Varieties of Innovation:
The Creation of Wind and Solar Industries in China, Germany, and the United States

by

Jonas M. Nahm

B.A. Social and Political Sciences
University of Cambridge, 2004

M.A. Political Science and Asia-Pacific Studies
University of Toronto, 2006

Submitted to the Department of Political Science in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
at the
Massachusetts Institute of Technology

September 2014

Signature redacted

Signature of Author: ....
Department of Political Science
June 24, 2014

Signature redacted

Certified by: ....
Edward S. Steinfeld
Professor of Political Science
Thesis Supervisor

Signature redacted

Accepted by: ....
Andrea Louise Campbell
Professor of Political Science
Chair, Graduate Program Committee

Varieties of Innovation:
The Creation of Wind and Solar Industries in China, Germany, and the United States

by
Jonas M. Nahm

Submitted to the Department of Political Science in partial fulfillment of the requirements for the degree of Doctor of Philosophy, September 2014.

ABSTRACT

Where and how does innovation take place in contemporary high-technology sectors? Theories of innovation presume a division of labor between firms in industrialized economies that invent and commercialize new technologies and those in developing economies that focus on production. Even as global supply chains have allowed firms to outsource and offshore manufacturing activities, such literatures assume that innovation itself still takes place within firms in advanced economies.

This study develops a framework to understand innovation in high-technology industries through a comparative analysis of wind and solar sectors in China, Germany, and the United States. I find that the rise of global production networks has altered the ways in which the range of engineering capabilities required for technological innovation are combined and established in high-technology sectors. First, in contrast to prevailing theories of innovation, I show that the fragmentation of production has distributed innovative capabilities across highly specialized firms in global supply chains, including manufacturing firms in developing economies. Skills that were once organized within large firms are now coordinated in global networks in a process I call *networked innovation*. Second, new options for specialization have mitigated pressures for convergence in the types of skills required to advanced to the technological frontier. As a result, firms are able to incrementally build on existing strengths and industrial capabilities as they participate in networked innovation through specialized capabilities, often repurposing governmental resources and institutions established for prevailing industrial sectors in the process. In this context, sectoral industrial policies for emerging industries no longer fully determine variation in firm specialization, but divergent industrial legacies, firm practices, and governmental resources provided for the broader economy shape how firms participate in networked innovation.

The findings build on more than two years of field research, including 224 interviews in wind and solar sectors and extensive analysis of archival documents and government yearbooks. In addition to contributing to literatures on the political economy of innovation, this study speaks to broader debates about the nature of economic development, industrial upgrading, and the role of sectoral industrial policy in shaping industrial capabilities under conditions of globalization.

Thesis Supervisor: Edward S. Steinfeld
Title: Professor of Political Science

Contents

Acknowledgements

The research for this dissertation was conducted over the course of ten field visits to China and Germany and many shorter research trips in the United States. I am grateful to the German National Academic Foundation, the MIT Energy Innovation Project, the MIT Project on Production in the Innovation Economy, and the Minerva Research Initiative for supporting this research. Additional assistance was provided by a Caroll Wilson Award, the MIT Energy Initiative, the MIT Center for International Studies, the Harvard Center for European Studies, and the Horowitz Foundation for Social Policy Research.

At MIT, I was lucky to have three dissertation committee members who patiently guided me through the process. Although Edward Steinfeld, Suzanne Berger, and Richard Lester contributed to this research in different ways, they shared the vision that a PhD program, at the very core, should be an apprenticeship. I am grateful to have been their apprentice. Working with Richard Lester on the Energy Innovation Project at the Industrial Performance Center, I was first introduced to conducting research as part of large, interdisciplinary research teams that included social scientists as well as engineers. The ability to communicate across disciplinary lines has been central to much of this project. Suzanne Berger, at MIT and on field trips to Germany and across the United States, taught me the art of interviewing, identified traces of an argument in the data I collected, and showed me how to distinguish the stem from the branches of this study. I am especially indebted to Edward Steinfeld, who believed in this project from the very beginning and cheered me on in all the right moments. In weekly conversations, on trips to China, and in the process of co-authoring papers and book chapters, Ed encouraged me not to shy away from controversial questions, but to tackle them with enthusiasm, nuanced arguments, and rich empirical detail.

For solving all the logistical, administrative, and emotional challenges of writing this dissertation, I relied on a team of exceptional administrators at MIT. Janine Claysmith, Pamela Clements, Maria Di Mauro, Diana Gallagher, Paula Kreutzer, Helen Ray, Kate Searle, and Susan Twarog were the best reason to work from the office. A special thank you goes to Anita Kafka, who saved me more than once, and who also does not eat lunch at her desk.

Many friends and colleagues attended talks, read chapter drafts, and contributed ideas and feedback to this study. I am indebted to Laura Chirot, Greg Distelhorst, Erica Dobbs, Kristin Fabbe, Gabi Kruks-Wisner, Joyce Lawrence, Akshay Mangla, Florian Metzler, Timea Pal, Miranda Priebe, Hiram Samel, Gustavo Setrini, Kyoung Shin, and Rachel Wellhausen for their engagement with this project. Nathan Cisneros and Alanna Krolikowski helped me work out key parts of the argument. Meg Rithmire was there from the beginning, showing me that it can be done and sharing the lessons learned in doing so.

My field research relied on the generosity of many, who shared their networks, spare bedrooms, and insights on renewable energy industries. In China, Li Shuai and Wang Lei opened doors I didn't know existed. Without Li Shuai's ability to charm executive assistants, many interviews would not have happened. Victor Bekink has taught me much of what I know about the solar industry and provided access in China and Germany alike.

Writing the dissertation has impacted no one more than Jason, who truly lived with this project for the last four years. His patience, love, and support through the ups and downs of the process, including many months of field work, have meant the world to me.

Chapter 1: Introduction and Theory

1. Introduction

In 2009, a small German engineering firm with decades of experience in the wind energy sector entered an agreement with an emerging Chinese wind turbine manufacturer for the development and production of a novel type of wind turbine that was smaller, lighter, and more efficient than any turbine currently on the market. According to the German managers involved in the negotiation, the Chinese firm prevailed against a number of potential global partners because it offered a set of engineering capabilities required to configure the turbine design for large-scale manufacturing. While the German engineers contributed an innovative design concept, it were the capabilities residing in the Chinese manufacturer that allowed the team to overcome the challenges involved in manufacturing a product that relied on novel components used in no other wind turbine in the world. The wind turbine that resulted from the two-year collaboration retained core features of the original design, yet the internal layout of the wind turbine had been fundamentally altered during a process of re-engineering managed by the Chinese firm.[1]

In the same year, a Silicon Valley startup, Innovalight, entered a joint development agreement with a Chinese solar photovoltaic (PV) manufacturer, JA Solar, to commercialize a new component for the production of high-efficiency solar cells. Founded in 2002, Innovalight had developed a nanomaterial with potential applications in products ranging from integrated circuits to LCD displays. Together with the U.S. National Renewable Energy

[1] Author interviews: CTO of Chinese wind turbine manufacturer, August 28, 2011; CEO of German engineering firm, May 20, 2011; head of China operations, Germany engineering firm, January 13, 2011.

Laboratory (NREL), the firm developed an understanding of how the nanomaterial, a silicon ink, might increase the efficiency of solar cells, but neither Innovalight nor NREL had the know-how required to apply the component to high-volume solar PV production. Ultimately, it were the engineering capabilities of the Chinese solar PV manufacturer JA Solar that allowed the two firms to jointly integrate the component into the production of high-efficiency solar cells. The collaborative research and development activities between U.S. and Chinese engineers took place in JA Solar's test facilities in China, using production equipment supplied by small- and medium-sized firms from Germany's machine tools sector.[2]

These two vignettes about product development in emerging, high-technology industries bear little resemblance to conventional ideas about innovation, which generally describe it as the domain of large firms in advanced economies. Why do the German and American firms above rely on engineering capabilities of Chinese manufacturing firms as they move new technologies from lab to market—firms that are known for their mass production capabilities, not commercialization of cutting-edge technologies? Where in the globalized network of Chinese, German, and American firms is innovation taking place? What exactly are the innovative capabilities that firms in each location contribute, and how do such capabilities emerge?

This dissertation examines technological innovation in global, high-technology industries through a comparative study of wind and solar sectors in China, Germany, and

---

[2] Ucilia Wang. 2011. "DuPont buys solar ink maker Innovalight." Available from http://www.reuters.com/article/2011/07/25/idUS165538390720110725. (Accessed March 11, 2012). JA Solar. 2010. JA Solar Signs Strategic Agreements with Innovalight for Joint Development of High Efficiency Solar Cells. Available from http://investors.jasolar.com/phoenix.zhtml?c=208005&p=irol-newsArticle&ID=1446259&highlight= (Accessed March 11, 2012). See also Nahm and Steinfeld 2014, 297-98.

the United States. Most theories of innovation—broadly defined as the process by which firms develop, master, and commercialize new product designs, services, and production processes—make two broad assumptions about technology development in global industries.[3] First, they generally take for granted a division of labor between firms in industrialized economies that invent and commercialize new technologies and those in developing economies that absorb technologies from abroad and focus on manufacture.[4] Globalization may offer new possibilities to geographically separate innovation and production, but, according to literatures on global supply chains, new options for the organization of production have reinforced, not weakened, this global division of labor.[5] Second, literatures on innovation and industrial development presume that at least innovation itself still largely takes place within the four walls of one firm, even as the emergence of global production networks has been accompanied by a decline of the vertically integrated enterprise. Institutional differences, divergent industrial policies, and distinct national networks of universities and research institutes may lead to variation in the types of innovation that thrive in different economies. Nevertheless, standard theories of innovation imply that most processes of technology development are vertically integrated in the firm, whether the development process is incremental or radical in nature, and whether manufacturing occurs in house or outsourced to low-cost production locations.[6]

---

[3] Definition of innovation based on Nelson 1993, 4; Schumpeter 1934.

[4] For literatures on technological innovation that see innovation as primarily occurring in advanced economies, see, among others, Hall and Soskice 2001; Nelson 1993; Vernon 1966.

[5] Steinfeld 2004; Sturgeon 2002a.

[6] Gereffi et al. 2005; Hall and Soskice 2001; Sturgeon 2002a.

A closer look at wind and solar industries in China, Germany, and the United States, however, reveals an altogether different pattern of innovation in contemporary global supply chains. As the two examples at the beginning of this chapter illustrate, wind and solar firms now rarely manage the entire process of innovation in house, instead specializing in distinct steps of the innovation process. Firms in the United States have mastered the invention of new technologies, but have generally not established capabilities that would allow them to commercialize and scale the production of their designs. In Germany, the most successful wind and solar firms have competed in global supply chains with skills in customization and small-batch production of componentry and complex production equipment, but have not matched U.S. strengths in invention. In China, which conventional theories have disregarded as a potential locale for innovation on the basis of its developmental status, wind and solar firms have built innovative capabilities in adjusting, improving, and re-engineering novel product designs and componentry for commercialization and scale-up to mass production.

Literatures on innovation offer few tools to explain these cross-national patterns of specialization among innovative firms. The diversity of firm specializations in different steps of the innovation process is even more surprising if we consider industrial policies for renewable energy sectors, which are broadly similar in China, Germany, and the United States. In all three economies, governments have combined support for renewable energy markets with public funding for research and development activities in the hope of creating domestic wind and solar sectors. Yet not only have firms pursued different paths of specialization in spite of similar policy environments, but have done so in ways that break with conventional expectations about patterns of innovation and the division of labor in global industries: the empirical record suggests that just as production is in many sectors distributed across global supply chains, innovation now similarly spans the organizational boundaries of the firm. This is the case whether such innovation entails incremental improvements of existing products, which conventional theories have described as particularly suited to firms in Germany, or radical departures from established practices, which existing literatures have seen as more likely to happen in the United States.[7] This is also the case in China, which conventional theories would expect to be a recipient of technology transfers, rather than a contributor to collaborative processes of technology development.[8] What firms in China, Germany, and the United States have in common, however, is their specialization in distinct steps of the innovation process that allow neither of these firms to bring new products to market without accessing external engineering capabilities. Given these patterns of specialization, *where and how does innovation take place in emerging, high-technology industries?*

This study develops a framework to understand innovation in high-technology industries through a comparative analysis of wind and solar sectors in China, Germany, and the United States. The explanation offered in this dissertation starts from the premise that innovation is not confined to invention, but that the ability to innovate through invention and improvement of product designs and production processes is required along the entire trajectory from lab to market, including in commercialization and scale-up to mass production. My research suggests that changes in the organization of production, in particular the emergence of global production networks, have altered the ways in which

[7] The distinction between advanced industrialized economies prone to incremental innovation and those more suitable for radical innovation is made in literatures on the Varieties of Capitalism. See Hall and Soskice 2001. For a critique of the empirical validity of this distinction, see Taylor 2004.
[8] Gereffi 2009; Lewis 2007; Vernon 1966.

the range of engineering capabilities required for technological innovation are combined and established in high-technology industries.

First, I propose that the fragmentation of production and the decline of the vertically integrated firm have not just dispersed manufacturing activities, but have also distributed innovative capabilities across global supply chains. Firms can specialize in distinct engineering skills and access the full range of capabilities required for technological innovation through collaboration with other firms. Capabilities that were once organized within the four walls of large vertically-integrated firm in advanced economies are now coordinated and combined in global networks in a process I call *networked innovation.* In industries characterized by networked innovation, I expect that no one technological leader can be identified, as many firms are innovating at the technological frontier in their respective area of specialization. As innovation is disaggregated along the trajectory from invention to mass production, product development and commercialization are no longer solely the domain of firms in advanced industrialized economies, but allow and even require engineering contributions from manufacturing firms that are increasingly located abroad.

Second, the ability to contribute to technological innovation through narrow sets of engineering capabilities has altered the process by which such capabilities are established. New options for specialization in narrow technological capabilities have mitigated pressures for convergence in the types of skills required to advanced to the technological frontier in any given industry. As a result, firms are able to incrementally build on existing strengths and industrial capabilities as they participate in networked innovation, often repurposing governmental resources and institutions established for prevailing industrial sectors in the process. My research indicates that sectoral industrial policies for emerging industries no longer fully determine variation in firm specialization, but that divergent industrial legacies, firm practices, and governmental resources provided for the broader economy shape how firms participate in collaborative processes of product development. By allowing firms to contribute to technological innovation through specialized capabilities, the rise of global production networks has allowed firms to craft distinct paths for participation in networked innovation that renew, rather than abandon, existing industrial capabilities for application in emerging industries.

In addition to contributing to literatures on the political economy of technological innovation, this comparative study of technological innovation in wind and solar sectors in China, Germany, and the United States speaks to broader debates about the nature of economic development and industrial upgrading.[9] My findings challenge the prevalent notion that industrial upgrading is first and foremost a process of emulation of technological leaders in advanced economies. Instead, I find that firms in developing economies no longer have to acquire the capabilities of firms in advanced economies to participate in technological innovation, but can incrementally establish innovative capabilities in commercialization and mass production. The collaborative nature of product development similarly challenges the notion that the rise of global production networks has separated innovation in advanced economies from production activities in developing locales, as networked innovation in wind and solar industries relies on critical contributions from both.[10] Lastly, this study contributes to debates about the role of

[9] For a discussion of catch-up development as emulation of firms in advanced economies, see, among others Amsden 1989; Amsden 2001; Kim 1997.
[10] Gereffi et al. 2005; Sturgeon 2002a; Vernon 1966.

sectoral industrial policy in shaping industrial capabilities and state-society relations under conditions of globalization. My findings suggest that firms incrementally build on existing industrial capabilities even in emerging industrial sectors—like wind and solar—that are subject to sectoral intervention and ambitious upgrading goals. This implies that industrial policies are capable only of encouraging far more modest industrial transformations than envisioned in literatures on the developmental state, which foresee the ability of government to create high-technology industrial sectors in places without any pre-existing industrial capabilities.[11] It also suggests, however, that national patters of industrial capabilities are likely to remain distinct even under conditions of globalization.

The remainder of this chapter proceeds with a review of literatures on the political economy of innovation, analyzing existing arguments about how innovation occurs and how the state enables firms in different economies to participate in technological innovation. The following section develops a new framework for understanding technological innovation in contemporary global supply chains. I end with a discussion of the main contributions of the argument to broader debates in political economy and provide a brief chapter overview.

[11] Amsden 1989; Evans 1995; Johnson 1982; Wade 1990.

2. Theories of Innovation: A Review of the Literature

Scholars of political economy have long understood innovation as a critical source of technological advantage, economic growth, and national competitiveness.[12] In this study, I define innovation as the process by which firms develop, master, and commercialize new product designs, services, and production processes.[13] As such, innovation is distinct from mere invention, as innovation includes the process by which new and improved technologies and practices are introduced in commercial markets.[14] In light of the links between innovation and the creation of economic value, governments have faced strong incentives to support innovative firms in the domestic economy. Academic debates about the nature and origins of innovation have therefore also been debates about the role of the state in encouraging innovation and the possibilities for government to do so. How and where does innovation happen in global industries and what can be done to increase the number of domestic firms that participate in such high-value activities in global supply chains? In the following section, I review prevailing views on the nature of innovation and its links to the institutions and policies of the state offered in literatures on the Product Cycle, National Innovation Systems, and the Varieties of Capitalism.

A first view, grounded in Vernon's seminal paper on the Product Cycle, has described innovation as the domain of firms in advanced industrialized economies.[15] According to Vernon, only firms in advanced economies possess the engineering capabilities required to develop new technologies and to manage challenges in commercialization until production processes are fully understood. In addition to meeting

[12] Boskin and Lau 1992; Romer 1994; Schumpeter 1934; Solow 1956.
[13] Nelson 1993, 4; Schumpeter 1934.
[14] Nahm and Steinfeld 2014, 290.
[15] Akamatsu 1962; Cumings 1984; Vernon 1966; Vernon 1979.

the skill requirements of innovation at the technological frontier, such firms can rely on sophisticated domestic markets and consumers able to afford the price premium commanded by new technologies. Once products are reliable, manufacturing processes standardized, and price premiums gained from initial technological advantage depleted—in other words, once products are fully commodified—manufacturing activities shift to developing economies with lower technical capabilities and less sophisticated market demand.

Implicit in Product Cycle arguments is the notion that close geographic and managerial linkages between invention and production are required in early stages of product development. Until manufacturing processes are fully standardized and product designs perfected, knowledge-intensive engineering capabilities are required to make iterative design changes and solve challenges in scale-up and mass production. As levels of product maturity eventually lower skill requirements and subsequently allow for the relocation of production activities, theorists of the Product Cycle expect a global division of labor between firms in advanced economies engaged in innovation and production of products at the technological frontier and firms in developing locales focused on mass manufacturing of products that are fully commodified.[16]

Vernon conceived of Product Cycle theory before globalization fundamentally changed the organization of production, yet recent literatures on global supply chains have argued that the rise of global production networks has intensified the geographic and organizational concentration of innovation in firms in advanced economies. Starting in the mid-1990s, a series of technological innovations opened new possibilities for the

---

[16] For dynamic versions of Product Cycle theory, see Antràs 2003; Grossman and Helpman 1991; Krugman 1979.

organization of production, as new digital technologies suddenly allowed for complex design blueprints to be electronically transmitted to far-way production locations. As a consequence, firms were able to break the connection that had long required the co-location of R&D and manufacturing in early stages of product development. Firms in advanced industrialized economies could now focus on core strengths in R&D, while moving manufacturing activities abroad to take advantage of low-cost production conditions in developing economies. The standardization of interfaces between different components—the result of what Baldwin and Clark have called architectural innovation—permitted firms to introduce modular product architectures, in which the design and fabrication of entire components could be entrusted to third-party suppliers.[17]

Literatures on global production networks share with Vernon's original Product Cycle proposition the notion that skill requirements for different research and production activities determine which industrial activities are located where. Scholars in both traditions agree that sophisticated firms in advanced economies engage in high-value, knowledge-intensive activities, while firms in developing economies are specialized in low-value production of commodity products in hierarchically structured global industries. Unless these firms can emulate the capabilities of firms in advanced economies to advance to the technological frontier, they are unable to participate in product innovation and can enter high-technology sectors only once standardization has lowered the skills required for manufacturing. Although literatures in this tradition do not offer an explicit view of the role of the state in enabling firms to do so, it is in their focus on skills and industrial capabilities

[17] See Baldwin and Clark 2000; Berger 2005, Chapter 4; Camuffo 2004; Fuller et al. 2003; Ge and Fujimoto 2004; Gereffi et al. 2005; Langlois 2002; Steinfeld 2004; Sturgeon 2002a.

that one can discern a potential role for government in enabling upgrading and innovation in the domestic economy.

A second view of innovation is offered by theorists of National Innovation Systems, which have highlighted the importance of networks and relationships between public and private actors in the development of different types of innovative capabilities. Scholarship in this tradition starts from the premise that firms establish innovative capabilities through relationships with external organizations. How technologies are created and diffused depends on the links between firms and the national infrastructure for supporting technological innovation comprised of government actors, universities and research institutes, suppliers, and customer demand in local markets. Emphasizing the notion that innovation occurs in broader ecosystems, scholars also point to the role of regulations, institutions, norms, routines, and culture in shaping how individual actors in innovation systems operate and jointly structure the creation and commercialization of new technologies.[18]

Under the umbrella of National Innovation Systems, scholars have employed a range of approaches and have focussed on different elements of national systems.[19] Nonetheless, scholars of innovation systems share a number of common assumptions about the role of the state in shaping the innovative capabilities of firms. They generally see government as critical actor in fixing market failures in R&D through publicly funded research and in

---

[18] Archibugi et al. 1999; Carlsson et al. 2002; Carlsson and Stankiewicz 1991; Edquist 1997; Edquist 2005; Freeman 1987; Lundvall 2007; Lundvall 2009; Nelson 1993. Scholars in this tradition concede that systems for the creation and commercialization of new technologies can in fact be regional or international, yet they emphasize the preeminent role of national-level institutions, law, and practices in shaping organizational behavior. See Lundvall 2007.

[19] A European tradition has highlighted the role of customer demand in shaping innovative capabilities of firms, while an American branch has emphasized differences in the organization and financing of R&D. See, for instance, Breznitz 2007, 24-29; Lundvall 2009; Nelson 1993.

coordinating the relationships through which results are disseminated in the private sector. The resources provided on part of the state and the relationships to industry further determine what types of capabilities can be established by firms internally and what types of knowledge can be accessed through relationships with other actors. Finally, they argue that the state, by means of regulation, influences the profitability of different types of industrial activities and shapes business models and research paradigms.

Research on the United States, for instance, has highlighted the role of large public investments in R&D in accelerating the rate of technological discovery, has attributed the creation of large, vertically-integrated firms to America's unique history of antitrust legislation, has emphasized the contribution of military R&D and procurement in the creation of commercial technologies, and described the role of licensing rules for federally-funded research in the emergence of high-tech startups firms.[20] Works on Germany have analyzed the influence of Germany's vocational training system, examined the role of public research organizations such as the Fraunhofer and Max Planck Institutes, emphasized the higher proportion of R&D conducted in firms as a result of low levels of public investments in research, and focused on links between protected European domestic markets and firm strategy.[21] Contending that innovation systems are vehicles for learning and the creation of knowledge even outside the boundaries of traditional R&D, works in this tradition have not exempted developing economies from their analysis. Instead, research on developing economies has identified factors that have increased the ability of firms to absorb imported technologies, so-called absorptive capacity, for instance through public investments in

---

[20] Mowery 1992; Mowery 1998; Mowery et al. 2001; Mowery et al. 2004; Mowery and Rosenberg 1999.
[21] Freeman 1995; Keck 1993.

scientific and technical training, import protection, the state-led creation of vertically integrated enterprises, and the encouragement of links between firms, suppliers, and subcontractors.[22]

Although literatures on National Innovation Systems have compared the make-up of ecosystems for the creation of innovative capabilities through rich empirical analysis, they have resisted theory-building about causal links between systemic features and innovation outcomes. By drawing attention to the broad range of actors that influence how knowledge is created, these works have argued that firm-level learning and technological innovation are deeply embedded in broader national ecosystems that cannot be reduced into a matrix. A multitude of factors shape national patterns of learning and innovation, leading to differences in innovative capabilities not just between advanced and developing economies, but also create divergent networks for the acquisition and diffusion of knowledge among advanced industrialized nations.

A third view on innovation has sought to identify systematic causal links between institutions and innovation outcomes at the national level. Scholars of the Varieties of Capitalism have proposed that dense networks of mutually reinforcing institutional arrangements structure the relationships between economic and political actors. These institutional arrangements either favor industries relying on incremental innovation through the continuous, small-scale improvements or industries focused on radical innovation that breaks with past industrial practices. In coordinated market economies, such as Germany, institutions governing labor markets, financing, relations between firms and suppliers, and employee participation in corporate governance create an environment

[22] Fagerberg and Srholec 2008; Kim 1993; Liu and White 2001; Mowery and Oxley 1995.

best suited to firms pursuing incremental innovation—a skilled workforce with low turnover, collaborative relationships between firms and suppliers, long-term financing through bank loans, and corporate strategies that emphasize product differentiation through quality improvement. In liberal market economies, such as the United States, domestic institutions foster labor market flexibility, well-developed equity markets, short-term profit horizons, and corporate governance rules that enable rapid changes in corporate organization—all of which encourage firm strategies based on radical innovation. In short, the characteristics of domestic institutions and the difficulty of changing mutually reinforcing institutional arrangements shape processes of industrial development by creating lasting conditions that favor different kinds of firm activities, competitive strategies, and innovative capabilities.[23]

Although Varieties of Capitalism literatures have not extended their analysis to developing economies, their institutional arguments are pessimistic about the ability of government to actively create conditions suitable for different types of innovation. Path-dependent institutional structures are seen as primary to industrial policy and sectoral intervention in influencing firm behavior and offer few options for rapid industrial change.[24] Hence, institutions not only enable learning and the creation of knowledge, but also constrain what types of innovative activities can take place in different contexts. As a consequence, Hall and Soskice argue that industries predominately based on incremental improvements, such as metal fabrication, machine tools, and factory equipment, tend to locate in coordinated market economies, while industries based on radical innovation, such

[23] Casper et al. 2009; Hall and Soskice 2001; Soskice 1997.

[24] A main critique of works in this tradition has been their inability to account for substantial changes in institutional structures over time. See Streeck and Thelen 2005.

as semiconductors, software, and biotech, settle in liberal market economies.[25] Ultimately, theorists of the Varieties of Capitalism predict a global division of labor along industry lines, organized according to innovation requirements of different industries and the varying institutional endowments of national economies.[26]

Comparative literatures on innovation have thus focused on a range of different factors that shape how and where innovation takes place in global industries. Product Cycle theory has drawn attention to challenges in scale-up and commercialization that require co-location of innovation and manufacturing in early stages of product development. Literatures on National Innovation Systems have pointed to the importance of organizations and actors external to the innovative firm in shaping industrial capabilities. The Varieties of Capitalism school has refined this view and emphasized the role of institutional arrangements in enabling different types of innovation outcomes.

