.03 | 1.73 | 1.69 | 0.22 |

Figure 83 - MAU & WSO Method Results under the HNG Scenario with Electricity Consumer SVN
Figure 84 - MAU & WSO Method Results under the HNG Scenario with System Operator SVN
Figure 85 - Pugh Method Results under the Carb Scenario with Electricity Consumer SVN

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Value to System</th>
<th>Reduce Regulation Reserve</th>
<th>Reduce Contingency Reserve</th>
<th>Reduce Need for Transmission</th>
<th>Increase Carbon Off-set</th>
<th>Increase Total System Capacity</th>
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<td>2</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<td>IE</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Loc Gov/Reg</td>
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<td>1</td>
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<tr>
<td>NGO</td>
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<td>1</td>
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<td>1</td>
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<td>System Owner</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<td>Wind Plant O&amp;O</td>
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<td>1</td>
<td>1</td>
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Table showing the Pugh Method Results under the Carb Scenario with Electricity Consumer SVN.
Figure 86 - Pugh Method Results under the Carb Scenario with System Operator SVN
<table>
<thead>
<tr>
<th>System Capability</th>
<th>Increase Energy Generation</th>
<th>Reduce O&amp;M Expenses</th>
<th>Reduce Maintenance Downtime</th>
<th>Reduce Outage Loss &amp; Construction Costs</th>
<th>Value to Plant</th>
<th>Value to System</th>
<th>Reduce Regulation Reserves</th>
<th>Reduce Contingency Reserves</th>
<th>Reduce Need for Transmission</th>
<th>Increase Carbon Offset of Base Load</th>
<th>Increase Total System Capacity</th>
</tr>
</thead>
<tbody>
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<td>IE</td>
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</table>

Figure 87 - Pugh & WSO Method Results under the Carb Scenario with Electricity Consumer SVN
<table>
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<tr>
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Figure 88 - Pugh & WSO Method Results under the Carb Scenario with System Operator SVN
### System Capability

<table>
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<tr>
<th>Increase Energy Generation</th>
<th>Reduce O&amp;M Expenses</th>
<th>Reduce Maintenance Downtime</th>
<th>Reduce Curtailment Loss</th>
<th>Reduce Development &amp; Construction Costs</th>
<th>Value to Plant</th>
<th>Technology &amp; Stakeholder X-Matrix</th>
<th>Value to System</th>
<th>Reduce Regulation Reserves</th>
<th>Reduce Contingency Reserves</th>
<th>Reduce Need for Transmission Capacity</th>
<th>Increase Carbon Offset of Baseload</th>
<th>Increase Total System Capacity</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

**System Stakeholder**

<table>
<thead>
<tr>
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<th>Value to System</th>
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<th>Value to System</th>
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</thead>
<tbody>
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<td>EPC</td>
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<td>0.30</td>
<td>NGO</td>
<td>0.09</td>
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<tr>
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<td>Supp/OEM</td>
<td>0.10</td>
<td>Wind Plant O/O</td>
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</table>

**Grid Scale Storage**

<table>
<thead>
<tr>
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<th>On-Site Mfg Systems</th>
<th>Transmission PFC</th>
<th>NT Forecasting</th>
<th>LT Forecasting</th>
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*Figure 89 - MAU & WSO Method Results under the Carb Scenario with Electricity Consumer SVN*
Figure 90 - MAU & WSO Method Results under the Carb Scenario with System Operator SVN
Appendix B – Trade Plots

Figure 91 - Trade Plot for Pugh & WSO Method for Baseline Scenario – Negative GSS Score Not Shown

Figure 92 - Trade Plot for Pugh & WSO Method for Sunset Scenario
Figure 93 - Trade Plot for Pugh & WSO Method for HNG Scenario

Figure 94 - Trade Plot for Pugh & WSO Method for Carb Scenario – Negative GSS Score Not Shown
Figure 95 - Trade Plot for MAU & WSO Method for Baseline Scenario

Figure 96 - Trade Plot for MAU & WSO Method for Sunset Scenario
Figure 97 - Trade Plot for MAU & WSO Method for HNG Scenario

Figure 98 - Trade Plot for MAU & WSO Method for Carb Scenario