For all their differences in approach and focus, however, two common denominators exist across these different views of innovation. First, scholarship in all three traditions has argued, either implicitly or explicitly, that a division of labor exists between firms in advanced economies that innovate and firms in developing economies that manufacture after the innovation process is completed. In other words, literatures on innovation suppose that innovation and mass production are distinct, sequential in timing, and hierarchical in skill requirements. This view is most clearly articulated in Product Cycle theory, yet even literatures on National Innovation Systems, which have described learning

[25] Hall and Soskice 2001, 39.
[26] Empirical evidence does not equally support this view of innovation and industrial specialization across all industries and national contexts. See, for instance, Akkermans et al. 2009; Taylor 2004.

in developing economies, distinguish between innovative capacity in advanced economies and absorptive capacity required for technology transfers in developing ones.

Second, comparative literatures on innovation share the notion that innovation is vertically integrated within the firm and occurs in distinct national industrial ecosystems. Firms are relying on the broader R&D infrastructure and institutional arrangements of the domestic economy in establishing different types of innovative capabilities. However, it is within the four walls of the firm that resources, capabilities, and market opportunities are combined and coordinated in the process of product development, regardless of whether product development relies on incremental, radical, or architectural innovation. In the case of the Product Cycle, such coordination takes the form of tight organizational links between R&D and manufacturing in early stages of product development. Theorists of National Innovation Systems and the Varieties of Capitalism instead emphasize the process by which firms bring resources resources of the broader economy to bear on creation of knowledge within the firm. Although researchers part company about which elements of industrial ecosystems are most important for innovation outcomes, most agree that the capabilities required for different types of innovation are established, combined, and coordinated by firms embedded in the broader industrial base

The two industries at the core of this study, wind turbines and solar photovoltaic modules, present an empirical record that has not followed the core assumptions of comparative literatures on innovation. In both industries, firms collaborate to develop new products with distant partners, leap-frogging, obviating, or reversing the traditional sequence of innovation activities. In doing so, wind and solar PV firms circumvent the traditional division of labor between industrialized and developing economies and transcend the national innovation systems expected to anchor and support them. Existing views of innovation offer few tools to understand a situation in which the capabilities required for product development span the organizational boundary of the firm, and the resources required to establish such capabilities transcend the boundaries of the state. If they have considered the rise of global production networks at all, such literatures have mainly seen consequences for the location of manufacturing. Yet how have these changes affected innovation?

3. An Alternative Explanation: Networked Innovation in Global Production Networks

This study examines how changes in the global organization of production have altered the process by which innovation occurs in global supply chains. The framework offered here builds on insights from comparative literatures on innovation, but revisits two distinct aspects of the innovation process in global industries. First, how have changes in the organization of production affected affected the distribution of capabilities required for product innovation? That is, how are innovative capabilities that were once organized by individual firms coordinated and combined in fragmented global supply chains? Second, how do firms come to occupy particular nodes of specialization in industries that are no longer vertically integrated within national industrial systems? The following sections discuss both aspects in turn.

Networked Innovation and a New System of Global Production

I propose that the fragmentation of production and the decline of the vertically integrated firm have not just dispersed manufacturing activities, but have also distributed innovative capabilities across global supply chains. As I outline in this section, capabilities that were once organized within the four walls of large vertically-integrated firm in advanced economies are spread across multiple firms and are coordinated and combined in global networks in a process I call *networked innovation.* In contrast to the vertically-integrated firms of the past that possessed the full range of skills required for innovation, firms in contemporary high-technology sectors have new options to specialize in distinct engineering skills, as they can access the full range of capabilities required for innovation through collaboration with other firms. The following discussion first reviews the range of innovative capabilities once housed in the vertically-integrated firms, then outlines how the rise of global production networks has affected the distribution of such capabilities, and concludes with a discussion of how such capabilities are coordinated and combined in global networks under conditions of networked innovation.

As theorists of the product cycle have long pointed out, product innovation relies on a broad range of engineering capabilities, not just in invention, but also in commercialization and scale-up to mass production. Literatures on technological innovation have treated innovative capabilities residing in the manufacturing process as primarily related to process innovation, describing changes and improvements in the manufacturing process and the method of product delivery. [27] Scholars of product innovation have instead focused on differences between radical and incremental innovation, the former introducing new concepts and technologies that depart significantly from past practice, and the latter improving gradually on existing designs.[28] More recent work has added the concept of architectural innovation, referring to changes in the overall architecture of a product without altering its underlying components.[29] Yet the empirical evidence presented in the following chapters suggests that commercialization and production of new products in high-technology industries often face challenges in the process of scale-up to mass manufacturing that cannot be met through process innovation alone, instead requiring changes to product design.

---

[27] OECD 2005, para. 163.

[28] See, for instance, Abernathy and Clark 1985; Abernathy and Utterback 1978; Porter 1986; Tushman and Anderson 1986.

[29] See Henderson and Clark 1990. For an application of these concepts to the case of China, see Ernst and Naughton 2008a.

In this study, I use the term *innovative manufacturing* to refer to the process in which such changes are made through a set of engineering and design activities at the intersection of traditional R&D and manufacturing. Such innovation includes, for instance, the substitution of materials, re-design of particular components, the reorganization of the internal product architecture, and the integration of new technologies and components into products already manufactured at scale. Although innovative manufacturing comprises some activities traditionally understood as process innovation, it has far-reaching consequences for product innovation and product design.

A number of factors give rise to the importance of innovative manufacturing in product development. At the technological frontier, where technologies push against the limit of established practice and experience, commercialization often entails experimentation, innovation, and learning in ways that ultimately impact the product design itself. Whether and how a new technology can be produced—let alone be produced in large numbers and at a price that allows it to sell—cannot always be anticipated even with advanced computer modeling capabilities. The use of new materials, new-to-the-world designs that require complex manufacturing processes, and unforeseen interactions between product characteristics give rise to new challenges in product development that can rarely be resolved through traditional, lab-based R&D activities. This is especially true in emerging industrial sectors, where novel technologies frequently require a departure from established manufacturing practices, yet such challenges also arise in established industrial sectors with complex manufacturing needs. Both Airbus and Boeing, for instance, have recently struggled with lengthy delays in the development of new airplane models as a result of difficulties in the production and scale-up of their designs.[30]

In the past, vertically integrated firms were able to engage in such iterative processes of translating between complex designs and manufacturing requirements within the four walls of the company. For this reason, comparative literatures on innovation have long seen large, vertically-integrated firms as the locus of technological innovation in economies around the world. The core advantage that vertically-integrated firms possessed over smaller enterprises was their ability to establish the full range of engineering capabilities required for innovation within the four walls of the firm. Large enterprises were able to make the capital, human, and financial, investments required to establish this broad range of engineering capabilities in ways that smaller firms could not. Yet, housing manufacturing and R&D capabilities under one roof, vertically integrated enterprises not only possessed all the necessary capabilities to bring a product idea to market, but they were also able to coordinate and establish critical linkages between innovation and production capabilities in early stages of product development. By reducing transaction costs and concentrating all the necessary activities required to bring a product idea to market, vertically-integrated businesses could manage both innovation and production more efficiently than other firms.[31]

In the late 19th century, large vertically-integrated enterprises allowed Germany and the United States to begin to catch up with Britain, the leading industrialized economy

---

[30] "Hit by Delays, Airbus Tries New Way of Building Planes." *Wall Street Journal*, July 11, 2012. The case is also discussed in Hellemans 2007.

[31] Where scholars of East Asian economic development saw a need for the state to encourage the creation of such business in late developing economies, Chandler, in a study on the origins of large business in the United States, argued that the dominance of conglomerates in the U.S. economy was a result of their competitive success. See Chandler 1977, chapters 3 and 9. On East Asia, see, for instance, Amsden 1989; Evans 1995; Johnson 1982.

at the time. After World War II, many of the same conglomerates played a critical role in commercializing technologies developed for military purposes during the war, supporting postwar economic growth and recovery in advanced economies.[32] And just as Germany and the United States relied on large firms in their attempts to compete with British industrial prowess, later generations of developing economies also chose vertically-integrated conglomerates to spearhead industrialization and catch-up development. Most prominently, in their ambition to establish advanced technological capabilities during the postwar decades, Japan, Korea, and Taiwan moved from manufacturing to more complex, innovative, and valuable activities in global industries by means of vertically-integrated business groups, whether they were called *zaibatsu* (Japan), *chaebol* (Korea), or *guanxi qiye* (Taiwan).[33]

As is clear from literatures on global supply chains and modular production networks, a series of technological innovations over the course of the 1990s opened new possibilities for the organization of production that challenged the advantage of vertically-integrated enterprises.[34] Advanced communication technologies suddenly allowed for complex design blueprints to be electronically transmitted to far-away production locations, allowing firms to break the connection that had long required R&D and manufacturing to occur in close proximity. The standardization of interfaces between different components made possible by new digital technologies allowed firms to introduce modular product architectures, in which not just manufacturing was outsourced or off-

[32] Chandler and Hikino 1997.

[33] Johnson discusses the role of business groups in Japan's postwar economy in Johnson 1982. For a discussion of Korean business groups, see Amsden 1989. Chung and Mahmood provide an overview of business groups in Taiwan in Chung and Mahmood 2010.

[34] This paragraph draws heavily on Berger 2005, chapter 4.

shored to low-cost production locations, but the design and fabrication of entire components could be entrusted to third-party suppliers.[35] In the past, integral architectures had required different teams within the same firm to closely collaborate in product design and manufacturing, giving a competitive edge to vertically integrated firms which were able to develop and maintain such diverse capabilities. Now, the use of computer-aided design tools allowed for the creation of precise production specifications, so that components fit together with minimal tolerances regardless of where they were manufactured.

As a consequence of these new options for the organization of production, firms in advanced economies began to focus on core strengths in research and development and many moved manufacturing activities abroad to take advantage of low-cost production conditions in developing economies. At a time when the capital investments required for the construction of new manufacturing facilities increased rapidly, they gladly spread investment risk to suppliers and third-party manufacturers.[36] Furthermore, by relying on contract manufacturers, businesses in advanced economies could react more quickly to rapid changes in market demand, as production could be scaled without going through the lengthy process of establishing additional manufacturing capacity in-house. For firms in developing economies, by contrast, global production networks lowered barriers to entry, permitting them to enter global supply chains for high-technology products through contract manufacturing of advanced designs, or by hosting foreign-invested manufacturing

[35] Although the possibility of separating manufacturing and innovation (through offshoring and outsourcing) and the option to develop modular production architectures are separate developments, they are mutually influencing and driven by the same underlying technological developments. See Camuffo 2004; Langlois 2002.
[36] Berger 2005, 73; Ezell and Atkinson 2011, 22.

facilities. Detailed electronic blueprints meant that knowing how to make something no longer required knowing how to design something, reducing the importance of tacit knowledge and experience that traditionally linked manufacturing and innovation.

How have such changes in the organization of production affected the distribution of innovative capabilities? One possibility, offered in standard literatures on innovation, is that new opportunities for the organization of production have primarily affected the location of manufacturing activities, but have left untouched the firm in the advanced industrial economy as the central locus of technological innovation. Indeed, U.S. corporate spending on research and development increased by 186 percent between 1992 and 2008, while investment in manufacturing declined.[37] Between 2000 and 2008 one, capital investments by U.S. firms in domestic manufacturing facilities fell by 7 percent. This development was most pronounced in low tech sectors such as apparel, where domestic investments fell by 73 percent, but included high-technology industries such as automobiles, where investments in manufacturing decreased by 42 percent.[38] Technological developments enabled firms in advanced economies to reorganize their production networks and financial markets rewarded such restructuring.[39]

The study of global wind and solar industries yields a different interpretation of the effects of global production networks on the organization of innovation in global supply chains. Although investment statistics document rapid changes in the location of manufacturing activities in global industries, they reveal little about the distribution of capabilities that were once housed in the vertically-integrated firm. Particularly in

---

[37] Data compiled by Bureau of Economic Analysis, cited in Pisano and Shih 2012, 93-95.
[38] Bureau of Economic Analysis, Fixed Account Tables (3.8ES, International). Summarized in Ezell and Atkinson 2011, 22.
[39] Davis 2009, chapters 1-4.

emerging industrial sectors, such as the wind and solar industries at the core of this research, the empirical record suggests that production activities are not nearly as modularized and the distinctions between higher-value added design and low-tech manufacturing not nearly as clear as scholars of modular production networks envision, even if production and innovation activities now undoubtedly occur in highly fragmented global supply chains. In other words, evidence for the geographical separation of upstream R&D and downstream manufacturing does not, in an of itself, discount the possibility that innovative capabilities continue to matter not just in invention, but also in scale-up and mass production.

My research indicates that innovation continues to require engineering contributions not just in early stages of product design, but throughout the entire process of commercialization. Consequently, the rise of global production networks and the relocation of manufacturing activities has also affected the distribution of innovative capabilities related to scale-up and mass production. As firms in China and other middle-income economies have focused on building capabilities around scale-up and large-scale production, firms in advanced economies have in many cases lost the manufacturing infrastructure on which capabilities in innovative manufacturing can be established.[40] In vertically disintegrated industries, where R&D centers and manufacturing locations are geographically and organizationally separated, R&D staff often do not possess the manufacturing experience to anticipate the needs of the production process, relying

[40] Pisano and Shih, in a variation on this argument, propose that the decline of manufacturing in the United States prevents firms from realizing their innovative potential in areas where manufacturing skills are essential to product innovation. Restoring competitiveness for U.S. firms in their view requires a revitalization of the American manufacturing sector. See Pisano and Shih 2009; Pisano and Shih 2012.

instead on engineering capabilities residing in the manufacturer or supplier. The manufacturers that possess the infrastructure on which innovative manufacturing capabilities can be established are increasingly located away from the traditional centers of innovation in advanced economies.

While this project examines the implications of this phenomenon in the case of wind and solar industries, the fragmentation of innovative capabilities across several firms, including the manufacturer, is common to a number of emerging industrial sectors with rapid technological change and large capital requirements. Firms like Dell, Sun, and Cisco have long focussed on research and development in the United States, all while disposing of in-house manufacturing capabilities.[41] The collaborative relationships between Taiwanese semiconductor foundries and fab-less chip designers without in-house manufacturing capabilities are early examples of this type of fragmentation of innovative capabilities across several firms.[42]

Although the role of manufacturing capabilities in product innovation is not new in principle, the fragmentation of global supply chains has complicated the commercialization process, as the capabilities required for product innovation are now distributed across multiple firms and national boundaries. How are capabilities for innovation combined and coordinated, if the vertically-integrated firm embedded in national industrial system is no longer the locus of innovation?

Evidence from global wind and solar industries suggests that the increasing specialization of firms in distinct steps of the innovation process requires collaboration and

[41] See, for instance, Berger 2005; Breznitz 2007; Gourevitch et al. 2000; Kenney and Florida 2004; McKendrick et al. 2000; Sturgeon 2000; Sturgeon and Lester 2004.
[42] Fuller et al. 2003; Saxenian 1994; Saxenian and Hsu 2001.

coordination in global networks. In industries in which capabilities in innovative manufacturing continue to be of importance for product innovation, product designs are developed through simultaneous processes of R&D and innovative manufacturing, in which a variety of innovative activities occur concurrently and entail collaboration across multiple firms. Firms can participate in global networks for innovation with highly specialized skills and are no longer required to establish the full range of capabilities required for radical, incremental, and architectural innovation in house or even within national ecosystems. At the same time, specialized innovative capabilities necessitate coordination and collaboration with other firms to access the full range of capabilities required for invention and commercialization, many of which are no longer in close geographical proximity. As the locus of coordination for the full range of innovative capabilities required for innovation has shifted from large firms to global networks of specialized firms, I refer to such collaborative processes of product innovation as *networked innovation.*

Three factors distinguish networked innovation from the conventional characterization of innovation and manufacturing activities as sequential in timing, distinct, and hierarchical in skill requirements. First, under conditions of networked innovation, innovation and manufacturing activities are not sequentially organized. In contrast to product innovation in modular production networks, in which products are handed off to manufacturers only once they are fully standardized, networked innovation requires sustained interaction between different firms specialized in different steps of the innovation process. In some cases, an initial invention by one firm is finalized under cooperation with multiple partners. In other cases, the capabilities of a manufacturer may give rise to a product idea that is developed in collaboration with firms possessing strong R&D capabilities. What such instances have in common, however, is that they break with conventional views that see innovation and mass production as sequential in timing, as innovation and production activities in such industries are integrated, mutually dependent, and often simultaneous.

Second, in a system of networked innovation, in which complex product architectures and firm-level specialization in production and R&D activities by definition require interaction with the capabilities of other firms to bring a product to market, innovation and mass production activities are no longer distinct. Product development occurs through multi-directional learning and interdependent relationships that cut across multiple firms with different types of engineering capabilities. This interaction between firms differs from learning across multiple business units within the conglomerate firm, as firms with a variety of specializations need to collaborate in product development. However, the interdependence of firms in product design makes such interactions equally different from the relationships in modular production networks, in which lead firms rely on suppliers for the development and production of components. In environments of networked innovation and collaborative product development, innovative ideas travel in multiple directions, including from manufacturers to firms possessing basic research and early R&D capabilities, and from firms in middle-income economies to those in advanced industrialized ones.

Third, in industries characterized by networked innovation, leaders in technological innovation and industry development appear across the entire trajectory of product development, including the stages of scale-up and mass manufacturing. No single link in the chain of production can be identified as the lead position. Consequently, economies and the firms within them cannot easily be grouped into global technological leaders and those attempting to catch up, calling into question the notion that industrial activities are structured along a single hierarchy of complexity and value from manufacturing to advanced innovation. While firms in advanced economies are still more likely to possess capabilities in basic research and early stage R&D, the importance of innovative manufacturing challenges views that portray production merely as the execution of product design. As a result of the co-dependence of highly specialized firms on external partners with complementary skills, engineering capabilities are no longer hierarchical.

As the empirical chapters to follow outline in detail, the relationships through which firms contribute innovative capabilities to networked innovation take a variety of legal and organizational forms. In some cases, firms with complementary engineering capabilities sign collaborative research agreements that anchor the non-hierarchical, mutually-beneficial collaboration firmly in a legal contract. In other cases, networked innovation takes place in supplier relationships between firms with complementary skills. Even contract manufacturing and licensing agreements—supply chain relationships that are traditionally seen as far more hierarchical—allow for collaboration, multi-directional learning, and the participation of multiple firms in joint processes of product development.[43] Frequently, a single innovation requires many such relationships at once.

These varied relationships have in common that they bring together knowledge-intensive capabilities created in diverse firms and far-flung geographical locations. The study of global wind and solar industries suggests that such knowledge, despite advances

[43] For a framework on hierarchy in the governance of global supply chains, see Gereffi et al. 2005.

in digital technologies, cannot be fully codified in production equipment or design blueprints. Even if production machines and blueprints now travel more easily to far-away destinations, this study suggests that using, adapting and improving technologies—let alone inventing new ones and producing them at scale—continues to require tacit skills that cannot be reduced to the flick of a switch. This knowledge no longer resides under the roof of the vertically-integrated enterprise, but is distributed across a wide number of firms, including innovative manufacturers, and coordinated and combined in global networks.[44]

State Resources and Innovative Specialization

Literatures on innovation have described a strong role for public actors in enabling and shaping innovation outcomes. How have changes in the organization of innovation—the emergence of the phenomenon of networked innovation—affected the ways in which firms make use of and build on national resources for innovation? How do firms come to occupy particular nodes in global systems of networked innovation that allow participation in product development with specialized skills?

As I have introduced at the beginning of this chapter, Chinese, German, and American wind and solar firms have contributed distinct, specialized engineering capabilities to collaborative product innovation in global renewable energy industries. In China, wind and solar firms have specialized in the types of skills required to adjust, improve, and re-engineer novel product designs and componentry for commercialization and scale-up to mass production. Many of the technologies that Chinese firms modified

[44] Nahm and Steinfeld 2014.

originate in the United States, however, where firms have focused on the invention of new technologies, but have rarely established capabilities required for the commercialization of their designs. In Germany, by contrast, the majority of wind and solar firms are suppliers for complex componentry and production equipment with capabilities in customization, prototyping, and small-batch production. My research shows that firms have occupied such distinct nodes in global innovation networks despite broadly similar industrial policies for renewable energy sectors. In all three economies, governments have sought to create domestic wind and solar sectors by providing subsidies for renewable energy markets and funding for traditional research and development activities.

In this section, I propose that new options for specialization in narrow technological capabilities have mitigated pressures for convergence in the types of skills required to advance to the technological frontier in any given industry. As a result, firms are able to incrementally build on existing strengths and industrial capabilities as they participate in networked innovation, often repurposing governmental resources and institutions established for prevailing industrial sectors in the process. The study of wind and solar industries suggests that by permitting firms to contribute to technological innovation through specialized capabilities, the rise of global production networks has allowed firms to craft distinct paths for participation in networked innovation that renew, rather than abandon, existing industrial capabilities. This section proceeds with a review of the relationship between public actors and innovation outcomes, then discusses how changes in the global organization of innovation have altered this relationship. I conclude with a discussion of links between public support and firm specialization under conditions of networked innovation.

In light of the role of innovation in the creation of economic value, governments have faced strong incentives to support innovative firms in the domestic economy. Governments have done so by providing public resources for firms that existing literatures have described as elements of national innovation systems. These resources include skills and training institutions, funding for universities and research institutes, but also laws and regulations that have structured how private sector firms can utilize and commercialize technologies originating in government-funded research.[45] In addition to such broad institutional support, governments have also used a range of industrial policies and sectoral interventions to support the creation of innovative firms in select industrial sectors. In contrast to the broad, national resources that firms could use to build innovative skills, such industrial policies have often provided far more specific support for the creation or improvement of particular technologies and the establishment of domestic firms in desirable economic sectors. In the renewable energy industries at the core of this study, for instance, sectoral industrial policies have included R&D funding for specific energy technologies, subsidies for domestic renewable energy markets, and local content requirements.

Among developing economies, sectoral interventions have historically gone beyond measures to increase and distribute resources required for innovation. In particular, they have included attempts to create vertically-integrated industry structures that would allow firms to coordinate and combine the full range of capabilities required to advance to the technological frontier. By producing complete products—rather than supplying components to other firms or assembling components manufactured by other firms—large,

[45] Archibugi et al. 1999; Carlsson et al. 2002; Carlsson and Stankiewicz 1991; Edquist 1997; Edquist 2005; Freeman 1987; Lundvall 2007; Lundvall 2009; Nelson 1993.

vertically-integrated enterprises offer the possibility of building the entire range of capabilities required for the creation of a particular product under the roof of one firm. To accelerate the creation of industry structures conducive to industrial upgrading and innovation, governments in Japan, Korea, and Taiwan, the so-called developmental states, encouraged the development of conglomerate firms, channelled resources into select industrial sectors, limited entry to ensure scale economies for existing firms, and created financial incentives for firms to keep a wide range of innovation and production activities within the firm. Vertically-integrated firms were seen as so central the creation of knowledge, that governments needed to create such industry structures where none existed.[46]

Implicit in prevailing views of the role of the state in enabling innovation has thus been the notion that for domestic firms to participate in innovation at the technological frontier, the national industrial base must both supply the resources for innovation and the firm structures to create, combine, and coordinate the full range of innovative capabilities required for product development. Scholarship on the Varieties of Capitalism has reminded us that institutional arrangements of the domestic economy may favor the creation of different types of innovative capabilities among domestic firms. However, such works maintain that even in economies that have specialized in incremental or radical types of innovation and have attracted the correspondent industrial sectors, the full range of capabilities required for that type of innovation is supported by the national industrial base and coordinated in domestic firms.[47] In short, literatures on innovation have assumed that

[46] Amsden 1989; Amsden 2001; Cheng 1990; Cheng 1993; Johnson 1982; Kim 1997; Park 2002; Wade 1990; Woo-Cumings 1999.
[47] Hall and Soskice 2001.

broadly similar sets of skills have to be stablished to reach the technological frontier in any given industry. One role of the state is to support and ensure that such capabilities can be established in the domestic economy.

Under conditions of networked innovation, however, multiple sets of skills allow for participation in product development and innovation at the technological frontier. How have these changes affected how such capabilities are established in national ecosystems?

For firms, conditions of networked innovation have increased opportunities for upgrading and lowered barriers to entry. Instead of having to master innovative activities across the entire product development trajectory, firms can upgrade within global supply chains through specialization in niche capabilities, while complementing such capabilities through collaboration with others. Particularly for firms in China, this offers more opportunities for industrial upgrading, as even niche capabilities can be brought to bear on global processes of product innovation. Similarly, innovators in advanced economies now contribute to product development without skills in manufacturing or component specification, much in contrast to a pre-digitization era in which the importance of tacit knowledge required the tasks of product design, component sourcing, and assembly to be conducted through tight managerial and geographical linkages under the roof of the vertically-integrated firm.

At the same time, the fragmentation of global production has extended uncertainties traditionally only found in firms with upstream research and development capabilities into the manufacturing process itself. The distribution of innovative capabilities across global supply chains has dispersed the uncertainties of pushing the technological frontier, including to firms with innovative manufacturing capabilities. For the late industrializers in

Korea and Japan, manufacturing was primarily an exercise in emulation and reverse engineering orchestrated by vertically-integrated firms.[48] The study of contemporary wind and solar sectors suggest, by contrast, that even manufacturers need to innovate at the technological frontier in order to commercialize and manufacture new-to-the-world product designs. Consequently, manufacturing firms in developing economies (and governments trying to support them) now live in a world without clear recipes for what types of capabilities are necessary for competitiveness. That is, firms no longer know what they should know for successful industrial upgrading. Even if they have acquired important capabilities, they rely on collaboration with the right partners for product development.

For the state, new opportunities for industrial upgrading and changes in the process of industrial upgrading—including new challenges in dealing with fragmented production systems, and new complexities in finding appropriate partners for technology commercialization—make it harder to anticipate what kinds of innovative capabilities firms require, and what policies and resources will support firms in establishing such skills. This is especially true for governments in developing economies, which could previously rely on the precedents of firms in advanced economies to develop strategies for upgrading. Incentivizing firms to invest in innovative capabilities and punishing them for failing to meet upgrading goals was possible in part because the broad trajectory of upgrading was known, at least for firms that had not yet reached the technological frontier. Yet even for governments in advanced industrialized economies, the broad range of innovative specializations that allow firms to participate in networked innovation make it difficult to predict how exactly domestic firms are going to take advantage of new opportunities in

[48] Amsden 1989; Amsden 2001; Cheng 1990; Cheng 1993; Johnson 1982; Kim 1997; Park 2002; Wade 1990; Woo-Cumings 1999.

global supply chains. As a consequence, government bureaucracies are unlikely to possess any special insights that would allow them to strategically target particular capabilities for development and to provide firms with the incentives and resources to meet these goals.

How do firms make use of publicly provided resources and institutions under conditions of choice and uncertainty? Evidence from global wind and solar industries suggests that the combination of greater opportunities to participate in product innovation at the technological frontier and less predictability about the resources and skills required to do so have altered the ways in which firms rely on the national infrastructure for innovation and the government policies to support it. Governments have indeed continued to use sectoral intervention and traditional tools of industrial policy, often explicitly in the hopes of creating domestic enterprises occupying high-value nodes in global supply chains. My research suggests, however, that although such policies have created incentives for firms to enter new economic sectors, which firms responded and what innovative capabilities they established is determined by factors beyond the industrial policies themselves. I distinguish between three broad aspects of broader industrial ecosystem that determine firm specialization.

First, as literatures on National Innovation Systems and the Varieties of Capitalism have indicated, resources, networks, and institutions of the broader economy matter for what kinds of innovative capabilities can be established domestically. Although new industrial sectors, such as the wind and solar industries at the core of this project, provide a clean slate on which new entrants can apply and develop their capabilities without the effect of incumbent firms, they evolve within extant political economies and national infrastructures to support innovation. As literatures on innovation have indicated, such broader innovation systems include public investments in education, skills, infrastructure, and public R&D institutions, but, importantly, also comprise regulatory institutions that favor certain activities over others. These resources provide the platform on which specializations in emerging industries develop, yet they also constrain actors in important ways. Capabilities in rapid scale-up of new manufacturing processes, for instance, are unlikely to evolve in an ecosystem that offers financing only for small-scale development projects and features lengthy planning approval processes.

Second, my research suggests that industrial legacies determine the range of firms that respond to industrial policies and other incentives for industry entry. Under conditions of networked innovation, lower barriers to entry and the possibility of advancing to the technological frontier with narrow, specialized skills attract a wider range of firms from existing industrial sectors. These firms can build on existing strengths in applying themselves to new industries, without having to establish the full range of capabilities once required to compete in high-value, innovative activities. Firms entering emerging industrial sectors bring with them skills and capabilities from previous industrial activities. In addition to providing know-how, firms' past industrial activities influence strategies for competitiveness—what worked well for a firm in the past will shape decisions about the future. Even when firms do not have legacies in other sectors but start in emerging industries, capabilities and templates are transferred through employees whose past experiences provide a legacy of sorts even for recently founded firms.

Faced with multiple opportunities for participating in networked innovation, I find that firms rely on past practices and existing industrial capabilities in choosing a node of specialization. Although firm capabilities undergo significant transformation and augmentation in their application to a new industry, they determine how firms take advantage of the opportunities for upgrading provided by emerging industrial sectors. In selecting an upgrading trajectory, firms can match existing strengths and capabilities with opportunities in emerging industrial sectors, particularly when different niche specializations offer trade-offs between skills required for competitiveness. Even if governments intervene selectively to encourage the development of particular capabilities, firms can pursue alternative trajectories for upgrading in ways not feasible when the full range of innovative capabilities had to be established within the firm. As a consequence, firms frequently utilize government policies in unanticipated ways, repurposing public resources intended to foster traditional R&D capabilities for niche specialization.

Third, in applying their capabilities to new economic sectors, firms tend to rely on resources, institutions, and networks familiar to them from past industrial activities. As firms tend to fall back on existing capabilities within the firm when choosing a node of specialization, they often rely on resources that they have used in the past. Industrial legacies shape which of the many elements of the broader innovation infrastructure are taken up and utilized when firms build innovative capabilities. In some cases, resources that are critical to building specialized innovative skills fall outside the bounds of national innovation systems altogether. In China, for instance, government support for manufacturing activities provided in local economic development zones allowed firms to build the manufacturing infrastructure on which skills in innovative manufacturing could be developed. In Germany, where many firms from machine tools and automotive supply sectors entered renewable energy industries, industry associations, vocational training institutions, and collaborative research programs provided for legacy industries became central to innovation and industrial development even in new economic sectors.

The study of wind and solar sectors suggests that the phenomenon of networked innovation has not diminished the role of government in supporting the creation of innovative capabilities in the domestic economy. However, changes in the organization of innovation in global production networks have created opportunities for firms to pick narrow nodes of specialization, which many have used to incrementally build on existing strengths without establishing the full range of innovative capabilities required for product development. In doing so, firms continue to rely on public support for innovation. Yet for public resources to be advantageous to firms seeking to enter new industries, firms must be able to utilize these resources with the capabilities they already possess. And not all public resources are equally compatible with firms' existing strengths and strategies for competitiveness. By allowing firms to contribute to technological innovation through specialized capabilities, the rise of global production networks has allowed firms to craft distinct paths for participation in networked innovation that renew, rather than abandon, existing industrial capabilities for application in emerging industries.

4. Contributions of the Argument

The comparative analysis of innovation in wind and solar industries in China, Germany, and the United States challenges long-held ideas about the the division of labor in global supply chains, nature of economic development, and the role of the state in industrial upgrading.

Literatures on innovation have broadly agreed that a division of labor exists between firms in advanced economies that innovate and firms in developing economies that manufacture after the innovation process is completed. Such views have been especially pronounced in scholarship on global production networks, which has argued that the development of new digital technologies has increasingly allowed innovation and design activities to be physically separated from manufacturing.[49] Manufacturing activities have indeed shifted rapidly to developing economies in a process of vertical disintegration over the past two decades, allowing China to triple its manufacturing output in the course of a decade without building the kinds of vertically-integrated national champions that were at the heart of industrialization in Japan and Korea.[50] Yet the comparison of innovative capabilities in China, Germany, and the United States indicates that the fragmentation of global production has not in all cases led to a neat division of labor between innovators in advanced economies and manufacturers in developing ones. In emerging industrial sectors, such as the wind and solar industries at the core of this research, production activities are not nearly as modularized and the distinction between

[49] See Baldwin and Clark 2000; Berger 2005, Chapter 4; Camuffo 2004; Fuller et al. 2003; Ge and Fujimoto 2004; Gereffi et al. 2005; Langlois 2002; Steinfeld 2004; Sturgeon 2002a.
[50] IHS Global Insight data sited in Peter Marsh, "China Noses Ahead as Top Goods Producer." *Financial Times*, March 13, 2011. For additional data see UNIDO, *World Manufacturing Production: Statistics for Quarter IV*. Vienna, 2011.

higher value-added design and low-tech manufacturing not nearly as clear as many scholars of modular production networks envision. My findings instead suggest that roduct innovation occurs through collaborative, multidirectional relationships that include innovative manufacturing firms located in developing economies, as firms in different parts of the world have specialized in different types of innovation.

The framework offered in this study also contributes to debates about the nature of industrial upgrading among firms in developing economies. Scholars of economic development have long understood industrial upgrading in developing economies as a process of emulation of capabilities of firms in advanced industrialized economies. Works in this tradition have argued that firms from developing economies can compete in high-technology industries only after acquiring the capabilities of firms at the technological frontier through emulation and reverse engineering. Stressing the presence of market failures in developing economies, this literature has described the need for strategic government intervention to help firms catch up with leaders in product innovation.[51] Absent supportive government policy, scholars have seen firms from developing economies as able to enter high-technology sectors only once products and manufacturing processes are mature and standardized, lowering the skills and capabilities required for manufacturing.[52] Such views describe firms as positioned along a single trajectory of industrial upgrading, with some firms able to upgrade to more advanced activities, and

[51] Scholars have disagreed on the process by which learning and emulation occurs. One perspective has held that once stable macro-economic parameters are set, market forces allow firms to traverse the trajectory of industrial upgrading. See, for instance, De Soto 2000; World Bank 1993. A different perspective has held that government intervention is necessary for firms from developing economies to successfully advance in the global economy. See, among others, Amsden 1989; Amsden 2001; Evans 1995; Gerschenkron 1962; Johnson 1982; Kim 1997; Kohli 2004; Wade 1990.
[52] This view has been central to product cycle theories, which have explained the global division of labor as determined by relative levels of product maturity. See Vernon 1966; Vernon 1979. For recent applications of product cycle theory, see, for instance, Antràs 2003; Reynolds 2010.

some high-technology industries lowering barriers to entry through standardization and commodification of production. Consequently, they presume a division of labor between innovators in advanced economies and firms in developing economies seeking to become innovators through emulation and learning, with few opportunities for collaboration and multi-directional learning between them. By contrast, my findings indicate that Chinese wind and solar energy firms are participating in product innovation by establishing distinct engineering capabilities in scale-up and mass production, without matching the skills and capabilities of firms in Germany and the United States. That is, Chinese firms are not becoming like their peers from advanced economies as they develop innovative capabilities, but are establishing distinct skills and technological capabilities in the process of industrial upgrading.

Lastly, the comparative analysis of innovation in renewable energy sectors in China, Germany, and the United States offers a new view on state-industry relations. Political economists have long debated the role of the state in driving domestic industrial outcomes. On the one hand, scholars have pointed to East Asian developmental states to argue that strategic industrial policy interventions can create thriving, innovative firms even in locations with very little history of industrial activity. Neoclassical economists have instead pointed to market forces and factor accumulation to explain the rise of East Asian firms. The framework offered in this study suggests that industrial policy plays a more nuanced role in driving industrial outcomes in the three economies under investigation. Governments have indeed used sectoral intervention and traditional tools of industrial policy to create innovative firms. However, this research suggests that although such policies create incentives for firms to enter new economic sectors, which firms respond and what innovative capabilities they establish is shaped by industrial legacies and existing industrial practices. Governments are thus likely limited in their ability to initiate processes of radical industrial transformation through sectoral intervention, as industrial activities even in emerging industries are incremental variations on existing strengths.

5. Plan of the Dissertation

This chapter is followed by four empirical chapters, each presenting a distinct argument and empirical data to support the two central goals of this dissertation. Chapter 2 shows that a new global production order has been established in wind and solar industries, one in which firms collaborate on product development in fragmented global supply chains, manufacturing and innovation are often tightly integrated, and many paths allow firms to participate in innovation. Chapters 3-5 each present empirical evidence from one economy to demonstrate how government policies, institutions, and industrial legacies have shaped patterns of upgrading and firm specialization. Chapter 3 explains why firms in Germany—even in new sectors such as wind and solar—have reproduced historical patterns of flexible specialization, customization, and complex small-batch production. Chapter 4 discusses how firms in China have specialized in innovative manufacturing and discusses the linkages between Chinese firms and foreign partners that allow them to participate in global processes of technology development without early-stage R&D capabilities. Chapter 5 presents evidence from the United States, where a strong innovation infrastructure and few manufacturing capabilities have encouraged firms to focus on the invention of new technologies without co-locating scale-up and production activities. Chapter 6 returns to comparative analysis, reflecting on what can be generalized from the cases presented in this dissertation to broader questions of the role of government in industrial upgrading and economic development. An appendix on qualitative data discusses data sources, sampling strategy, and case selection.

Chapter 2: Collaboration and Innovation in Global Wind and Solar Sectors

1. Introduction

In 1999, two decades after the 1970s oil crises first shifted global attention to renewable energy sources as potential alternatives to fossil fuels, global generating capacity for solar power amounted to 192 megawatt (MW), the equivalent of a small coal power plant. In the same year, global wind turbine installations reached 13,600 MW, comparable in capacity to thirteen nuclear reactors.[53] Despite the difference in size between wind and solar installations, both sectors were small when compared to the electric power sector at large: the United States alone had power plants with a generating capacity of more than 647,000 MW in 1999, forty-seven times the size of all of the world's wind and solar power installations combined.[54]

Little more than a decade later, both wind and solar industries had grown exponentially. In 2012, nearly 70,000 MW of solar PV modules were feeding power into global electricity grids, and 238,000 MW of wind turbines were converting wind into electricity.[55] More than a fifth of global electricity was generated from renewable sources.[56] What were niche industries in the 1990s—plagued by quality and reliability issues, small production volumes, and production costs that prevented renewable energy from competing with fossil fuels in the absence of subsidies—had become sizable global sectors. Automation replaced manual assembly for many steps of the production process, wind

---

[53] Data compiled by Earth Policy Institute, 2012. See http://www.earth-policy.org/data_center/C23. Accessed March 8, 2013.
[54] IEA Electricity Information Statistics, 2013.
[55] Earth Policy Institute, 2012. European Photovoltaic Industry Association 2012.
[56] REN21 2012, 108.

turbines and PV modules increased in size and efficiency, production costs dropped almost as rapidly as production volumes increased, and wind turbine and solar PV manufacturers were commercializing new product generations in ever shorter intervals.

In this chapter, I trace the evolution of wind and solar sectors from niche production to their current status as global industries, focussing on firms from China, Germany, and the United States. I show that although technologies for many current wind turbine and solar PV technologies originate in the United States and Europe, the product designs, fast-paced product cycles, and scale economies that have allowed emerging renewable energy sectors to evolve into viable global industries have built on manufacturing strengths residing in Chinese firms. I argue that Chinese renewable energy firms, by contributing engineering capabilities focused on improving product designs for mass productions, were critical enablers of the rapid increase in solar panel and wind turbine manufacturing from the early 2000s onwards. Chinese capabilities in scale-up and mass production, however, have not displaced strengths in small-batch production and advanced R&D that continue to reside in German and American wind and solar firms. Instead, Chinese wind and solar firms have encouraged a new, collaborative mode of product development and commercialization, one in which specialized firms in far-flung geographical locations work together to bring new products to market. More than simply shifting the geography of wind and solar sectors towards East Asia, the entry of Chinese firms fundamentally changed the ways both industries operate.

At the core, these changes suggest that the traditional product cycle no longer fully explains the global developmental patterns of emerging industrial sectors.[57] Much of the

[57] Vernon 1966.

current literature on innovation and global industrial development, particular on emerging economies such as China, continues to accept the notion that in the majority of industries, the most sophisticated products and production technologies are developed by global incumbents from advanced industrial economies. The products are manufactured and sold in the world's wealthiest markets, and only migrate to developing economies once these markets are saturated, production is fully standardized, and cost reduction—not product innovation—allows the product to expand market reach.[58] By contrast, the evidence presented in this chapter indicates that the development and production did not simply relocate to ever-cheaper production locations as product technologies matured, but increasingly relied on global collaboration between firms with highly specialized capabilities, including firms from advanced economies such as Germany and developing locales such as China.

Th chapter proceeds by discussing the evolution of wind and solar industries through three main stages of industrial development: experimentation and prototyping prior to the 1970s oil shocks, small-batch production in a first wave of wind and solar industrialization from the oil crises of the 1970s until the mid-1990s, and maturation and large-scale production since the entry of Chinese wind and solar firms beginning in 2001.

---

[58] Ernst and Naughton 2008b; Ernst and Naughton 2012; Ge and Fujimoto 2004; Thun and Brandt 2010. For a discussion of the literature on product innovation in developing economies, see Nahm and Steinfeld 2012.

2. Experimentation and Demonstration: Wind and Solar Energy Until the Oil Crisis

Neither wind turbines nor solar photovoltaic cells were novel technologies when the 1970s oil shocks moved alternative energy sources into the spotlight. The first solar cells were developed in the early 1950s and wind turbines were first used to generate electricity in the second half of the 19th century. Yet decades of research and development efforts had not established either of the two technologies as a viable option for large-scale electricity generation. Although early experimentation showed that wind turbines and solar cells could in principle become important sources of electricity, high manufacturing cost and reliability issues prevented both technologies from becoming alternatives to fossil fuels. The postwar decades were marked by experimentation and prototyping, the diffusion of early scientific discoveries into research and development laboratories all over the world, and the commercialization of wind and solar energy technologies for niche applications.

In the case of solar photovoltaic technologies (PV), the need for a costly high purity silicon in early technology generations limited the use of solar cells to specialized applications in the space sector. The first solar cell was developed in AT&T's Bell Labs in 1954, the same year that scientists at RCA Laboratories in Princeton, New Jersey, and at the U.S. Air Force Aerospace Research Laboratory in Dayton, Ohio, also published evidence of semiconductor devices capable of converting light into electricity.[59] By 1955, solar cells had reached eight percent conversion efficiency under laboratory conditions, prompting a flood of speculative media reports about possible future uses of 'limitless' solar energy. [60] In reality, however, such applications were far and few. In 1956, Bell Lab scientists calculated that the amount of solar cells needed to power a single-family home would cost more than

[59] Loferski 1993, 67.
[60] Deudney and Flavin 1983, 89.

1.4 million dollars, preventing any use of solar energy in large-scale electricity generation.[61]

The high cost of solar cells was less of a concern in the space sector, where they found an early application as power supply for satellites. President Eisenhower in 1955 announced plans to launch U.S. satellites into space, only to be beat to the finish line by the Soviet Union, which launched two Sputnik satellites in 1957. In a scramble to find a reliable and light-weight power source for the American satellite—batteries were bulky, heavy, and capable of holding only limited amounts of electricity—Bell Lab's solar cells offered a promising solution. The first U.S. satellite partially powered by solar cells, Vanguard 1, was launched to orbit in 1958, and outlasted the Soviet satellites as well as an earlier, battery-powered U.S. satellite by several years (Vanguard's battery failed after 20 days yet the solar cells provided power until 1964).[62] Despite such early success, the market for solar cells remained limited to satellites and other small, highly specialized applications such as solar powered radios and calculators.[63]

The majority of R&D and utilization of solar PV technology during the 1950s and 1960s occurred in the United States. A global survey conducted by the journal *Solar Energy* in 1958 listed 55 research centers conducting solar energy research, 32 of which were in

---

[61] Perlin 1999, 36.

[62] Bailey et al. 2002, 400.

[63] Perlin 1999, 35-40. The main solar firm at the time, Hoffman Electronics, which produced solar cells for the Vanguard satellite based on a license to Bell Lab's original solar technology, had four competitors in the United States: Heliotek, which also supplied solar power devices for space applications and eventually merged with Hoffman when both were acquired by Textron in 1960, as well as RCA, International Rectifier, and Texas Instruments. The latter three, in contrast to Hoffman and Heliotek, were large corporations that had diversified into the solar sector from radio and semiconductor industries. All three left the sector by the end of the 1960s, discouraged by the limited commercial market for solar PV. See Colatat et al. 2009a.

the United States.[64] However, the prominent use of solar cells in the space race spurred similar R&D efforts in other countries. The Soviet Union caught attention of Bell Lab's solar technology early on and sent its own solar-powered satellite into space only weeks after the Vanguard launch.[65] A few years later, in 1962, the German government created the "Gesellschaft für Weltraumforschung" (Association for Space Research), a public-private partnership with the goal of coordinating the development and production activities necessary to build a first German satellite. Building on research conducted in the United States and work flowing out of Germany's own university labs, Siemens and Telefunken entered the solar industry. At its launch in 1969, the first German satellite, AZUR, was powered by Telefunken cells with efficiencies exceeding 10 percent.[66] Even in China a number of research institutes began work in the solar field in the late 1950s. Here, too, solar PV was primarily used to power satellites. In 1973, China's second ever satellite was launched into orbit, powered by China-made solar cells.[67]

By the end of the 1960s, just prior to the first oil shocks of 1973, the annual world market for solar cells remained small, not exceeding 10 Million dollars and roughly 100 kW of capacity.[68] Although production costs of solar panels had been reduced from 600 dollars per watt in the 1950s to 100 dollars per watt in the late 1960s, the sun remained a prohibitively expensive source of energy.[69] Governments, in particular in the United States, remained the main customers for solar PV technology for their space programs well into

---

[64] World Research Activities 1958. Also cited in Warnke 1998, 308. Note that the definition of solar energy was much broader at the time. It included research on solar thermal technologies as well as biofuels such as algae.
[65] Perlin 1999, 49.
[66] Strobl et al. 2009, 8.
[67] Zhao 2004.
[68] Colatat et al. 2009a, 4; Palz 2011, 18.
[69] Deudney and Flavin 1983, 91; Perlin 1999, 53.

the 1970s.[70] Wolfgang Palz, co-organizer of the 1973 UNESCO conference on "The Sun in the Service of Mankind", argued that at the time, "we did not have a great deal more than the know-how about the market of applications for satellites."[71] In 1972, a study convened by the Space Science Board of the National Academies of Sciences found that the "conversion efficiency of solar cells has increased slowly over the last 10 years to a current level of about 11 percent. Of interest is that virtually none of this increase occurred during the past five years. The panel believes that this plateau reflects a cessation of research and funding rather than a fundamental limitation in cell efficiency."[72] Ultimately, the researchers concluded, governments as well as private companies were unwilling to fund the improvement of a technology with such limited applications.

If the 1950s were the modest beginnings of the modern solar PV industry, they were the end of an era in the wind sector. In 1956, Jacobs Electric Wind Company went out of business and Wincharger, a second large American producer of wind turbines, all but ceased production.[73] Jacobs had manufactured some 30,000 2-3 kW wind turbines since its founding in 1927; Wincharger, founded in 1935, had sold more than 400,000 small and affordable wind generators that could charge batteries used lighting and radios.[74] Both companies supplied agricultural communities before electrification, building on a century-long history of small U.S. firms producing wind turbines for rural America. Overall, six million small wind generators are estimated to have operated in the United States between the mid-19th and mid-20th century.[75] Their market rapidly eroded when the Rural

[70] Yang et al. 2003.
[71] Palz 2011, 18.
[72] Rappaport et al. 1972, 10.
[73] Righter 1996, 102.
[74] Righter 1996, chapter 4.
[75] Bereny 1977, 167.

Electrification Administration started subsidizing the construction of electric grids in agricultural communities in 1935; by 1956, nearly all American communities were electrified, leaving only a niche market for wind energy.[76]

While electrification all but stopped the sale of small wind turbines, not just in the United States, but also across the rest of the industrialized world, an international group of wind energy pioneers continued to experiment with larger wind turbines that could feed electricity into the electric grid, rather than replace it. In the United States, these efforts were spearheaded by Palmer Cosslett Putnam, an MIT graduate who in the 1930s started developing a large-scale wind turbine with 1.25 MW of generating capacity, equivalent to some 500 Jacobs wind turbines. The Putnam turbine began operating on a Vermont hilltop in 1941, yet after 1100 operating hours a blade fell off and caused structural damage.[77] As the wartime effort made the acquisition of materials and components increasingly difficult and financial support was limited, the Putnam turbine was not rebuilt, ending America's experimentation with large-scale wind turbines for more than 30 years.[78]

In Germany, research into the feasibility of large-scale wind turbines began during World War II, when the Nazi regime was searching for ways to reduce reliance on energy imports. In 1940, the Austrian engineer Ulrich Hütter was hired to explore the feasibility of wind energy for a subdivision of Gustloff, a state-owned defense conglomerate.[79] Although Hütter was drafted for the war effort in 1943 and Gustloff ceased the exploration of wind energy as the war drew to a close, many of the design principles Hütter established during

---

[76] U.S. Census data in Wolman 2007.

[77] Putnam brought together a team of engineering professors from MIT, Stanford, and Cal Tech to develop the blades, conduct wind tunnel testing, and configure the overall turbine design. Righter 1996, chapter 6. Heymann 1998.

[78] Smith 1973.

[79] Heymann 1995, 260-68.

the war—including blade Aerodynamics and the use of composite materials—found their way into post-war prototypes. After building a few smaller test turbines in the late 1940s, Hütter developed lightweight, advanced 100 kW turbine with the highest Aerodynamic efficiency ever recorded. However, after just three weeks of tests in 1957, the rotor blades were destroyed during a storm. A series of stalled repairs lasted the better part of a decade and the turbine was ultimately dismantled in 1968 due to lack of funds.[80] Hütter had established many of the theoretical principles of modern wind turbines, however, much like Putnam, he was ultimately unable to secure sufficient funding to also master the manufacture.[81]

Despite limited commercial success, both wind turbines and solar energy technologies attracted a global following of researchers and scientists during their early years. Rather than being confined to the United States, where a vast majority of initial utilization occurred, R&D on new energy sources took place through global networks in which researchers working in various locations shared and compared their results. A 1961 U.N. conference on new sources of energy was attended by Marcellus L. Jacobs of Jacobs Electric Wind Turbines, Ulrich Hütter, and Danish wind pioneer Johannes Juul, alongside researchers from France, India, and Japan.[82] A 1973 conference on wind energy organized

---

[80] Heymann 1998, 653.

[81] Even in Denmark, where experiments with large-scale, grid-connected wind turbines were more successful than in Germany and the United States, a wind industry capable of competing with fossil-fuel based power generation was not established in the post-war decades. The electrician Johannes Juul constructed a 15 kW turbine in 1949, followed by a 40 kW turbine in 1952, and, finally, a 200 kW turbine in 1956, which operated reliably until 1967. The gradual increase in turbine size allowed Juul to master the technical problems that had led to the failure of the Putnam turbine and utilized a trial-and-error approach over Hütter's reliance on theory. Despite the reliability of Juuls 200 KW turbine, Danish utilities decided that wind turbines could not economically produce electricity and were unwilling to invest in this new technology. Heymann 1998, 652-52.

[82] Proceedings of the United Nations Conference on New Sources of Energy: Solar Energy, Wind Power, and Geothermal Energy. Rome, 21-31 August 1961.

by NASA and the National Science Foundation drew a similarly international congregation.[83] In the solar sector, the 1973 UNESCO congress on "Sun in the Service of Mankind," chaired by a working party of scientists from France, the United States, India, Chile, Canada, Australia, Niger, Israel, Japan and the USSR, brought together more than 1000 researchers from all over the world.[84] Conference proceedings of such meetings reveal broad similarity between the technologies researched in various locations, suggesting that even in the early years of wind and solar development, R&D results were circulated widely. Much work on solar energy was based on licenses to technologies originally developed by Bell Labs and competing researchers at RCA, other firms poached engineers from these labs and developed their own cell technologies.[85] In the wind sector, turbine designs differed largely in size, number of blades, and upwind or downwind location. Design principles were implemented differently, but the underlying theoretical principles remained largely the same.

Ultimately, neither wind nor solar energy technologies had been established as viable options for large-scale electricity generation at the time of the first oil embargo in 1973. The postwar decades demonstrated that wind turbines and solar panels could be used to generate electricity, not just in remote locations, but also connected to commercial electricity grids. High production cost and reliability issues, however, confined both industries to a niche existence, unable to gain traction among commercial players and increasingly cut off from government support.

[83] Wind Energy Conversion Systems 1973.
[84] Palz 2011, 16-17.
[85] Green 2005, 487-88; Loferski 1993, 71.

3. From Prototyping to Niche Production in Germany and the United States: Wind and Solar Industries from 1975-1995

After low and relatively stable energy prices in the postwar decades, a surge in oil prices during the 1973 oil crisis sparked a worldwide interest in renewable energy as a potential alternative to fossil fuels. The price of crude oil quadrupled between September 1973 and January 1974, and by 1980, after a second oil embargo, oil prices had risen 500 percent above pre-crisis levels.[86] In response, governments in many advanced industrialized nations sharply increased R&D budgets for alternative energy technologies. U.S. government funding for solar PV R&D spiked from $14 million in 1974 to $921 million in 1980 (in 2011 dollars), while the German federal government increased its solar R&D budget from $1.4 million in 1974 to $181 million in 1982. On a smaller scale, government funding for wind turbine technologies also increased, in the U.S. from $3.4 million in 1975 to $168 million in 1981, and in Germany from $7.9 million in 1977 to $53 million just four years later.[87] Figure 1 summarizes renewable energy R&D budgets for Germany and the United States.

The increase in R&D funding was in part intended to address two production-related challenges in establishing wind and solar as viable alternatives to fossil fuels. In the wind sector, the design principles for large-scale, grid-connected wind turbines had been developed in the postwar decades, yet very few turbines reliably produced electricity once they had been manufactured. Spectacular turbine failures such as the lost blade of the early Putnam design remained common throughout the 1980s. In the solar sector, aside from

[86] For a brief account of government responses to the 1973 and 1979 oil shocks, see Ikenberry 1986.
[87] IEA Energy Technology R&D Statistics, 2013.

unsolved problems of rapid cell degradation under sun exposure, the primary concern was cost.[88] How to produce at large enough scale to reduce cost, and how to scale demand to reach large production volumes?

Solar Photovoltaic Industry Development, 1975-1995

Immediately following the 1973 oil embargo, American government officials, industry representatives, and scientists developed a ten-year technology roadmap for solar PV at a joint meeting in Cherry Hill, New Jersey. The group requested $295 million for solar PV research and predicted that the cost of solar electricity would drop rapidly with increasing production volumes of solar cells, from $100/watt at 10kW of annual production in 1973 to $0.10/watt once annual manufacturing reached fifty million kW.[89]

The U.S. government largely followed the group's recommendations. To administer the increased funds available for solar PV research, the U.S. government created the U.S. Solar Energy Research Institute (SERI) within the newly established Energy Research and Development Administration (ERDA) in 1974. The new organization had the goal of coordinating a path to energy independence and centralized all governmental research programs on alternative energy, including wind, geothermal, nuclear, and solar PV. ERDA was dismantled in 1977 when Congress approved the creation of a Department of Energy

---

[88] Brandhorst 1984.

[89] Annual manufacturing levels of 50 million kW (50 GW) have not been reached at the time of writing, but global manufacturing volumes are approaching this figure. In 2011, nearly 30 GW of solar modules were installed. Considering inflation, prices are currently roughly twice what was predicted in 1973 for 50 GW annual manufacturing volume. See Earth Policy Institute, 2012. http://www.earth-policy.org/data_center/C23. Accessed March 8, 2013. National Research Council 2012, 361; Palz 2011, 16.

(DOE) in its place, and the SERI eventually became NREL, the National Renewable Energy Laboratory.[90]

In addition to these institutional changes, the government enacted a series of policies intended to increase solar manufacturing volume and decrease manufacturing cost. The Carter administration formally announced the goal of meeting twenty percent of U.S. energy demand from solar by the year 2000 and, through the Public Utilities Regulatory Policies Act (PURPA), required utilities to purchase electricity from renewable sources. In 1978, Congress passed the National Energy Act, which included tax credits for the use of solar panels and other renewable energy sources. A year later, President Carter announced a national solar energy strategy, which included $1 billion federal investment through credits, loans, grants, the establishment of a national solar bank, and orders for government agencies and the military to pursue solar energy whenever it could save fossil fuels. [91] Seeking to emulate the structure of the fossil-fuel based electricity sector, in which large, centralized power plants generate electricity, the federal government launched a 'block buy' program, through which 12,000 kW of solar generating capacity were bought between 1977 and 1987 and installed as centralized power stations.[92]

These programs supported the creation of a terrestrial solar industry in the United States and propelled the U.S. to a leading position in solar manufacturing until the mid-1990s.[93] For small solar firms, some of which were founded prior to the 1970s oil shocks and were marketing products based on Bell Lab's original technology, government policies created the necessary demand to stay in business (e.g. Solar Power Corporation).

[90] Loferski 1993, 74; Strum and Strum 1983, 134,42-3.
[91] National Research Council 2012, 361; Strum and Strum 1983, 145-47. Sissine 2006, 4.
[92] Palz 2011, 28-9.
[93] Moore 1981.

Other firms were now beginning to commercialize recent discoveries in solar photovoltaic research (e.g. Solar International). In 1977, 13 solar firms were operating in the United States, jointly manufacturing 0.4 MW (400 kW) in solar modules. By 1983, this number had risen to 8.2 MW, largely due to California's support of the solar industry after the Reagan administration had withdrawn the majority of federal funds starting in 1981.[94]

The government investments in the solar industry created interest by large multinational oil companies, who began using solar technology to power offshore drilling operations and were betting on large future markets for solar energy.[95] By 1980, nine of the ten largest U.S. solar firms had been purchased by large, multinational corporations, six of which were oil firms. Standard Oil took a stake in Solarex of Maryland; ARCO purchased Solar Technology of California, Northrup Solar of Texas, and Energy Conversion Devices of Michigan; Exxon bought Solar Power Corp. of Massachusetts; Mobil invested in Mobil-Tyco, also based in Massachusetts; and Shell Oil bought Solar Energy Systems of Delaware. Jointly, oil firms now controlled the vast majority of the world's solar manufacturing capacity, prompting congressional hearings on the effect of large oil's investments on the innovative capability of the American solar sector.[96]

Despite the growing size of the American solar sector and the financial prowess of its big oil backers, problems persisted. World production of solar panels doubled over the course of the 1980s, yet American manufacturing volumes stagnated as the Reagan administration shifted resources to traditional R&D programs over support for deployment and commercialization. Government laboratories continued to improve conversion

[94] Bereny 1977, 137. Taylor 2008. Data compiled by Earth Policy Institute. http://www.earth-policy.org/data_center/C23
[95] Perlin 1999, chapter 7.
[96] U.S. Senate 1980.

efficiencies for cell technologies, but solar firms struggled with manufacturing. Cells installed in California's largest solar power station, for instance, delivered far less electricity than promised due to premature cell degradation and problems with the tracking system intended to position the solar panels in the direction of the sun.[97] Cracked cells, corrosion, leaks in the cell casing, and short circuits were common once solar panels were installed in the field. The U.S. Department of Energy subsequently launched a program for failure reporting to provide feedback to manufacturers that could be used for design and manufacturing improvements.[98]

Although the cost of solar electricity continuously declined and consecutive generations of solar panels became more reliable, solar power was still far from being competitive with traditional sources of electricity by the late 1980s. Between 1987 and 1995, most American oil companies divested of their solar division.[99] While U.S. research institutes remained leading on the technology side—spearheading, for instance, the development of new thin film solar cells which reduced production cost by depositing photovoltaic material on substrates much cheaper than conventional silicon—America's share of global solar PV production continued to decline, from 84 percent in 1980 to 43 percent in 1995.[100] As Figure 2 illustrates, Asian and European nations began to take the lead.

---

[97] Palz 2011, 28-9.

[98] Dumas and Shumka 1982.

[99] Grant and Cibin 1996, 291-94; Pinkse and van den Buuse 2012, 18; West 2013, 8.

[100] During the 1980s, the most advanced research on thin film technologies was conducted by SERI as well as the University of Delaware, Southern Methodist University, and Colorado State (in addition to Stuttgart University in Germany). ARCO solar and Photon were important corporate contributors to this technology before commercialization in the 1990s. See Zweibel et al. 1990. For data on U.S. share of global PV production, see Le 2012; U.S. Department of Commerce 1994, 18-6.

In Germany, the federal government also increased its funding for solar PV research in the wake of the oil crises, albeit not nearly to the same levels as in the United States. The first targeted energy research program (*Energieforschung und Energietechnologien*), running from 1977-1980, included a sub-program aimed at developing "Technologies to Harness Solar Energy." The program was renewed from 1981-1989 and funding was increased by an additional 350 million German mark after Germany's exposure to radiation from the Chernobyl nuclear disaster lent the deployment of alternative energy technologies new urgency. The German government programs were specifically targeted at lowering production cost of solar panels, both for thin film technologies and for traditional crystalline modules. Funds were distributed to universities, research institutes such as Fraunhofer, and large industrial enterprises.[101]

In contrast to the United States, however, no attempt was made to increase domestic demand for solar PV aside from a small demonstration program implemented by the Fraunhofer Institute for Solar Energy Technology (ISET) in 1985. As a consequence, domestic markets remained small. In 1990, 1.5 MW of solar panels had been installed, roughly ten precent of the installations in the United States at the time.[102] While American law-makers worried about the impact of multinational oil companies on the competitiveness of solar startups, the lack of domestic demand prevented such startups in Germany all together. Outside of academic laboratories and research institutes, only large, diversified companies were able to fund solar PV R&D, and little of it was commercialized.

---

[101] Bruns et al. 2011, 171-2; Bundeminister für Forschung und Technologie der Bundesrepublik Deutschland 1977. Immediately after the 1973 oil shock, a first energy research program was launched to bundle all non-nuclear energy research in one central government program, however, this program did not include specific funds for solar energy technologies.
[102] Bruns et al. 2011, 172. Earth Policy Institute, 2013.

Siemens had begun the development of thin film technology in 1965 and delivered panels for installation in U.S. block buy programs in California in 1983, but its panels performed poorly.[103] The sole other actors in the German solar industry during the 1980s were Telefunken, which continued to receive funds from the Federal Research Ministry to continue its work on crystalline cell technologies first begun during the 1960s space program,[104] Wacker, a German chemical multinational funded to develop lower-cost silicon, and NUKEM, a subsidiary of the German utility RWE, which attempted to develop utility-scale thin film technologies.[105]

Despite a number of breakthroughs in reducing production cost of solar cells— for instance, Wacker in 1978 developed the first polysilicon cell which could be manufactured at a fraction of the cost of traditional single-crystal silicon technology—Wacker sold its solar cell dvision to Bayer chemical. Siemens retired its solar technology and instead bought the American firm ARCO from Shell in 1990.[106] The German solar companies realized that they were unable to compete solely through research on production technology without the major advances in cell efficiency that research institutes in the United States and Japan were celebrating at the time. Yet, even with a focus on production and manufacturing technology, the solar panels produced by German firms performed poorly. A monitoring program coordinated by the International Energy Agency showed that German cells manufactured prior to 1991 displayed a wide spread in performance,

---

[103] Palz 2011, 28-9. Maycock 1991.
[104] Telefunken merged with AEG in 1967 and was now called AEG-Telefunken.
[105] Bruns et al. 2011, 165-67.
[106] Bruns et al. 2011, 167,73 .

performance degradation over time, and frequent inverter failures, making them unfit for large-scale commercial application.[107]

The commercial failure of solar technologies in Germany during 1970s and 1980s suggests that firms were unable to manage the necessary interconnection between chemical processes, semiconductor manufacturing principles, glass and plastics technology, and power electronics required to replicate laboratory results at commercial scale. The lack of sufficient demand was problematic, but even where demand existed as a result of government demonstration programs and subsidies for solar electricity, firms were unable to meet it with products of sufficient quality. As a consequence, the industry—not just in Germany but also in the United States—was in constant flux. Large companies purchased startups and university spinoffs, but later divested, or received R&D funding for technologies that they never commercialized. Small firms with innovative technologies were unable to secure sufficient funding to bring their products to market, faltering when their initial funding ran out.

Although the global center of gravity in the solar industry in terms of R&D efforts and commercialization projects remained in the United States, research was conducted by a range of global actors. The National Renewable Energy Lab in Golden, Colorado, continued to set efficiency records throughout the 1980s, as did a research team around Martin Green at the University of New South Wales in Australia. Stanford, North Carolina State University, Georgia Tech, École Polytechnique Féderale of Lausanne, and the University of Stuttgart were active in the solar field. Commercial actors included Sharp in Japan, Varian Semiconductor of Massachusetts, ARCO, Solarex, and Boeing, among

[107] BINE Projektinfo 03/03. http://www.ecotec-energiesparhaus.de/Daten/BINE-Performance-von-Photovoltaik-Anlagen.pdf. Accessed March 23, 2013.

others.[108] Chinese firms and Chinese research institutes had not yet entered the global solar industry. Conference proceedings from the 1970s and 1980s document an active international community of solar researchers, in which scientific discoveries were disseminated widely and collaboration between industry and academia often took place across national borders.[109]

With the exception of purchasing materials from chemical firms specialized in the production of silicon materials, individual solar firms retained almost all the necessary steps to commercialize new technologies in house. Research and development efforts, the construction of production equipment, the manufacturing of silicon wafers and cells, and, finally, module assembly, were generally conducted by one and the same firm, absent an international division of labor or a network of specialized supplier firms. Automated manufacturing, such is the norm in the solar industry today, was virtually non-existent and the majority of production steps were performed manually or on equipment borrowed from related industries that had been repurposed in house. As a consequence, production volumes remained small and cell performance varied across firms and production batches. Niche production characterized the solar sector until the mid-1990s.

Wind Energy Industry Development, 1975-1995

The wind energy industry, much like the solar sector, benefitted from the renewed attention to alternative energy sources in the wake of the 1970s oil shocks. By the end of

---

108 See NREL compilation of research cell efficiencies over time. http://www.nrel.gov/ncpv/images/efficiency_chart.jpg. Accessed March 23.

109 IEEE, for instance, has held an annual international photovoltaic conference since 1961, with global attendance. See http://www.ieee-pvsc.org/PVSC39/pages/about-history.php. Accessed March 23, 2013. For a history of research collaboration in the solar sector, see Palz 2011.

1973, the U.S. federal government instituted a federal wind power research program, effectively picking up where R&D efforts had stopped after the failure of the Putnam turbine in 1941. Coordinated by the National Space Administration's (NASA) Lewis Research Center and the Solar Energy Research Institute (SERI), the wind power research program was allocated some $380 million between 1973 and 1988.[110] In contrast to research approaches favored in Denmark, where the government supported small-scale experimentation, SERI urged the development of large, multi-Megawatt turbine designs that could be operated by electric power utilities much like centralized power plants. DOE officials argued that only large-scale turbines with blade diameters of several hundred feet could produce electricity at competitive prices.

To set the trajectory for government support of wind turbine development, Louis Divone, the head of the Wind Energy Technology Division at DOE, conducted a workshop with Ulrich Hütter, the engineer behind the German postwar turbines, Palmer Putnam, who had designed the Putnam turbine in Vermont in the 1940s, and William Heronemous, an engineering professor at the University of Massachusetts, Amherst, who envisioned the creation of wind parks in the Central Plains capable of producing as much electricity as several hundred nuclear power plants.[111] The U.S. government approach to the creation of a wind energy sector was thus deeply influenced by past ideas about applying aerospace engineering principles to the design of large-scale turbines and eighty percent of funds in the wind power research program were applied to the development of 1-3 MW turbines in the tradition of Putnam and Hütter's designs.[112] SERI and the Lewis Research Center

[110] Righter 1996, 158.
[111] Righter 1996, 155-6; Vestergaard et al. 2004.
[112] Hütter held a series of consulting contracts for the NASA Lewis research center in the decade to follow. Heymann 1995, 349.

centrally coordinated the research effort, but R&D and demonstration projects were implemented by U.S. aerospace firms, including Alcoa Corporation, Boeing, General Electric, Grumman Aerospace, Hamilton Standard, Lockheed, McDonnell Douglas, and Westinghouse. U.S. government funds covered the majority of R&D development cost.[113]

A first, 100kW turbine, called MOD-0 (for modification), was designed by NASA engineers and Westinghouse in 1974 and installed in Ohio. It failed after 450 hours. A second turbine design, MOD-0A, with 200kW capacity, fared slightly better. Westinghouse installed four prototypes in Hawaii, New Mexico, Puerto Rico, and Rhode Island in 1979.[114] General Electric built a 2MW MOD-1 turbine in cooperation with Hamilton Standard, who designed the blades, and installed it in North Carolina in 1979. After a year, a drive train broke, and the turbine had to be dismantled. In parallel, Boeing developed a MOD-2 turbine with 2.5MW generating capacity, which featured a lighter turbine design and a more flexible tower to avoid some of the structural damage of its predecessors. Three turbines were installed in 1980 and 1981, but after just 11 days, the first generator failed. The turbines frequently underwent lengthy (and costly) repairs. Ultimately, over the course of seven years, the turbines only operated for a total of 680 hours.[115] General Electric and Boeing began the development of a last set of turbine designs in 1980, MOD-5A and

---

[113] Gipe 1995, 77; Righter 1996, 158. For an optimistic account of the planned research program by Lewis Research Center engineers, see Thomas and Donovan 1978. The approach to funding the development of large-scale wind turbines was not without its critics. Already in March 1977, Monte Carfield Jr., the Director of the Government Accountability Office, wrote in a letter to Robert W. Fri, the Acting Administrator of the ERDA: "To maximize the effectiveness of important research and development programs, such as the Wind Energy Program, it is essential that ERDA systematically assess the potential and the advantages and disadvantages of various program mixes before allocating resources. The decision to emphasize large wind energy systems was not based on that kind of analysis. Although Wind Energy Program officials still believe this emphasis to be correct, it has not yet been confirmed by factual data or actual studies." See Carfield 1977.

[114] Righter 1996, 159.

[115] For an overview of the MOD-2 program, see Linscott et al. 1981.

MOD-5B, with a planned generating capacity of over 7MW (for comparison, contemporary turbine sizes are between 1.5-5MW). General Electric closed its wind turbine division in 1983 and MOD-5A was never realized. Boeing, meanwhile, was asked to modify its design and installed a 3.2MW turbine in Hawaii in 1988. The turbine operated relatively smoothly until 1994, yet was far from economical. In spite of earlier plans, a MOD-6 series of turbines was never realized, as most of the large aerospace firms decided to cease wind turbine research and federal funds dried up in the late 1980s.[116]

Overall, the MOD programs failed to yield a single commercially viable turbine design. Design flaws, manufacturing problems, and structural failures had cut short operating hours of most of the turbines; even when turbines did operate reliably, their efficiency was far below expectations. The most successful MOD turbine, MOD-5B, only operated 46 percent of the time.[117]

Parallel to the wind energy technology research program, the U.S. federal government and the state of California began subsidizing the installation of wind turbines for electricity generation. The wind sector, just like solar, benefitted from the 1978 Public Utilities Regulatory Policies Act (PURPA), which required utilities to purchase energy from renewable sources at a price that reflected the utilities avoided cost, rather than the market electricity rate.[118] A ten percent tax credit for capital investments in the manufacturing sector had been passed in 1970 and a supplementary tax credit of 15 percent was introduced during the second oil crisis in 1979 for energy-related investments made until

---

[116] Heymann 1995, 349-54. Musgrove 2010, 89-100. For a thorough assessment of large turbine failures in the United States, see Gipe 1995, chapter 4; Righter 1996, chapter 8.
[117] Ackermann and Söder 2002.
[118] PURPA was passed by the federal government but implementation (i.e. the definition of avoided cost) was left to the states, so outcomes varied widely. See Redlinger et al. 1988, 182-5.

1985. The California legislature passed an additional 25 percent tax credit for wind energy in 1978, bringing tax credits to 50 percent of investment.[119]

The government subsidies created what is commonly called the "California Wind Boom." Between 1981 an 1986, 12,000 wind turbines with a generating capacity of one gigawatt were installed in California, roughly equal in capacity to a nuclear power plant.[120] Since the federal wind energy technology research program had not yielded any turbine designs that could be manufactured at scale, the California market was flooded with smaller turbines from U.S. startups as well as imported turbines from Denmark, which featured far greater reliability than American models. According to Robert Lynette, a wind energy consultant and former Boeing engineer involved in the MOD-2 program, "Companies sprang up over night to take advantage of the financial incentives. Most of these companies were poorly managed and under financed. They did not have products that were ready for mass deployment, but the market from 1981 to 1985 was so strong that almost any turbine could be sold."[121]

Turbine sizes increased quickly, from 50 kW generating capacity in 1981, to 100, 200, and ultimately 500 kW by the mid-1980s. American-made turbines—manufactured by U.S. Windpower (an MIT spinoff), Flowind, ESI, and Fayette—performed poorly, despite some federal government support for small turbine manufacturers through a wind turbine testing center in Rocky Flats, Colorado.[122] Designed relatively quickly and by firms without much engineering or manufacturing experience, their light-weight structures faltered

---

[119] Musgrove 2010, 112-3.
[120] Gipe 1995, 35; Musgrove 2010, 115.
[121] Lynette 1988, 328. The tax credit system rewarded installations, not performance, further adding to the problem of premature technology deployment.
[122] Righter 1996, 161.

rapidly once exposed to weather conditions. In 1985, out of 8,460 American-made wind turbines only 4,400 were operational.[123] Eight percent of turbines were total losses, meaning they had experienced technical failures that were too costly to repair, and sixty percent of turbines had experienced failures that could be repaired only through costly retrofits.[124] Imported turbines from Danish firms, which had a much longer tradition of manufacturing small wind turbines and which had increased turbine capacity incrementally, were more reliable. In 1985, 1932 out of 1976 Danish turbines in California were operational. The expiration of federal and state tax credits in 1985 and 1986 sent a wave of bankruptcies through the American and Danish wind sectors; of American firms, only U.S. Windpower was able to build on its experience and continue operations into the 1990s.[125]

In Germany, much like in the United States, the government initially focused its research funding on the development of large-scale wind turbines. A first research study on the feasibility of grid-connected, utility-operated wind energy turbines was commissioned by the Federal Ministry for Research and Technology in 1974. The study recommended the development of a wind turbine with one megawatt of generating capacity, on the basis of which a three megawatt and six megawatt turbine could be designed in successive steps.[126] Research and development funding, administered almost exclusively by the Federal Ministry for Research and Technology, reflected this focus on multi-megawatt wind turbines. Between 1975 and 1988, more than seventy percent of

---

[123] Heymann 1995, 400.
[124] Lynette 1988, 329.
[125] For a comparison of wind energy technology trajectories in Denmark and the United States, see Heymann 1998.
[126] Hoppe-Kilpper 2003, 29.

R&D funds were allocated for medium and large wind turbines (generating capacity of 200 kW or above), and less than twenty percent of research funds supported the improvement of small turbine designs (table 4).[127]

In 1977, the Federal Ministry commissioned the development of a three megawatt turbine, a project carried out by the German truck and machine manufacturer MAN and several utility companies. It took six years from initial conception until a prototype of the turbine, named GROWIAN, was installed in Northern Germany in 1983. The project consumed more than 90 million German marks, a significant portion of the total 218 million marks of federal funding allocated to wind energy research between 1975 and 1988.[128] In the end, the focus on large-scale wind turbines in Germany was as misguided as the U.S. wind energy technology program.[129] Scientific principles could not easily be translated into production and the turbine encountered a number of technical difficulties before it was dismantled in 1987. All in all, GROWIAN only operated for 320 hours over the course of 3 years, making GROWIAN one of the most prominent failures of German science and technology policy to this day.[130] Other large turbine projects funded by the federal government at the time experienced similar failures—plans for a five megawatt turbine were never realized, for instance, as the 400kW prototype suffered a fatal technical

---

[127] Calculations based on Federal Ministry of Research and Technology data cited in Hoppe-Kilpper 2003, 75-6. See also Hoppe-Kilpper 2004, chapter 3.

[128] Ohlhorst 2009, 97.

[129] In Germany, too, Hütter, now working at the University of Stuttgart, played a consulting role in federal research programs, explaining the focus on large turbines. Ohlhorst 2009, 95-7.

[130] Ohlhorst 2009, 96. For a critical assessment of the GROWIAN project [in German], see Pulczynski 1991. See also Hauschildt and Pulczynski 1995; Hauschildt and Pulczynski 1996; Heymann 1998; Heymann 1999; Nielsen and Heymann 2012.

problems—and the industrial partners that had participated in these projects (MAN, Dornier, MBB, among others) left the wind sector in the course of the 1980s.[131]

Unlike in the United States, where multiple tax credits caused rapidly increasing demand for wind turbines between 1981-1986, the German government did not pass any policies to create a domestic wind energy market until 1989, when a number of demonstration projects created the first grid-connected wind parks. In the shadow of the unsuccessful GROWIAN project, however, members of a growing environmental movement began to experiment with small turbines, often intended to produce electricity for private consumption.[132] Out of a total of 500 turbines operating in Germany in 1983, some 60 percent were do-it-yourself constructions.[133] The remaining turbines, bought and installed by farmers and environmental cooperatives, were produced by small German and Danish turbine manufacturers, often with backgrounds in constructing or maintaining agricultural machines. Three of these firms—Enercon, Husumer Schiffswerft, and Tacke—were eventually able to secure government funding for the development of 80-300kW turbines in 1985 and 1986, mimicking the Danish approach to technology development of gradually increasing turbine size.[134]

By 1992, after the Federal Ministry for Research and Technology had completed a first demonstration program to install 100MW of wind turbines and a 250MW demonstration project was underway, 964 turbines had been installed.[135] The

---

[131] Schlegel 2005, 26. Some local utilities bought wind-generated electricity, but rates varied widely. For most owners of wind turbines the goal was to avoid buying electricity from the grid, as the avoided cost were much greater than the rates paid by utilities. Hoppe-Kilpper 2004, 115.
[132] The impact of the environmental movement on energy policy is described in Hager 1995.
[133] Ohlhorst 2009, 99.
[134] Hoppe-Kilpper 2004, 35.
[135] Keuper et al. 1992, 21.

demonstration projects guaranteed a minimum of demand for wind turbines in Germany, turning what had been a disparate group of environmentalists into a small but growing industry. The beginnings were modest, however: the first German wind fair, bringing together 700 exhibitors from 35 countries in 1989, was held in an unheated cattle salesroom in Husum.[136]

Among the 12 firms with the most turbine installations in 1992, seven were from Germany (Enercon, Husumer Schiffsweft, Tacke, MAN, Krogmann, Südwind, and Ventis), four from Denmark (Vestas, AN Bonus, Nordtank, and Micon), and one from the Netherlands (Lagervey).[137] With the exception of MAN, these firms had in common their small size, experimental approach, and roots in the agricultural machinery sector. Although the wind industry in Germany was on the upswing, standardized production equipment had not been developed and no supplier industry existed. Components were bought from related industrial sectors and repurposed for their application in wind turbines as best as possible. Since government R&D projects on large-scale turbines in Germany and the United States had not yielded any results, firms were relying on an entrepreneurial do-it-yourself approach in applying engineering principles to turbines of increasing size. Sönke Siegfriedsen, head of the German wind turbine engineering firm Aerodyn, describes testing new turbines absent standardized measurement equipment by placing increasing numbers of sandbags on the blades, worried that new blade designs would be unable to withstand the required force.[138] In an interview, the head engineer for German turbine manufacturer explained that he "didn't like coming to the office on Mondays during [the early 1990s],

[136] Siegfriedsen 2008, 60.
[137] Keuper et al. 1992, 21; Schlegel 2005, 33.
[138] Siegfriedsen 2008, 58.

because there would always be a message about a failed turbine somewhere. After every storm you would get a call about a failed turbine. We learned a lot from these problems and it really taught us how to properly adjust specifications and improve turbine designs."[139]

Ultimately, the German wind energy sector, much like its American counterpart, remained in a state of prototyping, small-scale production, and technology experimentation until the mid-1990s. Kept alive by government demonstration programs rather than large-scale market demand, firms were gradually improving their technology, but their products remained unfit (and uncompetitive) for large-scale, electricity generation. This situation was representative of the wind sector in general. Even in Denmark, where firms like Vestas had been able to gather experience during the California wind boom, mass production had not yet been achieved.[140]

4. Wind and Solar Industries Since 1995: From Niche Production to Global Industries.

After more than 40 years during which much of the activity in global renewable energy sectors was located in the United States—the U.S. was the site of early, large-scale deployment of wind turbines in California, the U.S. space program was first major application of solar PV technology, and U.S. research and development funding far exceeded that of other advanced industrialized nations—the center of gravity began to shift starting in the mid-1990s, first to Germany and then to China. More than simply relocating due to a changing geography of demand for renewable energy products, wind and solar industries over the past twenty years witnessed a globalization of production and innovation that transformed how both sectors operate. The development of large,

[139] Author interview, CEO of German engineering firm, May 20, 2011.
[140] For a full discussion of the situation in Denmark, see Heymann 1998.

diversified supply chains in both wind and solar sectors permitted firms to specialize in specific production steps, while in previous decades the absence of supplier firms had required vertical integration. The development of these supply chains occurred almost simultaneously in various locations around the globe—including China—and was not in all cases directly linked to local demand. Rather than migrating to successive production locations as the industry matured, the development of wind and solar sectors over the past two decades was facilitated by collaboration and multi-directional learning between firms in different economies.

Wind Energy Industry Development, 1995-2012

The transformation of wind and solar sectors into global renewable energy industries began in Germany in 1991. In addition to two wind energy demonstration programs, the German federal government in 1990 passed the so-called feed-in-law (*Stromeinspeisegesetz*), which, starting in 1991, required utilities to connect sources of renewable energy to the grid and to buy electricity from renewable sources at increased rates. [141] For both wind and solar energy, tariffs were set at 90 percent of end user electric rates.[142] The feed-in-law represented a critical transition from ad hoc, temporary support for renewable energy through demonstration programs to long-term demand stimulation through the regulatory framework. As tariffs for electricity from renewable sources set by the feed-in-law were too low to allow for the economical deployment of solar energy

[141] Deutscher Bundestag 1990b. For a full discussion of the political circumstances that gave rise to Germany's regulatory framework for renewable energy, see chapter 4.
[142] For an overview of subsidy rates between 1991-1998, see Edinger 1999, 75.

technologies, this transition primarily affected the wind sector, where installed capacity grew from 20 MW in 1989 to 1,100 MW in 1995.[143]

Initially, this increase in market demand mainly benefitted small wind turbine companies such as Tacke and Enercon, which had gained experience from demonstration programs during the 1980s and were now able to sell larger quantities of the small-capacity turbines they had developed during the previous decade. However, the stability and consistency of market development also caught the attention of firms in other industrial sectors. The broad-based parliamentary coalition that had passed the feed-in-law and the relative absence of public opposition to the legislation suggested that government support for wind energy markets would continue relatively uncontested.[144] Firms with backgrounds in traditional industrial sectors saw the growing wind industry as a market opportunity, reasoning that their manufacturing experience was both needed and gave them an advantage over the experimental approach to manufacturing that prevailed in wind turbine startups. Hence, over the course of the 1990s, a wave of firms from other industries entered wind turbine supply chains, diversifying their existing product portfolio by innovating for the wind energy sector and bringing much-needed production experience to the industry.

Entrants to the wind sector came from a variety of industries and included manufacturers of control systems and software, producers of manufacturing equipment and machine tools, as well as steel and composite materials firms. Many of the new supplier

---

[143] Lauber and Mez 2004, 602.

[144] Utility companies did not start formally challenging the law in the court system until 1996, when number of wind turbines in Germany started to increase rapidly. A well-organized lobby on behalf of the wind industry, which now included industry associations from 'traditional' sectors such as the machine tools industry, was able to prevent any changes to the feed-in-law, however. See Jacobsson and Lauber 2005, 135-36; Laird and Stefes 2009.

firms possessed technical expertise and production experience that could be applied to the manufacturing of wind turbine components. For instance, a firm that for decades had supplied gearboxes for large tunnel-drilling machines in the mining sector was seeking to reduce its exposure to a declining mining industry in Germany. The firm decided to develop the capabilities to produce gearboxes for wind turbines in 1992, and, after four years of R&D, was ready to enter mass production in 1996.[145] A generator supplier for trains and industrial motors decided to diversify its product portfolio, and in 1998 began the development of a generator for the wind market.[146] Similarly, a specialty foundry was able to apply its casting technology to the production of wind turbine gearboxes.

The majority of component suppliers for wind turbines operating in Germany first entered the market during those years. Balluff, a manufacturer of sensor technology, developed its first applications for wind turbines; Bosch Rexroth and Eickhoff began supplying gearboxes for wind turbines; Hansa-Flex entered the wind sector as a supplier of hydraulics technology; Liebherr began manufacturing bearings, generators, and drivetrains for wind turbines; SIAG, a steel firm, started the production of wind turbine towers; and VEM Sachsenwerke, an electric motor producer, began suppling generators to turbine manufacturers.[147] To network the growing number of its members in the wind industry, the German Engineering Federation (VDMA)—the industry association for machine tools and related industries—founded a chapter (*Interessengemeinschaft*) for the wind industry in 1993.[148] A German wind industry industry association (*Bundesverband Windenergie*)

---

[145] Author interview, plant manager of German gearbox manufacturer, May 16, 2011.
[146] Author interview, plant manager of German generator manufacturer, May 17, 2011.
[147] For a list of component suppliers, see VDMA Powersystems and Bundesverband Windenergie 2009.
[148] Ohlhorst 2009, 145.

was founded in 1996, representing 3,300 turbine manufacturers, suppliers, operators of wind turbines, and firms from related service industries. By 2001, its membership had tripled to 10,000.[149]

The growing wind industry supply chain permitted firms to restructure their manufacturing operations and to focus on core strengths. With the exception of Enercon, which until this day manufactures all of its components in-house in order to protect proprietary technologies, wind turbine manufacturers began to rely on the expertise of outside firms for the production and design of components such as gearboxes, generators, blades, towers, and control software. Turbine design and component specification remained with the turbine manufacturer.

The rich production experience that supply firms had gathered in other industries contrasted sharply with the relatively young, small, and inexperienced wind turbine manufacturers, which had focused largely on design and prototyping for demonstration projects. The introduction of new production technologies by supplier firms—including lean production practices borrowed from the automotive sector—reduced cost, permitted increased production scale, and enabled the fabrication of ever larger turbine designs without the technical failures that had plagued large-scale turbines in previous decades. In interviews, suppliers—particularly in the generator and gearbox sector—frequently pointed to lean production concepts such as just-in-time-production, continuous improvement (Kaizen), six sigma, and the Toyota production model in explaining their contribution to the wind energy sector.[150]

---

149 Bundesverband Windenergie 2012.

150 Author interviews: plant manager of German gearbox manufacturer, May 16, 2011; plant manager of German generator manufacturer, May 17, 2011; head of European operations of global turbine manufacturer, May 19, 2011.

Over the course of the 1980s, the majority of debates within the wind industry on wind turbine design had been settled and almost all manufacturers had converted to the Danish model of building turbines with three blades that were positioned upwind and could be rotated along their own axis to adjust for variable wind speeds.[151] Aside from improving Aerodynamics, the main remaining challenge was scale, as increasing the size of turbines entailed exponentially larger loads and stresses on components, many of which could not be simulated well on computers. By combining results of ongoing R&D efforts with new production methods and technical expertise contributed by third party suppliers, turbine manufacturers were able to increase the average rotor diameter from 30 meters to 70 meters over the course of the 1990s, enlarging the area swept by the rotor blades by a factor of five, and improving average generating capacity from 250 kW to 1500 kW in the year 2000 (see Table 1).[152]

Although the development of a wind turbine supply chain was initially prompted by Germany's regulatory framework for the creation of wind energy markets, it was by no means a purely German phenomenon. Rather, German suppliers became a resource for an expanding global network of wind turbine manufacturers, increasingly seeking collaboration with foreign partners and competing with supply firms elsewhere. Aside from Denmark, which had long played a pioneering role in wind energy development, and Spain, which began subsidizing the large-scale installation of wind turbines in the late 1990s, the most important foreign partners of German supply firms where from the United States and China.

---

[151] Musgrove 2010, chapter 6.

[152] Data from Bundesverband Windenergie. See http://www.wind-energie.de/infocenter/technik. (Accessed March 25, 2013.)

In October 1997, Enron Corporation, an American electricity and natural gas company, purchased Tacke Windtechnik of Salzbergen. Enron had previously bought Zond, one of the few American wind turbine manufacturers remaining from the California wind boom in the 1980s, but experienced technical problems with the Zond turbine technology. The purchase of Tacke, which kept operating under its own name until GE took over Enron's wind business in the wake of Enron's accounting fraud scandal in 2001, gave Enron access to Tacke's turbine technology and supplier network. Enron retired the Zond turbine technology and Tacke's 1.5 MW turbine became Enron's workhorse wind energy product.[153] The U.S. wind market had stagnated since the end of the California wind boom until the Texas legislature passed a renewable portfolio standard in 1999, which required the state's electric utilities to install 2,000 MW of wind turbines in addition to preserving existing wind installations.[154] Rapidly expanding wind markets were no longer confined to Europe but now included the United States, allowing Enron's successor company, GE, to celebrate the 1000th installation of the original Tacke turbine in 2002.[155]

Although foreign wind turbine manufacturers entered the U.S. wind market in the following years, GE remained the market leader with Tacke technology, assembling more than 40 percent of wind turbines installed in the United States until 2011.[156] During that time, GE retained its relationships with German suppliers, in particular with Eickhoff, which had manufactured the gearboxes for the 1.5 MW Tacke turbine, but also with Winergy and Bosch Rexroth, the other large German gearbox suppliers, and VEM

[153]Lewis 2013, 95; Windpower Monthly 1997.
[154] Bird et al. 2005. Wiser and Langniss 2001. For a short narrative on how Texas came to be the state to revive the U.S. wind energy industry, see Righter 2011, 37-47.
[155] Windpower Monthly 2002.
[156] Wiser and Bolinger 2011, 14-15.

Sachsenwerke, a generator firm. It remained an active member of the German Engineering Federation's (VDMA) wind chapter, participating in collaborative research activities to further wind turbine designs.[157]

Over time, GE began sourcing components from other locations, adding suppliers from China (gearboxes, metal castings) and Brazil (blades). The early model of collaborative relationships that originated in the German wind sector during the 1990s was now being applied globally and maintained through successive product generations. At the core, it relied on bringing together specialized expertise residing in companies around the world to develop and manufacture ever larger turbine designs. According to GE's chief wind engineer, Vincent Schelling, GE has to "put the knowledge in the gearbox manufacturers' hands. It would be better if we designed the gearbox and they built it, but we don't have all the knowledge." Likewise, Thomas Narath of Eickhoff stated that "Gearbox design is always a close cooperation between the turbine OEM and the gearbox suppliers. OEMs usually deliver the main product specifications and a conceptual design which our engineering team further develops into a final product design," adding that it "also happens that gearbox development advancement points to a need for main chassis [i.e. wind turbine] design changes. This underlines the great value attached to regular exchange of ideas [...]."[158] Cross-border collaboration of the kind described here between GE and Eickhoff was central to the maturation of wind energy technologies starting in the late 1990s.

---

[157] VDMA website. http://wind.vdma.org/en/article/-/articleview/599526 (Accessed March 15, 2013).

[158] de Vries 2013; Windpower Monthly 2005a.

Around the time that the United States became an important market for German wind turbine suppliers, Chinese firms began to enter the wind energy industry. In spite of its status as a developing economy, China had taken an early interest in alternative energy technologies. Already in 1985, within a few years of the onset of economic reforms, a first demonstration project with imported Vestas turbines had been installed in Shandong province. Between 1985 and 1995, nine further demonstration projects followed, adding just over ten megawatt of generation capacity to the Chinese grid.[159] Starting with the ninth five-year plan in 1996, the Chinese State Development and Planning Commission (SDPC) began to encourage the establishment of a domestic wind power industry and the development of a domestic wind turbine manufacturing base.[160] Lacking the history of wind turbine R&D efforts of Germany and the United States—Chinese firms since the late 1970s had built a number of small turbines to charge batteries in off-grid locations, but had not successfully developed wind generators that could be connected to electric grids—the development of a domestic wind energy industry depended on technology transfers from abroad.[161] The Chinese State Development and Planning Commission, and its successor, the National Development and Reform Commission (NDRC), actively encouraged foreign wind turbine manufacturers and their suppliers to localize production in China and to transfer technology to domestic firms through licensing agreements and joint venture operations.[162]

---

159 Wen et al. 2008, 259.

160 Xia and Song 2009, 1968.

161 Zhu 2001, 20-30.

162 NDRC was established in 2003 when the State Development and Planning Commission, the State Council Office for Restructuring the Economic System and parts of the State Economic and Trade Commission were merged.

In 1997, *Ride the Wind* (乘风), a first localization program, provided incentives for the domestic production of 600 kW wind turbines to two joint ventures between Chinese firms and foreign partners, one set up between the Spanish firm Made and China's Yituo, a second between German wind manufacturer Nordex and Xi'An Aero Engine Company.[163] Although *Ride the Wind* failed to meet its target of installing 1,000 MW of wind turbines within three years due to unrealistic local content requirements and complex approval processes for grid installation, it foreshadowed a pattern of extensive collaboration between foreign and Chinese firms in the creation of a Chinese wind industry.[164]

Building on the *Ride the Wind* program, the State Council in late 1997 lowered value-added tax and import tax on advanced foreign wind technologies and gave preferential tax treatment to joint ventures between Chinese and foreign wind firms.[165] In 2000, wind turbine components were exempted from import tax and taxes on electricity from renewable sources were lowered from 17 percent to 8.5 percent.[166] By 2003, the Chinese government had moved away from funding market development through demonstration projects and established a *Wind Power Concession Program* (风电特许权项目), which introduced a government-run, tender-based bidding system for the development of preselected wind parks. It included a local content requirement of 50 percent, which was raised to 70 percent in 2004.[167] Between 2003 and 2007, 3,350 MW of wind turbines were

---

163 Lew 2000, 282. See also Nordex 2005. *Nordex Establishing Joint Venture in China* [Press Release]. Retrieved from www.nordex-online.com, March 25, 2013.
164 Lewis 2012, 51-52.
165 State Council 1997.
166 State Planning Commission and State Science and Technology Commission 1999.
167 Ru et al. 2012a, 65; Wang 2010a, 705-06.

installed through the *Wind Concession Program*, exponentially expanding the size of the domestic wind market.[168]

Market development was further accelerated in 2006, when the State Council implemented China's first Renewable Energy Law. Alongside a host of other measures to support renewable energy development, the Renewable Energy Law provided the foundation for establishing a feed-in-tariff for wind energy. Much like the feed-in-tariff in Germany, it required utilities to purchase electricity from renewable sources at highly subsidized rates, making wind energy competitive with traditional sources of electricity.[169] In 2009, China surpassed Germany and the United States to become the largest wind energy market in the world.

Although China's domestic wind market expanded rapidly—turning a sector that had been confined to relatively few geographic locations into a truly global industry—European and American wind firms did not set up their own manufacturing facilities in China until market development was well under way. Gamesa of Spain opened its first facilities in China in 2005, Vestas opened a blade factory in Tianjin in 2006, the same year that GE began the assembly of turbines in Shenyang. Nordex of Germany and Suzlon of India opened plants in Dongying and Tianjin in 2007. Supply firms followed the turbine manufacturers. FAG/Schaeffler of Germany, a bearings manufacturer, opened a facility in

---

[168] Ru et al. 2012a, 65. See also data on global wind turbine installations compiled by Earth Policy Institute 2013.

[169] State Council 2005. For a brief overview of the most important policies and regulations to support domestic wind market development, see Lewis 2012, 68-74. For the full text of the majority of renewable energy related policies see Li 2011b.

China in 2006; Bosch Rexroth, a gearbox manufacturer, and SKF, a Swedish bearings multinational, followed in 2008. [170]

With foreign wind firms only cautiously setting up their own manufacturing facilities in China, Chinese domestic wind turbine manufacturers and supply firms entered licensing agreements, joint-development contracts, and joint venture operations with foreign firms to access wind turbine technology. Already in 1997, Xinjiang Wind Energy Company, which later changed its named to Goldwind (金风), licensed a 600 kW wind turbine design from the German company Jacobs, followed by a 750 kW model in 2001.[171] Others quickly followed suit. For instance, Sinovel (华锐风电) in 2003 signed joint development agreements for a 1.5 MW turbine with the Fuhrländer of Germany, followed by similar agreements with Austria's Windtec for 3 MW and 5 MW turbines in 2007. The third large Chinese turbine manufacturer, Dongfang Electric (东方电气), purchased a license for a 1.5 MW turbine from Germany's REpower in 2004 and entered a joint development agreement for a 2.5 MW turbine with the German wind engineering firm Aerodyn in 2005.[172] Nordex, after its initial joint venture with Xi'An Aero Engine, entered a subsequent joint venture with Ningxia Electric Power Group (2005) and REpower set up a joint venture turbine assembly firm with North Heavy Industrial Group in 2006.[173]

All in all, among the 31 largest wind turbine manufacturers in China, sixteen entered license agreements with foreign firms, fourteen entered joint-development contracts, six autonomously developed wind turbine technologies, and three were joint venture

[170] Information retrieved from company websites, the China Wind Power Center database (http:// www.cwpc.cn), Windpower Monthly, and Li 2011a.
[171] Note that in 2001, the German firms Jacobs, BWU, and Pro + Pro Energiesysteme merged to form REpower. REpower was bought by India's Suzlon in 2007, but remains an independent brand.
[172] See Zhang et al. 2009b, 559.
[173] Company websites. See http://www.nordex-online.com and http://www.repowernorth.com.

operations. Seven firms both had joint-development and licensing agreements with foreign firms.[174] Collaboration between Chinese and foreign firms, rather than foreign direct investment, was a at the core of the rapid diffusion of wind energy technologies in the Chinese wind energy industry.

The absorption of foreign turbine technologies in Chinese firms was not without difficulty. Particularly during the early years, wind turbines in China experienced technology failures more frequently than in other wind markets, shortcuts in the design process later required expensive retrofits, and overall availability data for Chinese wind turbines was often below global averages.[175] Estimates suggest that Chinese wind parks have frequently failed to reach the international standard of 95 percent availability, meaning that turbines are shut down for maintenance and repairs more than five percent of the time. Even when operating, wind turbines in China are often doing so less efficiently than those in other countries due to technical failures and problem with grid connections. In 2008, wind turbines installed in China had a capacity load factor (i.e. the proportion of actual electricity produced compared to theoretical generation capacity) of 22 percent, compared to 33 percent in the United States, pointing to both technical problems and operational deficiencies.[176] Observers in China continue to worry that such figures indicate that domestic firms struggle with technology absorption in their relationships with foreign partners and maintain a dependency on imported technology. [177]

---

[174] List complied from Lewis 2012, 136-37; Wang 2010b, 197-203.

[175] Wu 2011. Retrofits due to technical problems are not solely in Chinese occurrence. For instance, both Suzlon and Vestas have had global call backs on turbine models and components. See Windpower Monthly 1999; Windpower Monthly 2008a.

[176] Unlike in other countries, wind park availability and capacity load factors are not publicly released by firms and there is no reporting requirement. Hence, such factors can at best be estimated. Capacity load factors are not solely affected by turbine technology, but also depend on grid connection and wind park operations. Data from Windpower Monthly 2008c.

[177] Zhang and Su 2012, 85-86.

For all its challenges, however, the Chinese wind turbine sector has not evolved into an industry that in all cases produces cheaper, lower-quality imitations of foreign technologies. From the beginning, Chinese producers were able to rely on a global supply chain for wind turbine components and entered collaborative relationships with specialized suppliers. Just as German gearbox manufacturers worked with GE on improving gearbox and turbine designs without co-locating production, Chinese firms also drew on expertise from abroad, jointly developing, improving, and commercializing wind turbine technologies. The Swiss multinational ABB; the German firms Euros, Bachmann, Jake, and VEM; the Danish blade manufacturer LM; and the Austrian control systems firm Windtec (now part of U.S. based AMSC) were among the early foreign suppliers to Chinese turbine manufacturers.[178] As a consequence of global sourcing, the level of local content for China-assembled wind turbines was as low as twelve percent in 2002, though it increased significantly as foreign suppliers set up manufacturing facilities in China and domestic firms entered the industry over the course of the decade (see Figure 2).[179]

Much like in the United States and Europe—and possibly more so—these relationships with supply firms, joint venture partners, and license grantors were not a case of one-directional technology transfer. Chinese wind turbine manufacturers and the growing number of Chinese suppliers for wind turbine components made critical contributions to industry development and technological innovation. While China-made turbines trailed global markets in size, Chinese producers excelled at innovating on cost and scale of manufacturing.[180] Through capabilities located at the intersection of

---

[178] Wang 2010b, 197-203.
[179] Wang 2010b, 68.
[180] Ru et al. 2012a, 61; Zhang and Su 2012, table 3.

traditional R&D and manufacturing, engineering teams in Chinese wind firms re-designed licensed technologies so that they could be manufactured cheaper, faster, and at greater scale. By replacing materials and reconfiguring the internal product architecture of wind turbines or specific components, Chinese turbine manufacturers improved on foreign-developed technologies and in many cases significantly changed product designs.[181]

Although considerations of market access and the complex regulatory environment in China certainly contributed to the willingness of foreign firms to enter joint-development agreements, such relationships frequently resulted in multi-directional learning that benefitted the foreign partner. According to an engineer working for a German wind turbine design firm, the ability to learn from the process during which the product design was reconfigured for mass manufacturing by Chinese engineering teams was a key motivator for the firm to jointly develop and commercialize a wind turbine rather than simply selling a license.[182] Even under licensing agreements, however, foreign firms were able able to learn from Chinese wind turbine manufacturers. In the case of a generator licensed from a German supplier, for instance, the Chinese firm was able to improve the original design through reconfiguration of the product architecture, so much so that it licensed the improved generator design back to the German firm.[183] In other cases, foreign firms tried to replicate capabilities in scale-up and mass manufacturing outside of formal relationships with Chinese partners, instead setting up their own manufacturing facilities in China and poaching engineers from their local competitors.[184] As

[181] Nahm and Steinfeld 2012.
[182] Author interview, CEO of German engineering firm, May 20, 2011.
[183] Author interview, plant manager of German generator manufacturer, May 17, 2011.
[184] Author interview, head of China operations, European wind turbine manufacturer, September 22, 2011..

much as Chinese firms were relying on foreign technology in the development of a domestic wind energy industry, their capabilities in scale-up and mass manufacturing of ever more complicated product designs increasingly became a resource for foreign wind turbine manufacturers in global supply chains.

For wind turbine manufacturers, the expanding Chinese supply chain frequently complemented relationships with suppliers from Germany and elsewhere. Where Chinese suppliers developed capabilities focused on cost, scale, and ease of manufacturability, foreign firms retained expertise in producing components for prototyping, small-batch production, and commercialization. In interviews, engineers for wind turbine manufacturers indicated that they were relying on European suppliers in early stages of product development, but switched to local partners for large-scale production, a stage of product commercialization where innovation is not focused on technological improvement, but on changing product designs to accommodate lower-cost manufacturing processes and materials.[185] For instance, as early as 2006, GE began co-developing gearboxes with Nanjing-based NGC (南京高速齿轮制造) to take advantage of local expertise in mass manufacturing, while continuing to rely on its existing German suppliers for small batch production runs and customization during early commercialization.[186] By 2008, more than half of NGC's products were exported and their gearboxes were used in a wide range of GE wind turbines in all of GE's global markets.[187]

---

[185] Author interviews: plant manager of German generator manufacturer, May 17, 2011; head of China operations, global wind turbine manufacturer, January 21, 2011; head of China operations, European turbine manufacturer, October 28, 2010. 0

[186] Windpower Monthly 2006.

[187] Windpower Monthly 2008b.

The contribution of Chinese wind manufacturers to global wind turbine supply chains was not limited to scale-up and mass manufacturing of existing turbine technologies. The German wind turbine manufacturer Vensys, for instance, entered a collaborative relationship with China's Goldwind for the commercialization of its novel direct-drive technology. Direct-drive eliminates the need for a gearbox, one of the most costly turbine components and one notoriously prone to technical problems. Vensys first licensed its technology to Goldwind in 2003 and commercialization and preparation for mass manufacturing now occurred in collaboration with the Chinese partner, for a first 1.5 MW model as well as subsequent product generations.[188] By 2008, the relationship between German and Chinese engineers had become so central to the development of the technology that Vensys sold a 70 percent stake to Goldwind over a number of other bidders. According to Vensys, Goldwind was chosen as a partner precisely for its capabilities in commercialization and large-scale production. Upstream R&D for new turbine generations has remained in Germany, yet design changes to improve cost and manufacturability occur in Goldwind facilities in China.[189]

More recently, in a process similar to the Vensys/Goldwind collaboration, China's Mingyang (明阳) worked with Germany's Aerodyn, an engineering firm, on the development and commercialization of a super-compact drive turbine technology. By integrating generator and gearbox into one component and reducing the number of blades to two, the companies were able to develop a lighter, smaller, and more efficient turbine design that significantly reduced the cost of raw materials and could be more easily used in

[188] Vensys sold similar licenses to manufacturers in other markets, but was not as closely involved in production and scale-up with its other licensees.
[189] See Peters 2009; Vensys 2012..

offshore applications.[190] What these examples illustrate is that China's capabilities in design for mass manufacturing made possible the commercialization of some of the most advanced turbine technologies over the past decade, technologies which for the first time significantly departed from the standard "Danish" turbine design that has come to dominate the industry at large.

By 2011, the world market for wind turbines had grown to more than forty megawatts annually (equivalent to roughly forty nuclear power plants), up from just over one megawatt in 1995. China's domestic market now accounted for a large proportion of global demand, helping lift wind turbine manufacturers from niche manufacturing to large-scale production. As indicated in Table 2, China alone installed eighteen megawatt of turbines in 2011, compared to seven megawatt in the United States and two megawatt in Germany.[191] More than half of all wind turbines manufactured in 2011 were assembled in China, where the average cost of wind turbines decreased from $885 per kW in 2006 to $644 in 2010. In the United States and Germany, by contrast, turbine prices increased: in Germany from $1,333 to $1,699 between 2006 and 2008 and in the United States from $1,183 in 2006 to $1,234 in 2010.[192] While the entry of German suppliers during the late 1990s permitted wind turbine manufacturers to more easily manage the technical challenges of increasing turbine size and generation capacity, the entry of Chinese producers added capabilities in cost reduction and design for mass-manufacturability. These new capabilities encouraged a global division of labor in the wind energy industry in which foreign firms retained expertise in product design, prototyping and small-batch

[190] Mingyang annual reports; Sun and Yang 2013.
[191] Installation data compiled by Earth Policy Institute, 2013.
[192] International Renewable Energy Agency 2012, 22.

production, but frequently collaborated with Chinese firms on bringing such technologies to mass production. As Chinese, German, and American firms built distinct capabilities along the trajectory from design to mass manufacturing, they established global patterns of production and innovation. Some of the most advanced turbine technologies are now commercialized through cross-border collaboration between Chinese firms and their foreign partners, and Chinese capabilities in low-cost manufacturing make viable turbine designs that otherwise would be unable to compete with standard technologies.

Solar Energy Industry Development, 1995-2012

As was the case in the wind energy sector, after decades of niche production and small-scale demonstration projects, the second wave of industrialization of the solar industry began in Germany. Due to the high cost of solar PV technologies during the early and mid-1990s—generation costs averaged €1.24/kWh—the electricity rates of €0.08/ kWh included in the German feed-in-tariff from 1990 were insufficient to create large-scale demand.[193] The German government thus initially continued to support the solar industry through temporary subsidy programs. Between 1991 and 1995, a 1,000 roofs photovoltaic program *(1000-Dächer-Programm)* of state and federal governments led to the installation of some 2,000 solar PV plants with a total generating capacity of four megawatt.[194] Additionally, number of municipal utilities began subsidizing solar energy so that annual installations of solar PV modules continued to increase even after the 1,000 roofs program expired in 1995.[195]

[193] Edinger 1999, 75; Meinhardt et al. 2007.
[194] Bechberger and Reiche 2004, 50; Nitsch and Fischedick 1999, 22.
[195] Nitsch and Fischedick 1999, 9.

The situation for the solar sector further improved when, after 16 years of conservative governments, the 1998 federal election was won by a center-left coalition that included the Green party as a long-term champion of renewable energy. The new government set ambitious goals for the development of renewable energy. Almost immediately after the election, a 100,000 roofs photovoltaic program (*100-000-Dächer-Programm*) was established, which helped increase Germany's installed solar PV capacity from 50 MW to 350 MW in 2003 and positioned Germany ahead of the United States and Japan as the world's largest solar market.[196] Support for solar energy switched from ad-hoc, program-based subsidies to long-term support through the regulatory system in 2000, when the federal government passed the Renewable Energy Law (*Erneuerbare Energien Gesetz*).[197] In contrast to the Feed-In-Law from 1990, the Renewable Energy Law determined specific rates for each energy source so that even costly technologies such as solar PV could earn a return for investors. These rates were guaranteed for 20 years and, in the case of solar, were higher than the price paid by end customers for electricity. The law foresaw an automatic decrease of subsidies for new installations in subsequent years, determined both by the number of installations in the previous year and technological developments that could reduce market price. In a concession to utilities, large-scale installations could now also benefit from these rates, making it possible for utilities to invest in large-scale renewable energy installations.[198]

The rate structure included in the Renewable Energy Law prompted exponential growth rates for the renewable energy market. Despite the fact that Germany receives less

---

196 Bechberger and Reiche 2004, 50; Jacobsson and Lauber 2006, 267-69.
197 Deutscher Bundestag 2000b.
198 See Laird and Stefes 2009, 2624; Lauber and Mez 2006, 110-12; Mez 2003; Reiche 2004; Stefes 2010, 158-59.

solar radiation than any U.S. state except for Alaska, by 2010, Germany accounted for 44 percent of global demand for solar modules and more than forty percent of the world's accumulated solar installations.[199] Germany now had more than five times the amount of installed solar generation capacity than the early pioneers of the industry, the United States and Japan (Table 3).

The period of rapid market expansion encouraged the formation of numerous solar PV companies in Germany. Much in contrast to the diversified industrial conglomerates and oil companies that had entered (and exited) the solar sector in previous decades, the new entrants to the industry were mostly specialized firms that exclusively developed and manufactured solar PV products. With the exception of two vertically integrated firms—Solarworld, which was founded in 1998, and Sovello, which entered the market in 2006—the new generation of solar firms focused on particular production steps in the solar supply chain.

Wacker, a chemicals company which over the course of the 1980 had briefly experimented with solar cell production, continued to produce silicon, the main raw material. It was now competing with PV Crystalox, a former equipment manufacturer for the semiconductor industry, which began supplying wafers as well as tailor-made silicon for the solar industry in 2002. Sunways started the production of solar cells in 1999, and Q-Cells began solar cell manufacturing in 2002 as the first company to introduce a standardized cell size of six inches. The availability of third-party wafer and cell manufacturers permitted an increasing number of firms to focus on module assembly, the final step in the production of solar panels in which individual cells are connected and

199 Le 2012, 158.

mounted in an aluminum frame. More than thirty module manufacturers entered the industry, including Solarwatt in 1993, Solon in 1997, Solar-Fabrik in 1998, Conergy in 1999, and Centrosolar in 2005. In addition to firms manufacturing traditional silicon-based solar panels, some twenty firms began the production of panels based on thin-film technologies.[200] All in all, more than 60 firms were producing silicon, wafers, cells, and modules in Germany by the end of 2010.[201]

The growing market for solar panels made necessary the development of specialized manufacturing equipment for wafer, cell, and module production. During the early 1990s, small-batch production and prototyping of new cell technologies had occurred in the absence of specialized equipment suppliers, forcing manufacturers to repurpose production equipment from other sectors—particularly the microelectronics industry—and to perform many production steps manually.[202] While the production requirements for solar cells were less demanding than integrated circuits with regard to particulate contamination—permitting the use of scrap silicon from the microelectronics industry —in other ways using equipment from other sectors presented enormous challenges. Wafers twice as thin as those used in semiconductors, for instance, required a re-design of all handling aspects of the production line to prevent breakage, and higher material purity requirements necessitated the introduction of new production and testing processes to isolate impurities. With rapidly growing demand for solar modules, repurposed equipment

---

200 Information compiled from company websites and Germany Trade & Invest 2009a; Germany Trade & Invest 2009b; Germany Trade & Invest 2011a; Germany Trade & Invest 2011b; Germany Trade & Invest 2012.
201 Bruns et al. 2011, 191; Grau et al. 2011, 15.
202 Author interview, CTO, German solar PV manufacturer, May 17, 2011.

at best presented a stopgap measure, as it prevented manufacturing volumes and cost reductions sufficient to establish solar energy as a competitive source of electricity.[203]

Similar to the wind energy industry, where the maturation of manufacturing processes was made possible by a growing number of third party suppliers, the regulatory support for solar energy in the late 1990s prompted producers of specialized manufacturing equipment to enter the industry. The majority of new entrants came from Germany's large industrial base of machine tools and automation equipment suppliers. For producers of semiconductor equipment, the decision to manufacture specialized equipment for the solar sector was often motivated by repair and maintenance requests from solar manufacturers who were using repurposed semiconductor equipment to manufacture solar wafers and cells. A producer of wet benches, for instance, recalled developing the first specialized wet bench for cell manufacturing in response to repeated technical questions from solar firms who were struggling with semiconductor equipment.[204] The growing solar industry also presented a market opportunity for manufacturers of machine tools and automation equipment who were looking to diversify their product portfolio.

By 2010, more than 100 German firms were supplying production equipment for the solar industry.[205] Many of these firms offered machinery for highly specialized applications in wafer, cell, or module manufacturing. They included manufacturers of furnaces and etching equipment, such as Schmid and Stangl; manufacturers of wire-saws such as Arnold and KUKA; producers of thermal systems and wet chemical processes like

[203] See Crane et al. 1996; Green 2001.
[204] Author interview, CEO, German equipment manufacturer, May 10, 2011.
[205] Grau et al. 2011, 15.

ATV Techologie, RENA, and Lotus; firms manufacturing anti-reflective coating machines and screen printers, such as Manz; and producers of automation equipment and robotics used in module assembly, such as Reis Robotics, Teamtechnik, and Böhm. Firms like Schmid, Centrotherm, and Roth & Rau began to offer turnkey production lines, which allowed cell manufacturers to purchase all the equipment required for solar cell production from one vendor.[206]

The availability of off-the-shelf manufacturing equipment for solar cell production lowered barriers for entry for solar manufactures, both in Germany and abroad. In previous decades, laboratory results were often difficult to replicate in field tests and manufacturing difficulties often led to large variances and degradation of solar cell performance over time. Installing a solar PV production line required combining chemical baths, screen printers, furnaces, and other equipment borrowed from various industries and putting them together in ways that had never been tried before.[207] Advanced manufacturing equipment now permitted solar manufacturers to more reliably translate their R&D efforts into mass production and reach scale economies. The greater consistency and standardization of manufacturing output—including the development of industry norms for wafer and cell sizes—further supported deverticalization, since the interfaces between different production steps were now compatible across producers. More importantly, equipment producers for the first time made possible large-scale production. For instance, in the 1970s and 1980s, wafers had to be cut from silicon ingots one at a time, a time consuming process that would have required the installation of huge numbers of saws to achieve scale. The introduction of wire-saws by equipment producers in the early

[206] Germany Trade & Invest 2012, 24. See also Roth 2007.
[207] Morris 2012, VI.

2000s allowed 4,000 wafers to be cut simultaneously, reducing cost, time, and capital expenses.[208] Where a single manufacturer was at best able to produce a few kilowatt of solar panels during the early 1990s, a single production line was churning out 66 megawatt of solar panels annually just ten years later. R&D efforts by universities, research institutes, and industry improved the conversion efficiency for multi-crystalline cells by 15 percent between 1995 and 2005, yet advances in manufacturing technology allowed the price of solar PV systems to drop by more than 40 percent over the same period, far exceeding gains from increased conversion efficiency.[209]

Although the availability of new, off-the-shelf production equipment in theory permitted anyone willing to invest to begin the production of solar cells with the flick of a switch, in practice the development and utilization of production equipment relied on collaboration between solar firms, equipment producers, and research institutes. To embed technological innovation in solar production equipment, research institutes and solar firms shared the results of internal R&D efforts with equipment producers who had experience with automation technology and equipment manufacturing but lacked knowledge of solar PV technologies. Solar manufacturers additionally participated in extensive field-testing of new equipment to ensure that production lines were capable of manufacturing new cell technologies at scale. At least initially, such collaboration occurred locally, made by the close proximity between new solar manufacturers and legacy firms from existing industrial sectors, and encouraged by Germany's federal R&D funding for industrial collaborative

---

[208] Swanson 2011, 543.

[209] Cell efficiencies over time gathered by NREL. See http://www.nrel.gov/ncpv/images/efficiency_chart.jpg [Accessed March 23]. Prices of solar PV systems over time compiled by Grau et al. 2011, 13, figure 2.4.

research.[210] Over time, supply firms relied on their increasingly global customer networks to find such partners abroad.

For solar firms, participating in R&D collaborations required walking a tight rope between protecting proprietary technologies and accessing advanced automation equipment to commercialize these technologies in practice. Investments in new production technologies made little commercial sense to equipment manufacturers if they could not be marketed to other customers, so few were willing to build equipment exclusively for a particular solar firm. Additionally, solar producers, through their collaboration with equipment suppliers, could access technological contributions made by competitors and research institutes, a benefit which to many outweighed the disadvantages of making proprietary technologies available to the competitors. In interviews, solar firms emphasized the risk of missing out on important technological innovations in the industry when not collaborating with equipment suppliers, deterring them from trying to manufacture equipment in-house.[211] The CTO of a producer of thin-film solar modules summarized this point, stating that "we often have internal debates over whether we want to be like Apple and follow a closed innovation concept, or whether we want to be more like IBM and use an open platform. In the end, we have decided to be more like IBM since we believe that the entire industry benefits from sharing know-how and collaborating through equipment suppliers."[212] Solar firms improved and altered purchased equipment in ways not shared with equipment suppliers once production lines had been installed in

---

[210] Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010; Rothgang et al. 2011; Seemann 2012.

[211] Author interviews: CTO, German solar PV manufacturer, May 17, 2011; head of German operations, global equipment manufacturer, May 18, 2011; CEO, German equipment manufacturer, May 10, 2011; CTO, German solar PV manufacturer, May 23, 2011.

[212] Author interview, CTO, German solar PV manufacturer, May 23, 2011.

manufacturing facilities. However, at the core of technological innovation and the development of mature production technologies was a highly collaborative process in which equipment producers acted as a focal point for contributions made by a wide range of firms.

The collaboration between solar firms and equipment manufacturers, however, was not limited to German firms. Although Germany had overtaken the United States and Japan as the largest solar market by 2004, eighty percent of modules installed in Germany were manufactured abroad.[213] The regulatory support for the solar market in Germany benefitted solar producers around the world, many of which also collaborated with equipment manufacturers in Germany. The 100,000-roofs program and the subsequent renewable energy law thus sparked a global process of industry maturation and technology innovation.

The most important foreign partners for German equipment manufacturers came from China. Despite lacking a history of solar PV R&D—apart from cell development for the space sector, Chinese firms and research institutes had not developed any commercializable solar PV technologies during the 1980s and 1990s—the Chinese solar sector quickly surpassed Germany in terms of manufacturing capacity.[214] In 2010, more than 45 percent of the world's solar panels were manufactured in China, compared to 8.4 percent in Germany and 4.6 percent in the United States. (Table 4)[215] Among the largest manufacturers of silicon, wafers, cells, and modules were Trina Solar, founded in 1997;

---

[213] Oppermann 2004, 49.
[214] Information compiled from company websites.
[215] Annual PV Production Data compiled by Earth Policy Institute, 2013.

Yingli Solar, established in 1998; Canadian Solar and Suntech, both founded in 2001; China Sunergy, set up in 2004; and JA Solar and LDK Solar, both established in 2005.[216]

In the rapid expansion of manufacturing capacity in response to German market demand—lacking a domestic subsidy program, 98 percent of China's solar PV products were manufactured for export, most of it for the German market—China's solar firms were able to build on the experience of Chinese returnees, many of which had completed graduate degrees and research visits at foreign solar PV laboratories. By far the most important source of basic technology for the Chinese solar sector was the School of Photovoltaic and Renewable Energy at the University of New South Wales in Australia. Shi Zhengrong, the founder of Suntech; Dai Ximing, the co-founder of JA Solar; Srinivasan Narayanan, the CTO of Trina Solar; Wang Aihua and Zhao Jianhua, the VP of Research and Development and the CTO of China Sunergy; and Zhang Guangchun, the vice president of Canadian Solar, had all completed PhDs or post-doctoral programs under the school's founder, Martin Green.[217] Rather than relying on licensing and joint development agreements, as was prevalent in the wind energy industry, China's solar firms were able to recruit foreign-trained researchers who indigenously developed solar PV technologies.

At the same time, Chinese firms were heavily relying on foreign producers of manufacturing equipment, entering collaborative relationships with some of the same equipment manufactures as their German competitors. Already in 2000, Centrotherm, a German manufacturer of cell and module production lines, began selling its products to

---

[216] Information compiled from company websites and annual reports.

[217] See Cathy Alexander, 2013, "Carbon Cutters." *Crikey,* March 7. Other solar firms recruited Chinese citizens from elsewhere in the world. Wan Yuepeng, CTO of Trina Solar, for instance, completed a PhD at Aachen University and worked for New Hampshire-based equipment manufacturer GT Solar prior to returning to China. See http://www.ldksolar.com/com_team.php. [Accessed March 27, 2013].

Chinese customers. Others quickly followed.[218] Between 2000 and 2007, the export quota for German PV equipment producers rose from 10 percent to 51 percent, most of it destined for Chinese manufacturing facilities.[219] As Chinese producers surpassed their foreign competitors in manufacturing capacity, Chinese firms became ever more important to German equipment manufacturers as customers and partners in the application of new production technologies.

The rapidly growing demand for new production lines often allowed equipment manufacturers to first apply new production technologies in China, relying on the skills in mass-manufacturing of Chinese solar firms throughout the commercialization process. Yet China differed from other markets not just in terms of aggregate demand for production equipment, but the scale of manufacturing activities in individual solar firms also far exceeded those elsewhere. In 2010, Suntech alone produced more solar modules than the top 5 German manufacturers combined.[220] Finding new ways to manufacture cheaper, faster, and at greater scale was central to the value proposition of China's solar firms and working with equipment producers to achieve cost reductions on new production equipment was standard practice. In the words of the CEO of one of China's major solar cell manufacturers, "solar PV is not so much a technology as it is a manufacturing business."[221] As China's solar firms were taking the lead on fully automating the production of wafers, cells, and modules, they continuously demanded new production equipment and retrofits to existing manufacturing lines. Over time, Chinese solar producers thus became important

---

[218] Nussbaumer et al. 2007, 109.
[219] EuPD Research data cited in Fischedick and Bechberger 2009, 26.
[220] Germany Trade & Invest 2012, 26. Christopher Martin, 2010. "Suntech Boosts 2010 Solar Panel Shipments, Production Capacity on Demand." *Bloomberg,* August 18.
[221] Author interview, CEO, Chinese solar manufacturer, August 10, 2011.

resources to foreign equipment suppliers in the commercialization of new production technologies. In interviews, equipment suppliers shared that the scale of production activities afforded their Chinese partners the option of setting aside considerable resources to test new production equipment. Several Chinese firms constructed demonstration facilities with full test production lines on which new technologies could be developed together with equipment suppliers.[222]

In the process of bringing new solar cell technologies from lab to market, China's solar producers were often willing to take considerable risk in the development and application of new production technologies and materials. China's solar industry thus increasingly provided a platform for innovators from around the world to first commercialize new-to-the-world technologies. For instance, Schmidt and Centrotherm, two German equipment suppliers, had experimented with the development of production equipment for the production of selective emitter cells, but were unable to find German solar producers willing to use this new technology. It was a Chinese cell manufacturer that was ultimately willing to partner with them in the commercialization of their selective emitter technology, adjusting their production process to test and optimize the new equipment.[223] Likewise, Roth & Rau, another German equipment supplier, in 2011 entered an agreement with a Chinese solar manufacturer for the development of new production equipment for the manufacturing of Cadmium-Telluride thin-film modules. For Roth & Rau, the agreement provided access to R&D on Cadmium-Telluride cells conducted by the Chinese partner and the opportunity to first commercialize production equipment for an

[222] Author interviews: CEO, Chinese solar manufacturer, August 10, 2011, CEO, Chinese solar manufacturer, August 26, 2011.
[223] Neuhoff 2012, 156.

advanced thin-film technology in the Chinese market. In return, the Chinese partner was able to access a new manufacturing technology prior to its competitors. An analysis of 178 Sino-German technology collaborations between 2010 and 2012 conducted by the German Ministry for Research and Technology found more than a dozen similar interactions between German machine builders and Chinese renewable energy firms.[224]

German equipment manufacturers, however, were not the only foreign partners for Chinese solar producers in the development of new solar technologies. For basic production equipment such as boilers and furnaces, Chinese solar firms were increasingly able to rely on domestic producers, even if such firms to date are unable to offer complete production lines like their foreign competitors.[225] Suppliers from other countries also formed relationships with Chinese solar manufacturers for the development of new technologies. This is especially true for firms from the United States, where the lack of large domestic solar market prompted industry entrants to look to China as a platform for product development.

Absent regulatory support for solar demand similar to Germany's feed-in-tariff, the United States accounted for a mere seven percent of global solar installations in 2011, leading its largest solar manufacturers, First Solar, Sunpower, and Suniva to primarily target foreign markets.[226] First Solar, an Arizona-based manufacturer of thin film modules, opened a plant in Frankfurt, Germany, in 2007, as it primarily relied on German market demand.[227] With relatively little domestic demand in the United States, American equipment and materials suppliers relied on China's solar producers as partners for

---

224 Grune and Heilmann 2012.
225 Grau et al. 2011, 20; Yang et al. 2003, 704.
226 Platzer 2012a; Swanson 2011.
227 See company website www.firstsolar.com

technology deployment. Applied Materials, an American supplier of production equipment for the semiconductor industry, in 2007 entered the solar business with a line of thin-film production equipment. By 2009, demand from China's solar manufacturers had grown exponentially, so much so that Applied Materials opened a solar research and development facility in Xi'an, China.[228] Suppliers of polysilicon, such as MEMC and Hemlock, were also able to benefit from growing demand in China.[229]

In addition to creating demand for their products, Chinese solar manufacturers partnered with American suppliers in technology development. Federal R&D funds for solar energy technologies in the United States continued to outpace those of other industrialized nations—in 2010 alone, the U.S. federal solar R&D budget was roughly four times the size of Germany's—and university spin-offs and solar startups that benefitted from these research funds in many cases collaborated with Chinese partners in technology development and commercialization.[230] For instance, Innovalight, a silicon valley startup founded in 2002, developed a nanomaterial with application in the solar industry with funding from the Department of Energy and the National Renewable Energy Laboratory (NREL). Although Innovalight and its research partners in the United States were able to determine that the silicon ink material could increase cell efficiency by up to fifty percent, it was through collaboration with a Chinese partner, JA Solar, that Innovalight was able to commercialize its technology. Under a collaborative development agreement, engineers from JA Solar and Innovalight jointly adapted the technology for use in mass manufacturing

---

[228] See Mike Splinter, 2009. "Bright Week for Solar Energy around the World." *Applied Materials Blog*, October 28. http://blog.appliedmaterials.com/bright-week-solar-energy-around-world [retrieved March 26, 2013].
[229] Platzer 2012a, 6.
[230] IEA Energy Technology R&D Statistics, 2013.

and successfully incorporated the new material in existing production processes in JA Solar's manufacturing facilities in China. JA Solars capabilities in large-scale manufacturing made it a critical enabler of the commercialization of Innovalight's silicon ink technology, which Innovalight was subsequently able to sell to a wide range of solar manufacturers in China.[231]

By 2012, only eight years after the global solar market first passed the 1 GW mark, global installations for solar panels surpassed 32 GW. Although the lion's share of global demand for solar PV technologies continued to reside in Germany, where generous government subsidies encouraged individual homeowners to install roof-top solar panels in increasing numbers, solar PV had become a global industry. With China-based producers commercializing new solar PV technologies and investing in new production capacity to accommodate rapidly growing markets, solar module prices fell from USD 2.75/watt in 2008 to USD 1.10/watt in early 2012.[232]

However, after the 2008 financial crisis caused a number of governments to reduce subsidy levels for renewable energy technologies, global overcapacity and ever-lower prices for solar technologies increasingly threatened profitability of solar producers around the world, particularly. Starting in 2012, a wave of bankruptcies affected firms in Germany (Q-Cells), the United States (Solyndra, Evergreen), and, most recently, China (Suntech), while governments in Europe and the United States began introducing anti-dumping legislation against Chinese PV products.[233] Yet for all the problems of individual

[231] See Nahm and Steinfeld 2012.
[232] IMS Research, 2012. "Crystalline PV Modules Fall to Single Digits." Retrieved from http:// imsresearch.com/press-release/Crystalline_PV_Module_Profits_Fall_to_Single_Digits, March 25, 2013.
[233] Bullis 2012; U.S. International Trade Commission 2012.

firms due to volatile government subsidies, changes in market demand, and overcapacity, the solar sector at large had evolved from niche production to mass manufacturing. It now relied on a global division of labor in which Chinese, German, and American solar firms, equipment producers, and materials suppliers collaborated on the commercialization of new technologies. While the entry of German equipment firms in the early 2000s first provided the industry with mature production equipment and American suppliers contributed innovative materials and next-generation thin-film technologies, increasingly it was in Chinese firms that these products were applied, improved, and combined with ever-more efficient solar PV technologies to allow the global solar industry to meet global market demand.

5. The Product Cycle and China's Role in Wind and Solar Industrialization

In 2011, five of the ten largest solar manufacturers and four of the world's top ten wind producers were from China.[234] At a time when renewable energy industries were just coming of age, making the transition from niche industries to sizable industrial sectors, the ability of Chinese firms to play a dominant role in global wind and solar energy industries took many by surprise. As late as 2006, development agencies funded by European governments had set up offices in Chinese cities to facilitate the establishment of local renewable energy sectors in an attempt to mitigate China's rapidly growing carbon emissions.[235] Now, buckling under pressure from European and American wind and solar companies, foreign governments were retaliating against Chinese import competition through tariffs, WTO grievances, and bilateral negotiations.[236] In less than a decade, and against the odds of being from a middle-income economy famous for mass manufacturing of cheap consumer products, Chinese firms were competing in global markets with advanced renewable energy technologies and rapidly declining production costs.

For all the success of Chinese firms in wind and solar sectors, however, few observers have argued that the ability of Chinese firms to command large market shares in global renewable energy markets signified China's arrival as a leading nation in high-technology industries.[237] Despite much concern among Western observers about the

---

[234] Xie Dan and Chen He, 2013. "Reflecting on ten years of renewable energy [新能源十年反思]." *Nanfang Ribao*, January 17.

[235] The first Chinese wind turbines were installed in Xinjiang province in 1988 with support from the Danish government. See Liu and Kokko 2010, 5521. For an overview of the role of foreign development agencies in the development of Chinese wind and solar industries, see Zhao et al. 2011.

[236] Bullis 2012; U.S. International Trade Commission 2012.

[237] David Shambaugh calls China a 'partial power,' arguing that while China has become a global economic power house, it's economic growth stems from cheap manufacturing rather than high-tech exports. See Shambaugh 2013.

possibility of 'losing the clean energy race' to China, few actually felt that China's position in global wind and solar sectors results from genuine innovative capabilities.[238] Instead, many reasoned that the global fragmentation of production opened new opportunities for middle income economies in manufacturing, allowing firms from developing locales such as China to enter global supply chains without capabilities in advanced innovation.[239] Where non-standardized production processes and the importance of tacit knowledge once required R&D and manufacturing to be closely integrated under the roof of the vertically integrated firm, the ability to electronically codify and transmit design blue prints in global supply chains allowed manufacturing activities to more easily migrate to low cost production locations. In that sense, observers of China's wind and solar industries reflected central tenets of the product cycle approach to understanding the global division of labor, arguing that China's renewable energy firms were able to capitalize on their factor-cost advantages in low-cost manufacturing, but had to access innovation through licensing and other forms of technology transfer from advanced industrialized economies.[240]

In some sectors, global patterns of industrial development have indeed broadly followed the product cycle. The auto sector, for instance, migrated from advanced to middle-income economies only once production had been standardized. Global auto firms

---

[238] The notion of a 'clean energy race' has been prevalent in politics and the media. See Keith Bradsher, 2010. "China Leading Global Race to Make Clean Energy." *New York Times,* January 30. Shunil Sharan, 2011. "America is losing the green energy race." *Washington Post,* December 7. Matthew Stepp, 2012. "Three Warning Signs America is Losing the Global Clean Energy Race." *Forbes,* October 22. For a report on America's competitive disadvantage in renewable energy industries vis-a-vis China, see Gordon and Wong 2010. Stories about the role of renewable energy subsidies have also been widely reported in the media. See, for instance, Feifei Shen, "China to pay $1.4 Billion in Subsidies for Renewable Energy." *Bloomberg News,* December 18, 2012. Howard Schneider, "U.S. to launch inquiry into China's subsidies for clean-energy firms." *Washington Post,* October 16, 2010.

[239] Camuffo 2004; Gereffi et al. 2005; Langlois 2002; Sturgeon 2002b.

[240] See, for instance, Lewis 2007; Lewis 2012.

and new entrants from middle-income economies first entered the production of technically less challenging components and eventually started appealing to local demand by assembling cheaper, less sophisticated cars in the developing world. Newcomers as well as foreign-invested firms were engaged in a process of technology absorption by replicating capabilities of firms in advanced economies.[241] In Asia, Akamatsu used the flying geese metaphor to describe this step-wise diffusion of industrial sectors from Japan to Korea and Taiwan based on each nation's changing comparative advantage.[242] The first Chinese auto firms—largely joint venture operations between foreign partners and Chinese state-owned enterprises—in the 1980s began manufacturing technologies no longer in demand in advanced economies.[243] Throughout the 1990s, for instance, the most popular car in China was the Santana made by Shanghai Volkswagen, at its core a 1970s Passat model that was no longer selling elsewhere.[244] To encourage the transfer and absorption of more sophisticated technologies in the domestic auto sector, the Chinese government from 1994 onwards consolidated auto firms into large vertically-integrated enterprises, enacted joint-venture requirements, and protected the domestic market from import competition through tariffs and local content requirements.[245] Although China's car manufacturers gradually increased technological standards of domestic car models—moving from the production of outdated foreign models to the manufacturing of small cars developed domestically—they continue to trail global technology developments. [246]

---

[241] Amsden 1989; Amsden 2001; Kim 1997.
[242] Akamatsu 1962.
[243] For a history of China's auto sector, see Gallagher 2006; Harwit 1995; Thun 2006.
[244] Thun 2006, chapter 4.
[245] Gallagher 2006, chapter 4.
[246] Gallagher 2006, 41-44; Lockström et al. 2010.

The evidence presented in this chapter, however, suggests that China's renewable energy industries have not followed in the footsteps of the automobile industry. Of course, some Chinese wind and solar firms have sought to compete through low cost production, using licensing and reverse engineering to access technology in advanced industrial economies and relying on factor cost advantages to produce them cheaply and in great volume. Yet, contrary to the notion of the product cycle, other renewable energy firms in China have not been passive recipients of mature technologies retired from the world's advanced wealthiest markets.[247] Neither have they emulated the capabilities of firms in the United States and Germany in their attempts to participate in innovation and product development in global renewable energy supply chains.

Instead, I have shown that Chinese wind and solar firms have been active agents in the maturation of global renewable energy industries, contributing knowledge-intensive capabilities in scale-up and mass manufacturing to global wind and solar supply chains at a time when renewable energy firms in advanced economies were still engaged in niche manufacturing.[248] The fragmentation of production and the creation of specialized supplier industries—initiated in the German wind sector in the early 1990s and in the solar industry a few years later—permitted Chinese firms to participate in global, collaborative processes of product development without possessing the full set of capabilities required to bring a product from lab to market. Niche capabilities in innovative manufacturing nevertheless established China's renewable industries as important locations for the commercialization of new wind and solar technologies. Counter to conventional wisdom

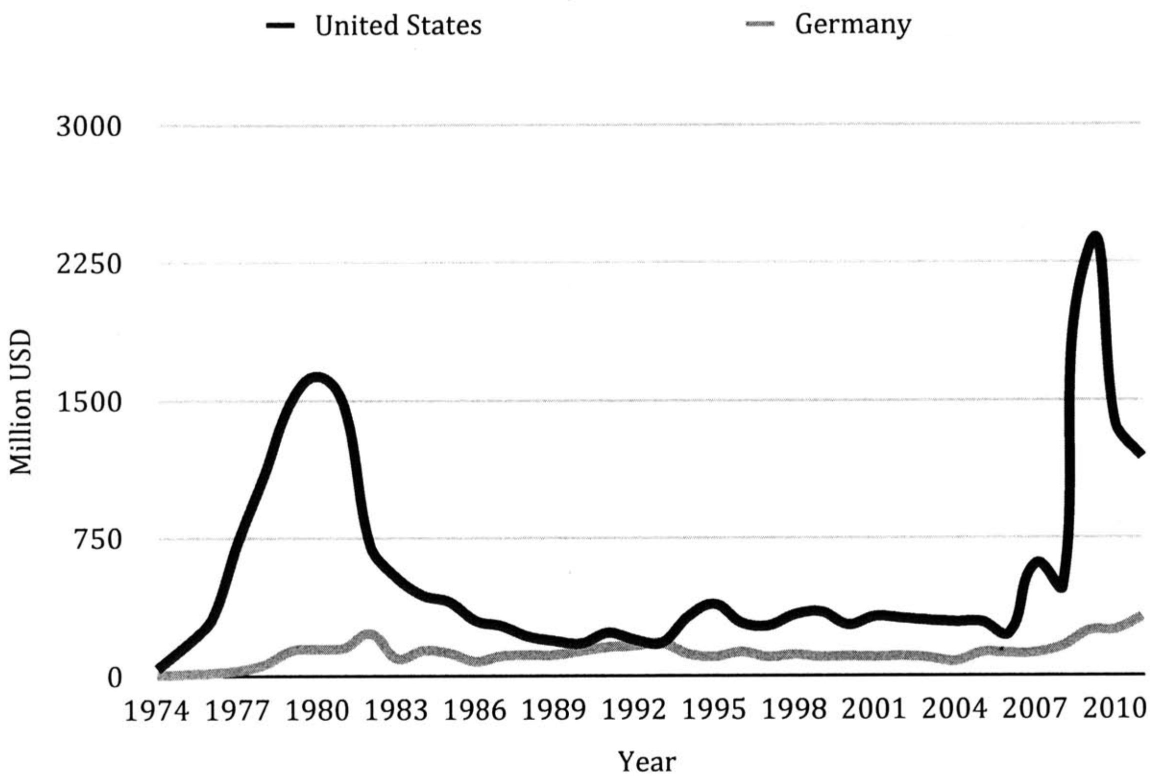
[247] Pisano and Shih 2009; Pisano and Shih 2012; Vernon 1966.
[248] Nahm and Steinfeld 2012.

about firms from developing economies, they also turned Chinese wind and solar companies into important sources of learning for firms around the world.

As a consequence of the global collaboration in product development at the core of renewable industries over the past decade, every wind turbine or solar panel assembled by a Chinese, German, or American firm results from complex interactions in truly global supply chains, bringing together specialized engineering capabilities across a wide range of innovation and production activities. The corporate logo placed on the final product—whether it is attached by GE in Pensacola, Yingli in Baoding, or Nordex in Germany—conceals this iterative process, one in which firms in developing economies and advanced industrialized countries innovate together. The evidence discussed in this chapter suggests that China's dominant role in global renewable energy supply chains is not built purely on factor cost advantages, but results from truly innovative capabilities in large-scale manufacturing. It also indicates, however, that despite their dominance in renewable energy industries, large Chinese wind and solar firms remain tightly integrated in and dependent on global networks of firms with specialized engineering capabilities, including German equipment suppliers and American startups I have discussed in this chapter.

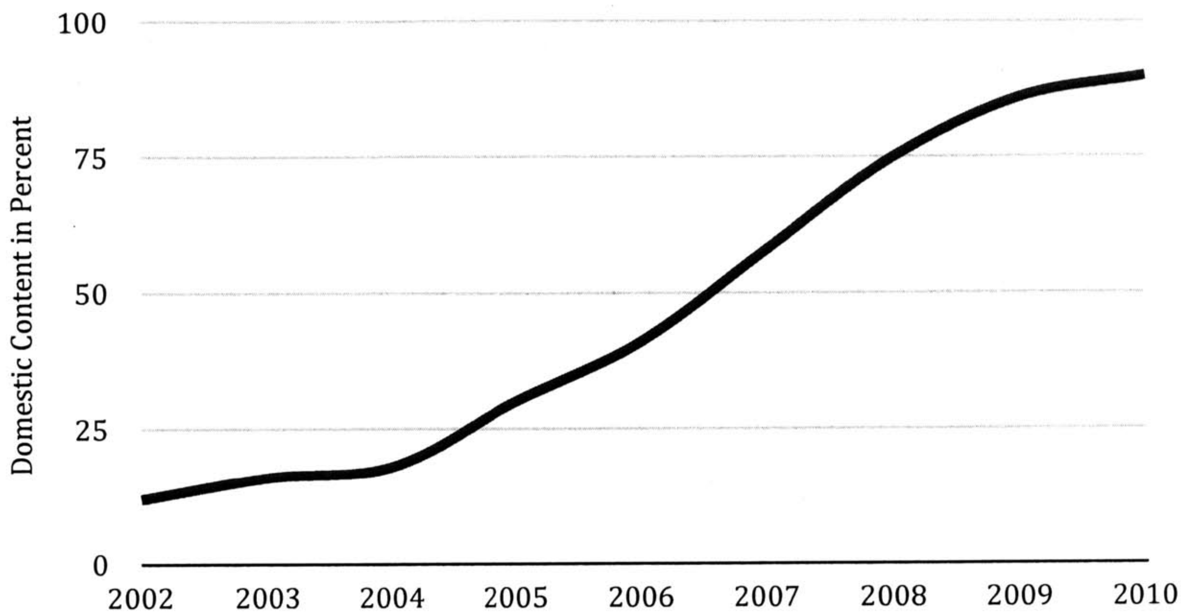
Figures and Tables

Figure 1: Government renewable energy R&D budgets, United States and Germany



IEA (2013), "RD&D Budget", IEA Energy Technology RD&D Statistics (database). doi: 10.1787/data-00488-en (Accessed on 15 May 2014)

Figure 2: Local Content of Chinese Wind Turbines, 2002-2010, in Percent



Sources: Wang, Zhengming. 2010. *The Evolution and Development of China's Wind Power Industry* [中国风电产业的演化与发展]. Zhenjiang: Jiangsu University Press. Chinese Wind Energy Association (CWEA). *Statistics of China's wind power installed capacity*. Beijing: CWEA, 2005-2010.

Table 1: Turbine Size and Capacity by Year (Germany)

	1980	1985	1990	1995	2000	2005	2010
Generation Capacity (kW)	30	80	250	600	1,500	3,000	7,500
Rotor Diameter (m)	15	20	30	46	70	90	126
Rotor Area (m2)	177	314	707	1,662	3,848	6,362	12,469
Nacelle Height (m)	30	40	60	78	100	105	135
Annual Elecriticy Generation (MWh)	35	95	400	1,250	3,500	6,900	20,000

Source: Bundesverband Windenergie. See http://www.wind-energie.de/infocenter/technik. Accessed March 25, 2013.

Table 2: Cumulative Installed Wind Power Capacity in China, Germany, and the United States 1980-2012 (in MW)

Year	China	USA	Germany
1980	n.a.	8	0
1981	n.a.	18	0
1982	n.a.	84	0
1983	n.a.	254	0
1984	n.a.	653	0
1985	n.a.	945	0
1986	n.a.	1,265	0
1987	n.a.	1,333	5
1988	n.a.	1,231	15
1989	n.a.	1,332	27
1990	n.a.	1,484	62
1991	n.a.	1,709	112
1992	n.a.	1,680	180
1993	n.a.	1,635	335
1994	n.a.	1,663	643
1995	38	1,612	1,130
1996	79	1,614	1,548
1997	170	1,611	2,080
1998	224	1,837	2,875
1999	268	2,472	4,442
2000	346	2,539	6,113
2001	404	4,232	8,754
2002	470	4,687	11,994
2003	568	6,350	14,609
2004	765	6,723	16,629
2005	1,272	9,147	18,415
2006	2,559	11,575	20,622
2007	5,871	16,907	22,247
2008	12,020	25,410	23,903
2009	25,805	34,863	25,777
2010	44,733	40,267	27,191
2011	62,364	46,929	29,071
2012	75,564	60,007	31,332

Source: Earth Policy Institute, 2013.

Table 3: Cumulative Solar PV Installations by Country, 2000-2012 (in MW)

Year	Germany	China	USA	Japan	World
2000	44	19	22	122	303
2001	154	24	51	244	668
2002	220	23	73	307	836
2003	249	29	107	407	1,055
2004	809	20	164	495	1,717
2005	1,621	18	204	562	2,544
2006	1,794	18	248	577	2,993
2007	2,114	30	352	497	4,157
2008	3,080	60	549	440	9,283
2009	5,615	200	819	710	14,084
2010	11,214	660	1,355	1,471	24,440
2011	14,893	3,000	2,745	2,287	47,455
2012	15,089	7,500	5,213	3,296	61,486

Source: Earth Policy Institute, 2013.

Table 4: Annual Solar PV Production by Country, 1995-2012 (in MW)

Year	China	Germany	USA	World
1995	n.a.	n.a.	35	78
1996	n.a.	n.a.	39	89
1997	n.a.	n.a.	51	126
1998	n.a.	n.a.	54	155
1999	n.a.	n.a.	61	201
2000	3	23	75	277
2001	3	24	100	371
2002	10	55	121	542
2003	13	122	103	749
2004	40	193	139	1,199
2005	128	339	153	1,782
2006	342	469	178	2,459
2007	873	811	260	3,814
2008	2,019	1,464	390	7,131
2009	4,242	1,599	569	11,416
2010	10,922	2,167	1,099	24,275
2011	20,903	2,331	1,056	37,130
2012	21,069	1,402	800	36,241

Source: Earth Policy Institute, 2013.

Chapter 3: Old players, New Industries—Reproducing Existing Industrial Specializations in Wind and Solar Sectors in Germany

1. Introduction

To the visitor, Germany's energy sector transformation is in plain sight. In the course of transitioning from a fossil fuel-based electricity sector to one in which more than 25 percent of power is generated from renewable sources, wind turbines have become a rural skyline of sorts, lining highways with imposing towers and wingspans greater that the world's largest airplanes.[249] Roofs in urban areas all over the country are covered with glistening solar modules, installed by homeowners in response to generous government subsidies. In the South, where the sun is more abundant, rows of solar panels interrupt agrarian landscapes, as swaths of farmland have been converted to solar plants.

Much less visible, however, is the industrial transformation that has accompanied Germany's growing demand for renewable energy. Hidden in faceless industrial parks, new sectors have sprung up around the manufacturing of wind turbines and solar cells over the past three decades. To date, German renewable energy industries have created nearly 400,000 jobs and are on track to rival the automotive sector in terms of employment and importance for the German economy as a whole.[250] These industries—much like in other economies that have created domestic markets for renewable energy products—include some assemblers of wind turbines and producers of solar panels, yet they also comprise dense networks of small- and medium-sized suppliers of components and production equipment. Rooted in traditional German industrial sectors such as machine tools,

[249] Share of electricity generated from renewable sources from Bundesverband der Energie- und Wasserwirtschaft, 2012. *Erneuerbare Energien liefern mehr als ein Viertel des Stroms* [Press release]. Retrieved from www.bdew.de, April 26, 2013.
[250] van Mark and Nick-Leptin 2011, 4-6.

automation equipment, and automotive supplies, these firms and their capabilities in managing complex manufacturing processes with high degrees of customization have been critical enablers of the transition from small-scale demonstration to mass production. German manufacturers of solar PV production equipment and wind turbine components not only introduced manufacturing equipment into Germany's wind and solar sectors, but, starting in the early 1990s, enabled the commercialization of new wind and solar technologies in collaboration with global partners. Today, the global reach of Germany's wind and solar suppliers is reflected in export quotas of more than fifty percent in the solar sector and up to eighty percent in the wind industry.[251]

Observers have frequently pointed to Germany's long-term subsidies for renewable energy markets as an important factor in the creation of domestic renewable energy industries.[252] Yet for all the economies that have used similar demand-side subsidies—by 2012, 99 national and subnational governments had enacted demand-side subsidies similar to Germany's feed-in-tariff—few have developed large renewable energy sectors, and virtually none have replicated Germany's dense networks of wind and solar suppliers. California's wind power boom of the 1980s—aside from benefitting Danish turbine producers—led to the creation of a number of small domestic wind turbine manufacturers, yet failed to stimulate a network of specialized suppliers for wind turbine components.[253] Similarly, Spain's feed-in-tariff, which between 2007 and 2012 led to 2.6 GW of solar PV

[251] Export quotas for solar compiled by EuPD Research, cited in Fischedick and Bechberger 2009, 26. Export quotas for wind turbines compiled by the German Wind Energy Association. See Rogers 2008.
[252] For a discussion of the role of policy stability and demand-side subsidies in the creation of renewable energy sectors, see, for instance, Fabrizio 2012; Gallagher et al. 2012; Stokes 2013; Vasseur and Kemp 2011; Wiser et al. 2007a; Wiser and Pickle 1998.
[253] Righter 1996, chapter 10.

installations and turned Spain into one of the largest solar PV markets in the world, spurred some domestic assembly of solar PV modules from imported components, but fell short of encouraging local equipment producers and other specialized supply firms to enter the industry.[254] Portugal and Ireland, which both generate roughly 10 percent of electricity from wind energy alone, did not develop any domestic industries focussed on production, not installation, of wind power equipment.[255] If Germany's subsidy regime has been applied widely and has not led to similar results elsewhere, subsidies alone are unable to offer any clues into Germany's development of sizable wind and solar industries.

The evolution of German renewable energy industries not only differs from other national contexts, but also breaks with broader theoretical expectations about Germany's ability to carry out large-scale industrial transformations.[256] Focusing on labor market regulations, firm ownership patterns, corporate governance structures, and financial markets, political economists have long understood Germany as governed by highly path-dependent institutions that encourage industrial specialization in sectors associated with incremental improvements to existing product lines, complex manufacturing techniques, and moderate technological change. [257] According to such views, German firms are unlikely to prevail in high-technology industries that require radical shifts in production processes

[254] del Río and Mir-Artigues 2012; Salas and Olias 2009.
[255] REN21 2010, 17.
[256] Scholars of Germany's renewable energy transition have often focussed on the role of demand-side subsidies in creating a domestic renewable energy industry, rarely exploring what factors may have influenced the development of specific capabilities within these emerging sectors. See Bechberger 2006; Bechberger and Reiche 2004; Jacobsson and Lauber 2005; Laird and Stefes 2009; Stefes 2010.
[257] Such views have been predominant in the Varieties of Capitalism literatures, which have contrasted Germany's institutional capacity for incremental change with institutional structures commonly found in Anglo-American economies assumed to allow more flexibility in managing radical technological change. See, among others, Casper et al. 2009; Hall and Soskice 2001; Soskice 1997; Vitols 2001; Wood 2001.

and the development of entirely new products, unless they offshore these activities to institutional environments which allow for more flexibility in adapting to rapid technological change. Political economy literatures have thus portrayed Germany as an economy unsuited to fast-paced industrial change and rapid technological development, precisely the type of change witnessed in the creation of German wind and solar industries over the past two decades. Why did domestic wind and solar markets attract large supply chains of component suppliers and equipment manufacturers, when similar policies failed to elicit industrial development in other contexts?

In this chapter, I offer a firm-centered explanation for the development of distinct industrial capabilities in Germany's wind and solar industries. Although industrial polices, most importantly in the form of subsidies for wind and solar markets, created new opportunities in renewable energy sectors, it were the responses of entrepreneurial firms in Germany's existing industrial core that led to the establishment of domestic wind and solar sectors. My findings suggest that the development of wind and solar industries occurred through three interconnected processes which took place concurrently throughout the 1990s and early 2000s. First, new industrial policies, such as the demand-side subsidies enacted over the course of the 1990s, reshaped industrial interests and caused both existing firms and new startups to enter wind and solar sectors. These policies created new constituents of policy takers which had an interest in maintaining state support for renewable energy industries and mobilized to protect favorable policies for wind and solar sectors. Second, who responded to the new opportunities created by sectoral industrial policies was determined by industrial legacies, which defined the range of actors and specializations in the existing industrial landscape. Industrial legacies broadly determined the types of firms that could enter wind and solar sectors, but they also defined the specializations, skills, and templates for competitiveness that existing firms could bring to bear on emerging industries. The creation and maintenance of these industrial legacies was itself reliant on state support, through institutions, public resources, and regulatory structures that favored some activities over others. Finally, in responding to sectoral industrial policies, entrepreneurial firms were able to repurpose institutions and state-provided resources to build on existing technological capabilities and develop new products and technologies for wind and solar industries. The existing institutions and resources were not targeted at renewable energy sectors, but nevertheless enabled firms to apply themselves to new industries. Repurposing of existing resources for application in new industrial sectors thus created industrial constituents simultaneously vested in institutions created to support legacy industries and in industrial policies targeted at emerging industrial sectors.

The remainder of this chapter examines these three processes in turn.

2. Renewable Energy Policy in Germany

The foundation for Germany's renewable energy transformation was laid on December 7, 1990, when the German parliament passed the *Stromeinspeisungsgesetz*, or Feed-In Law. After decades during which the state supported renewable energy technologies primarily through R&D grants and short-term demonstration projects, the Feed-In Law for the first time extended long-term subsidies to producers of renewable energy. These subsidies created incentives not only for the deployment of wind turbines and, ultimately, solar panels, but encouraged for new and existing firms to enter renewable energy sectors due to rising market demand. Very rapidly, and unexpectedly for German policy-makers at the time, the subsidies for renewable energy markets created a broad base of constituents, which mobilized to protect government support for renewable energy markets against political attacks.

Initially, the Feed-In Law required utilities to connect renewable energy generators to the grid and to buy their electricity at rates between 75 and 90 percent of average end-user tariffs, depending on the source of energy. It eliminated wholesale pricing for electricity from renewable sources and instead tied its price to the much higher average tariffs Germany's utilities charged their customers.[258] Compensation for renewables changed annually in line with changes to end-user prices—feed-in-tariffs were calculated once a year based on the average proceeds per kWh for all utilities in the country—and was now at least double what generators could previously achieve on wholesale electricity markets.[259] In 1991, for instance, generators were paid Euro 0.08 per kilowatt hour (kWh) for wind and solar energy and Euro 0.06 per kWh for hydroelectric power, compared to

[258] Mendonça 2007, 27-28.
[259] For an account for how feed-in-tariffs were calculated, see Suck 2005, 161.

average wholesale electricity prices of Euro 0.03 per kWh.[260] The cost of these subsidies was spread among end-users through a surcharge on electric rates, which effectively shielded the law from budgetary pressures that affected programs directly funded by the federal government.[261]

Initially proposed by an alliance of renewable energy advocates that included members of several political parties as well as environmental groups and industry associations, the law was passed by an alliance of left-wing opposition delegates that had long championed renewable energy, and, critically, conservative backbenchers from within the government.[262] Although concerns about climate change, acid rain, and widespread exposure to radiation after the 1986 Chernobyl nuclear disaster had propelled environmental issues onto the political main stage over the course of the 1980s, the environmental movement lacked sufficient political clout to enact such groundbreaking legislation on its own. The German Green Party, founded in 1980 by activists emerging from a growing anti-nuclear movement, first entered parliament in 1983, yet with a mere 28 of 519 seats remained in the opposition during the 1987-1990 legislative period.[263] To pass the Feed-In Law, the Greens found unexpected partners among delegates from the conservative Christian Social Union (CSU), who were seeking to protect small hydroelectric plants in their home districts in the South. Absent a regulatory framework for renewable energy, electric utilities had repeatedly lowered the fees paid to small hydropower

---

[260] For an overview of subsidy rates between 1990 and 1998, see Edinger 1999, 75.

[261] Deutscher Bundestag 1990b; Lauber and Mez 2004, 602; Vasseur and Kemp 2011, 315. A 1994 revision of the law raised the compensation for hydroelectric power and biogas from 75 percent to 80 percent of end-user rates, yet compensation for wind and solar power remained unchanged. See Deutscher Bundestag 1994.

[262] Jacobsson and Lauber 2005; Laird and Stefes 2009; Stefes 2010.

[263] For a history of the German Green Party, see Mair 2001; Mewes 1998; Papadakis 1983. On environmental politics in Germany more generally, see Hager 1995.

generators, now offering less per kilowatt hour of hydropower than it cost utilities to produce electricity in-house.[264] As a consequence, many small, rural hydro companies faced bankruptcy.[265] Under pressure from the hydroelectric industry association, which represented 3,500 owners of primarily southern hydroelectric plants, members of the conservative Christian Social Union (CSU) were willing to support the legislation in an unprecedented agreement with the Greens.[266]

Although the Feed-In Law eventually gave rise to exponential growth rates for renewable energy demand and rapidly growing industries for the production of wind and solar technologies, at the time neither parliamentarians voting for the legislation nor outside observers anticipated its far-reaching effects on energy markets and German industry. In an explanatory statement accompanying the draft legislation, the federal government cited climate change and the conservation of natural resources (*Ressourcenschonung*) as reasons for passing the law, all while adding that the legislation would serve to protect existing hydropower plants and at most double renewable energy generation capacity on the grid. The cost of subsidies was estimated to range between 50 and 100 Million German Marks annually, less than a tenth of a percent of overall revenues of the electricity sector.[267] Electric utilities, too, underestimated the potential effects of the Feed-In Law on the German electricity market, and, preoccupied with incorporating the electric generation infrastructure in the Easter German states just months after the fall of the Berlin Wall, failed to mount an effective opposition to the legislation. The Federation of German Industry, which opposed the bill, and its long-standing ally in the federal

[264] Suck 2005, 159.
[265] Andreas Berchem, 2006. "Das unterschätzte Gesetz." *Die Zeit,* September 25.
[266] Jacobsson and Lauber 2005, 134.
[267] Deutscher Bundestag 1990a, 4.

government, the German Ministry of Economics and Technology (*BMWI*), managed to restrict support for renewable energy to the electricity sector, but were unable to stop the legislation altogether.[268] Not least because the Feed-In Law was regarded as a small and inconsequential change to electricity sector regulation, the unlikely alliance of Christian conservatives and environmental progressives was able to convince a majority of the *Bundestag* to support the legislation.[269]

The implementation of the Feed-In Law on January 1, 1991 marked an important transition from temporary support for renewable energy to long-term demand stimulation through the regulatory framework. Even though the legislation primarily affected the wind industry—tariffs were too low to allow for the economical deployment of still very expensive solar energy technologies—it far exceeded expectations of government and outside observers alike. Between 1989 and 1995, installed wind generation capacity increased from 20 MW to 1100 MW, more than tripling overall renewable energy generation capacity on the German grid.[270] Much of this success was owed to farmers and citizen cooperatives, which invested in wind turbines during the early years of the legislation. More than half of wind turbines installed in 1992, for instance, were purchased by farmers who in many cases already owned suitable land for the construction of a turbine and were used to investing in projects with long-term returns. Over the course of the 1990s, a growing share of turbines was owned by operating companies set up by collectives of private citizens (*Betreibergesellschaften*).[271]

---

[268] Jacobsson and Lauber 2005, 133-34.
[269] Andreas Berchem, 2006. "Das unterschätzte Gesetz." *Die Zeit*, September 25.
[270] Advocate General Jacobs 2000; Lauber and Mez 2004, 602. Prior to the Feed-In Law, Germany's renewable energy generation capacity consisted of some 4,000 hydropower plants with a total generation capacity of 470 MW. See Deutscher Bundestag 1990a, 4.
[271] Durstewitz et al. 2003, 4-5.

Even though environmentalists celebrated the success of the law, utility companies increasingly saw the feed-in legislation as a threat. Particularly for utilities operating in the North, where most of the new wind turbines were being installed, the Feed-In Law presented a competitive disadvantage. Because the law did not include a redistributive mechanism to spread the cost of renewable energy subsidies, Northern German utilities had to shoulder a disproportionate share of the financial burden and were forced to raise electric rates in their service areas.[272] However, the Feed-In Law also undermined the business model of the German utility industry in a more general sense. Although the total renewable energy capacity on the German grid barely exceeded that of a single nuclear power plant until the mid-1990s, the decentralized ownership and operation of wind turbines challenged an industry that had long been structured around centrally-operated power plants. Electric utilities were concerned that the enthusiasm with which farmers and private individuals responded to the legislation foreshadowed a transition to a decentralized electricity system, one in which utilities with their large centralized coal power plants were no longer able to compete.[273]

With support from the Federation of German Industry, which worried about the effect of rising electricity cost on the competitiveness of German manufacturing, the Federation of German Utilities (VDEW) in 1996 launched a series of legal challenges to the Feed-In Law, both in parliament and in the courts. The utilities questioned the compatibility of the legislation with European law, arguing that the renewable energy tariffs amounted to illegal state subsidies.[274] When the federal government in 1997

[272] Reiche 2004, 145.
[273] Stefes 2010, 157. See also Andreas Berchem, 2006. "Das unterschätzte Gesetz." *Die Zeit,* September 25.
[274] Advocate General Jacobs 2000; Lauber and Mez 2004, 106-08.

responded by circulating a proposal to reduce tariffs for wind and solar power, renewable energy industries mounted a large campaign to prevent changes to the legislation. Renewable energy industry associations were joined in their efforts by a wide range of outside groups, which included the Association of Metal Workers, the German Engineering Federation (VDMA), farmer associations, church organizations, and labor unions.[275] Large companies like Siemens, which had recently entered the solar sector, threatened to move production and research activities abroad if their home market was no longer supported by the government.[276] Within seven years of passing the original Feed-In Law, the legislation had created a broad range of constituents across a range of industrial sectors and interest groups, which jointly mobilized to prevent changes to government support for renewable energy sectors. a broad range of constituents mobilized to protect state support for renewable energy sectors. The parliamentary committee charged with investigating whether tariffs should be reduced voted eight to seven in favor of leaving tariffs unchanged.[277]

Despite this victory for renewable energy supporters, the mounting opposition to the Feed-In Law and political contest over the future of renewable energy subsidies in advance of the 1998 federal election unsettled investors in wind energy. After a period of exponential growth rates, new installations of wind turbines fell from 505 MW in 1995 to 428 MW in 1996.[278] Matters did not improve when the Feed-In Law was incorporated in

[275] For an account of protests and lobbying efforts to preserve the Feed-In Law, see Hustedt 1998; Tacke 2003, 205-15.
[276] Jacobsson et al. 2002, 24.
[277] Bergek and Jacobsson 2003, 212-15; Jacobsson et al. 2002, 24. The European Court of Justice eventually confirmed this decision, ruling in 2001 that the Feed-In Law did not entail illegal state subsidies to renewable energy generators. European Court of Justice 2001. For a discussion of the decision, see de Vries 2006, 62.
[278] BWE data compiled in Reiche 2004, 67.

the Act on the Reform of the Energy Sector (*Gesetz zur Neuregelung des Energiewirtschaftsrechts*) in 1998, which implemented a European Union directive aimed at liberalizing Europe's energy markets. For the first time creating genuine competition between different electric utilities, the new legislation led to price declines for industrial and residential customers, and, subsequently, to a downward adjustment of feed-in rates.[279] Moreover, the federal government added a five percent renewable energy limit per electric utility, allowing utilities to refuse to connect additional renewable sources to the grid once the limit was reached.[280] Intended to level the competitive playing field for utilities in areas with high rates of wind turbine installations, the cap on renewable energy installations for individual utilities led to additional investment uncertainty for wind turbine operators.[281]

The situation for wind and solar industries improved considerably when after 16 years of conservative governments, the September 1998 federal election was won by a center-left coalition that included the Green party as a long-term champion of climate protection and renewable energy. In its coalition agreement, the new government reemphasized Germany's long-standing goal of reducing carbon-emissions to 25 percent below 1990 levels by 2005 and highlighted the increased reliance on renewable sources of electricity as a central instrument in this process.[282]

---

[279] Bechberger 2000, 9.

[280] Once the five percent limit was reached, electric utilities were able to pass on the cost for additional renewable energy tariffs to grid companies. Only once the grid companies had also reached a five percent limit, could grid connections for new renewable energy projects be denied altogether. Bechberger 2000, 6.

[281] Advocate General Jacobs 2000; Bechberger 2000, 9-13; Deutscher Bundestag 1998; Reiche 2004, 145-46.

[282] Sozialdemokratische Partei Deutschlands and Bündnis 90/Die Grünen 1998, 17, 19.

Immediately after taking office, the new government established a large demonstration program—the 100,000 Roofs Program—to support the budding solar industry, which, due to the high cost of solar technologies, had not benefitted from the feed-in-law.[283] A year later, the federal government began to work on a new legislative framework to replace the 1991 Feed-In Law. With the new legislation, the coalition government hoped to establish long-term regulatory support for the solar industry and to resolve the impasse created in many of the Northern *Länder* when an increasing number of utilities approached the five percent renewable energy limit.[284] After some debate between the coalition partners—Social Democrats initially favored renewable energy quotas for electric utilities while the Greens vehemently opposed a quota system—the government in late 1999 decided on a new legal framework for renewable energy.[285] Replacing the Feed-In Law, the Renewable Energy Sources Act (*Erneuerbare Energien Gesetz*) set prices not as a percentage of end user tariffs, but determined specific rates for each energy source so that even costly technologies such as solar PV could be deployed economically. In the case of wind power, the law differentiated tariffs according to the overall generation capacity of

---

[283] The program was intended to run for five years and provided low-interest loans for the installation of solar PV systems through the state-owned infrastructure and development bank, Kreditanstalt für Wiederaufbau (KfW). Ten percent of the loan sum was waived, with total subsidies —including an interest rate reduction to 4.5 percent below market rates—amounting to roughly 35 percent of overall investment. Although the program generated Euro 2.3 billion in investment in solar installations, it was widely criticized as inequivalent to the kind of long-term support the wind industry had been receiving through the feed-in-law. Bechberger 2000, 8; Bruns et al. 2011, 196; Sozialdemokratische Partei Deutschlands and Bündnis 90/Die Grünen 1998, 19.

[284] In drafting the legislation, the government built on a number of reports and studies which had been commissioned by the Ministry of Economics and Technology (BMWi), the Ministry of the Environment (BMU), and the German Wind Energy Association to examine how the share of renewable energy could be doubled by 2010. Although the reports came to somewhat different conclusions about the exact policy measures required to reach this goal, they agreed that tariffs should be differentiated according to the cost of different renewable energy technologies and that the five percent renewable energy limit should be replaced with a regional or national redistributive mechanism to spread the cost of subsidies. Bechberger 2000, 14-19.

[285] Bechberger 2000, 20-26.

new wind installations and offered slightly higher tariffs in locations with fewer wind resources. Tariffs were guaranteed for 20 years from the date of installation, helping investors forecast future revenue from renewable energy installations. In the case of solar, they were higher than the price of electricity paid by end customers. At the insistence of the Greens—and in a concession to utilities— larger installations could now also benefit from these rates, making it possible for utilities to invest in large-scale renewable energy installations.[286] The law foresaw an automatic decrease of subsidies (*automatische Degression*) for new installations in subsequent years, determined both by the number of installations in the previous year and technological developments that could reduce market price.[287] Lastly, the new law established a mechanism through which the cost of renewable energy subsidies was distributed across all electric utilities in the country, solving the problems that regional concentration of wind power had caused in the past.[288]

According to the federal government, the Renewable Energy Sources Act (RESA) would create incentives for private investors to invest in renewable energy technologies, which could help Germany meet its target of doubling the share of electricity from renewable sources between 2000 and 2010, and, in the long-term, strengthen the competitiveness of German firms in global renewable energy markets. In the explanatory statement accompanying the legislation, the government stated that demand-side subsidies provided through RESA would only minimally affect electricity prices, all while initiating a virtuous cycle of raising production volumes, decreasing cost, and increasing market

[286] For 2000, for instance, the legislation set a price of Euro 0.091/kWh for wind power and 0.506/kWh for solar power. Bechberger 2000, 46-50; Dagger 2009, 73-76; Deutscher Bundestag 2000a; Lauber and Mez 2004, 610.
[287] Bruns et al. 2011, 197.
[288] Deutscher Bundestag 2000a, section 11.

penetration of alternative energy technologies. Any surcharges required a result of renewable energy subsidies were believed to be offset by further reductions in electricity prices as a result of ongoing market liberalization.[289]

Predictably, RESA was opposed by the association of electric utilities, who continued to worry about a shift toward decentralized power generation. The Federation of German Utilities (VDEW), whose 1996 lawsuit against the Feed-In Law in the European Court of Justice was still pending, argued that RESA, just like the Feed-In Law, provided illegal state subsidies to renewable power generators.[290] In the opposition, the liberal party rejected the legislation as a fundamental distortion of market principles. Even representatives from the Christian Democratic Union (CDU) and the Christian Socialist Union (CSU), who in 1990 had played a pivotal role in passing the original Feed-In Law, now argued that RESA was going too far in its promotion of renewable energy and that the Feed-In Law was sufficient to meet environmental and climate goals.[291]

Unlike in 1990, however, when the environmental lobby had little political clout and the Green Party held just a few seats in the federal parliament, advocates of renewable energy were now firmly established in government and the further expansion of renewable energy was supported by an ever-growing number of outside groups. The German Farmers Association (*Deutscher Bauernverband*), whose members were heavily invested in wind energy, environmental groups, and churches favored the legislation. Industry associations

---

[289] "Auf diese Weise wird eine dynamische Entwicklung in Gang gesetzt, die privates Kapital mobilisiert, die Nachfrage nach Anlagen zur Erzeugung von Strom aus erneuerbaren Energien steigert, den Einstieg in die Serienproduktion ermöglicht, zu sinkenden Preisen führt, die wirtschaftliche Konkurrenzfähigkeit erneuerbarer Energien verbessert und ihre stärkere Marktdurchdringung zur Folge hat." Deutscher Bundestag 1999, 1.

[290] It was not until March 2001 that the court ruled that in the interest of climate change and environmental protection, subsidies for renewable energy generation did not constitute illegal government aid. See de Vries 2006; European Court of Justice 2001.

[291] Stefes 2010, 158-59.

and labor unions, which had benefited from the rapid expansion of renewable energy industries throughout the 1990s, also supported the legislation. In addition to the German Engineering Federation (VDMA), which at the time represented small- and medium sized businesses with more than one Million employees and some Euro 60 Billion in annual revenue, the powerful Industrial Union of Metal Workers (*IG Metall*) supported the law.[292] With broad societal backing and a parliamentary majority for the center-left coalition, the Renewable Energy Sources Act was passed with 328 of 550 votes in the *Bundestag* on February 25, 2000, and came into effect on April 1 of the same year.[293]

The introduction of demand-side subsidies sufficient for cost-effective deployment of solar PV technologies created rapidly growing market demand. Particularly after a 2004 amendment, which further increased the rates for solar electricity from Euro 0.457 to Euro 0.574, the German market for solar panels expanded exponentially, turning Germany into the largest solar market in the world.[294] Cumulative installations of solar panels nearly tripled between 2003 and 2004, from 370 MW to 970 MW, and increased to 16,957 MW by 2010. Germany now accounted for nearly half of the world's total solar energy generation capacity. In the wind sector, too, installed capacity continued to increase, from 6,113 MW in 2000 to 27,200 in 2011.[295] The expansion of domestic wind and solar sectors spurred by the Renewable Energy Sources Act not only benefited manufacturers of wind turbines and solar panels and their suppliers, many of which came from Germany, but also created new jobs in installation, maintenance, and operation of the growing number of wind and solar

---

[292] Bechberger 2000, 52; Deutscher Bundestag 2000c, 8433.
[293] The law required approval by the upper house, the *Bundesrat*, where it was ratified on March 17, 2000. See Bechberger 2000, 52. For the full parliamentary debate and final vote on the law in the *Bundestag*, see Deutscher Bundestag 2000c, 8459.
[294] Bruns et al. 2011, 208.
[295] Wind and solar data compiled by Earth Policy Institute, 2013.

parks. A 2011 survey of 1,200 firms in renewable energy industries commissioned by the Federal Ministry for the Environment (BMU) found that employment in renewable energy sectors had doubled since 2004. In 2010, 367,000 people were employed in "manufacturing, operation, and maintenance of renewable energy facilities."[296]

The growing size and importance of wind and solar sectors for the German economy as a whole made it difficult to withdraw or alter government support for these industries. In addition to industry associations and environmental groups, *Länder* governments in regions with renewable energy manufacturing and deployment now lobbied on behalf of local industries.[297] Although the cost of wind turbines and solar panels fell more rapidly than the automatic reduction of subsidies written into the Renewable Energy Sources Act, successive government administrations at the federal level struggled to adjust the legislation. A Conservative/Social-Democratic coalition, which won the 2005 federal election and replaced the previous Social-Democratic/Green Party government, left the tariff schedule unchanged. When a new, Conservative/Liberal government in 2009 attempted to cut subsidies for solar energy in a revision to the Renewable Energy Sources Act, several *Länder* governments blocked the amendment in the *Bundesrat*.[298] A similar process unfolded in 2012, when the federal government again tried to reduce subsidies in response to rapidly declining prices for renewable energy products, provoking protests by subnational governments and widespread demonstrations in front of government offices in

---

[296] van Mark and Nick-Leptin 2011, 5.
[297] For a list of renewable energy lobby organizations, see Grewe 2009.
[298] "Solarförderung vorerst nicht gekürzt." *Der Focus*, June 4, 2010. "Bundesrat stoppt Kürzung der Solarförderung." *Der Stern*, June 4, 2010. "Kürzung in homöpathischen Dosen." *Süddeutsche Zeitung*, July 6, 2010. For a detailed account of the negotiations leading up to the 2009 revision of the Renewable Energy Sources Act, see Dagger 2009.

Berlin.[299] Both instances resulted in a compromise between *Länder* governments and the federal administration which accelerated the reduction of subsidies as part of the Renewable Energy Sources Act, but not by nearly as much as requested by the federal government. As the cost for commercial solar parks approached competitiveness with conventional sources of energy, new versions of the legislation eventually phased out support for utility-scale solar installations and allowed some industrial customers to be exempt from the renewable energy surcharge on their electric rates.[300] The core principle of the feed-in tariff remained unchanged, however, and electricity generated from wind turbines and roof-top solar installations continued to receive above-market compensation.[301]

Despite the accidental origins of Germany's renewable energy legislation—the 1990 Feed-In Law was passed largely because government and outside observers underestimated its transformative effect on German energy markets—the regulatory environment for wind and solar sectors displayed remarkable stability throughout the 1990s and 2000s. With the exception of brief periods of legislative uncertainty prior to the 1998 federal election and following the expiration of the 100,000 Roofs Program in 2003, the period was marked by a gradual expansion of demand-side subsidies for renewable energy products and a stable investment environment for firms in renewable energy sectors. Electric utilities and energy-intensive industries were late to realize the potential

---

[299] "Bundesrat: Solarförderung wird vorerst nicht gekürzt." *DPA*, May 11, 2012. Simon Che Berberich, "Kahlschlag bei der Solarförderung - Ostdeutschland droht die Job-Katastrophe." *Der Focus*, March 05. 2012. Georg Ismar, "Kürzung bei Solarförderung massiv entschärft." *Die Welt*, June 26, 2012. Charlotte Theile, "Ärger unter der Sonne." *Süddeutsche Zeitung*, March 05, 2012.
[300] Gawel and Klassert 2013.
[301] See "Streit um Solarförderung beigelegt." *Der Tagesspiegel*, July 7, 2010. Kerstin Schwenn, Henrike Rossbach, and Thiemo Heeg, "Die Solarförderung wird deutlich gekürzt." *Frankfurter Allgemeine Zeitung*, February 22, 2012.

impact of Germany's renewable energy legislation and thus unable to prevent demand-side subsidies before sizable renewable energy industries had developed. Although the environmental movement played a role in the initial creation of the Feed-In Law, over time the growing economic importance of wind and solar industries turned renewable energy policy into an industrial policy issue, safeguarding legislative support for wind and solar sectors across government administrations of very different environmental convictions. Over the course of just two decades, renewable energy policy had moved from the fringes of the political process into the mainstream of Berlin policy-making.

3. The Development of Wind and Solar Industries

The switch from government support for renewable energy technologies through short-term demonstration programs to long-term subsidization of demand— in the wind sector starting with the 1990 Feed-In Law and in the solar sector with the 2000 Renewable Energy Sources Act—initially benefitted existing wind and solar firms, which had long struggled to find markets for their products. Ultimately, however, the stable market environment in wind and solar markets attracted large numbers of suppliers from adjacent industrial sectors, which applied their industrial capabilities to new opportunities in the production of components and manufacturing equipment. It were the responses of entrepreneurial firms from Germany's core industrial sectors that shaped the industrial capabilities in renewable energy industries, as these firms applied existing technological skills and core capabilities to growing wind and solar sectors. Not only did this process lead to rapidly rising numbers of small- and medium-sized firms in Germany's renewable energy supply chains, but also reproduced distinct specialization in complex manufacturing processes, small-batch production, and customization in new industrial sectors.

After the 1990 Feed-In Law created a rapidly growing market for wind turbines in Germany (see Figure 1), firms like Enercon, Fuhrländer, Husumer Schiffswerft, Südwind, Tacke, and Wind Technik Nord, all of which were founded in Germany over the course of the 1980s, were able to increase sales and invest in upgraded production facilities.[302] Market developments in Germany also prompted foreign wind turbine manufacturers, like Denmark's Nordex, to move facilities to Germany.[303] While these firms' establishment prior to consistent government support for renewable sources of energy suggests that the pioneers of commercial wind energy technologies were motivated by technical challenges and environmental goals rather than quick commercial success, the demand created by the Feed-In Law saved many of them from bankruptcy. As wind power generation capacity in Germany expanded in the decades after the introduction of the Feed-In Law—increasing between thirty and fifty percent annually through the course of the 1990s and slowing to annual growth rates between six and twenty percent in the early 2000s—a few additional manufacturers entered the sector. Jacobs Energie and DeWind were established in the 1990s in response to new market opportunities. Vensys and Bard joined the industry in 2000 and 2003, bringing gearless turbines and offshore wind technologies to the market. On balance, however, the assembly of wind turbines was dominated by firms with origins

[302] Company websites; Ohlhorst 2009; Tacke 2003.
[303] Nordex, 2010, "25 Years of Nordex." Nordex SE Corporate Communications, Hamburg.

prior to the Feed-In Law; more than half of wind turbine manufacturers operating in Germany in 2010, for instance, were founded during the 1980s or earlier.[304]

Since the subsidies included in the initial Feed-In Law were insufficient to increase demand for nascent solar energy technologies, the solar industry remained dependent on short-term demonstration programs throughout the 1990s. However, once the 2000 Renewable Energy Sources Act (RESA) increased electricity rates for solar energy to compensate for the high cost of solar technologies, solar firms, too, were able to rely on rapidly increasing demand (see Figure 1). As in the wind industry, these changes initially benefitted a number of existing firms, which included startups like Ersol (later Bosch Solar), Conergy, Q-Cells, Solarworld, Solon, and Sunways. It also helped firms such as Schott Solar and Schüco, which had been founded as glass or window manufacturers during the 1950s and entered the solar industry during the 1990s, to diversify their businesses into renewable energy. After decades during which challenging technological trajectories and uncertain market environments had prompted large conglomerates to divest of their solar businesses, the subsidies included in RESA once again made the photovoltaic industry desirable for large multinational cooperations. Firms like Bosch and Siemens, for instance, entered the solar sector by taking over existing firms. The established players in the solar industry were joined by large numbers of new entrants. More than fifty solar firms—many of them specializing in thin film technologies or niche applications such as transparent cell technologies—entered the German solar sector between 2000 and 2010.[305] Most solar

[304] For a compilation of wind turbine manufacturers operating in 2010, see Germany Trade and Invest, 2010, "Wind Energy Industry in Germany - A Sustainable Business in a Stable Environment." Berlin. Founding dates according to company websites.

[305] For a list of solar manufacturers operating in Germany in 2011, see Germany Trade and Invest, 2011, "Photovoltaics—made in Germany." Berlin. Founding years compiled from company websites.

startups took advantage of cash grants available as part of special development policies for Eastern Germany and located in Berlin, Brandenburg, Mecklenburg-Vorpommern, Saxony, Saxony-Anhalt, and Thuringia where grants of up to 50 percent of investment costs for capital-intensive manufacturing plants.[306] By 2010, a mere twenty years after the first comprehensive legislation to support renewable energy was introduced, 13 wind turbine manufacturers and more than 60 solar PV producers were operating in Germany.[307]

The proliferation of wind and solar manufacturers in Germany caught the attention of policy-makers around the world, prompting many governments to adopt legislation similar to Germany's feed-in-law. Yet while other locations with demand-side subsidies also witnessed the development of local renewable energy firms—in both Spain and China, for instance, local wind manufacturers thrived after the introduction of feed-in tariffs—few places established the dense networks of wind and solar supply firms that emerged in Germany between 1990 and 2010. By 2011, VDMA, the German Engineering Federation, listed more than 170 member firms active in the wind energy industry, only a few of which were manufacturers of wind turbines. The vast majority of firms instead manufactured towers, blades, mechanical components, hydraulics systems, and production equipment for the wind industry.[308] Similarly, in the PV sector, more than 70 firms offered production

---

[306] Grants comprised incentives available through two separate programs: the Joint Task Program for the Promotion of Industry and Trade (GRW- *Gemeinschaftsaufgabe)* available in all of Germany depending on local economic conditions and the Investment Allowance (*Investitionszulage*) designed specifically as part of the economic recovery program for Eastern Germany. See Germany Trade and Invest, 2013, "Facts and Figures 2013 - Cash Incentives." Berlin.
[307] Germany Trade and Invest, 2011, "Photovoltaics—made in Germany." Berlin. Germany Trade and Invest, 2010, "Wind Energy Industry in Germany - A Sustainable Business in a Stable Environment." Berlin. These numbers do not include suppliers of silicon, the basic raw material in solar PV production, nor do they include component suppliers to the wind industry.
[308] Germany Trade and Invest, 2010, "Wind Energy Industry in Germany - A Sustainable Business in a Stable Environment." Berlin. For a list of VDMA members active in the wind industry, see Arbeitsgemeinschaft Windenergie-Zulieferindustrie 2012.

lines, automation equipment, coatings, and laser processing machines. With roughly 41,000 employees in 2010, employment in solar PV equipment and component firms far surpassed the 22,000 jobs in Germany's PV manufacturers in the same year.[309]

Unlike the manufacturers of wind turbines and solar panels, which were founded by entrepreneurs willing to invest in risky, emerging industrial sectors, the vast majority of supply firms entered from industries long at the core of German industrial strength.[310] Although Germany had been overtaken as the largest manufacturer among OECD economies by Turkey and South Korea in 1985, it retained a large manufacturing sector, particularly compared to the United States, where the relative importance of manufacturing was declining. Between 1995 and 2005, the share of manufacturing value-added increased slightly in Germany, from 22.6 percent to 22.7 percent; in the United States, it dropped from 16.8 percent to 13.6 percent over the same period (see Figure 2).[311] A significant share of German manufacturing activity remained concentrated in the production of machine tools, automotive supplies, and automation and process equipment. In 1995, for instance, the production of machinery and equipment made up 28 percent of manufacturing activity in Germany, making it the largest manufacturing sub-sector, ahead of fabricated metal products, chemicals, and food products. Overall, 6.3 percent of value added in Germany came from machinery and equipment manufacturing firms, compared to 3.5 percent in the Untied States. Metal products, machinery, and equipment together accounted for more than half of manufactured output.[312]

---

309 Employment figures compiled from Germany Trade and Invest, 2011, "Photovoltaics—made in Germany" and "Photovoltaic Equipment." Berlin.
310 Herrigel 1996, chapters 1 and 5.
311 OECD STAN Indicators, "Manufacturing share of value-added 1970-2009," 2013.
312 Author calculations based on OECD STAN database, 2013. Machinery and equipment figures calculated using ISIC code C29T33.

SMEs played a significant role in these industries. In 2002, for instance, enterprises with less than 500 employees made up 98.2 percent of businesses and 38.2 of revenue in machinery and equipment manufacturing. In metal fabrication, 99.6 percent of firms and 38.1 percent of turnover came from small and medium-sized firms. [313]

As I introduced in Chapter 2, the early 1990s in the wind sector and the early 2000s in the solar industry were characterized by the absence of large, specialized supply chains, causing wind and solar manufacturers to resort to improvisation, repurposing of equipment, and the modification of components from other industrial sectors. Germany's existing manufacturing sector possessed a rich fabric of firms with capabilities that could potentially address the needs of wind and solar manufacturers—capabilities in the production of components required in the wind sector and skills in the manufacturing of production lines and automation equipment necessary in the solar industry. However, the small size and ownership structure of German manufacturing firms made many of them reluctant to place bets on emerging renewable energy industries. For some firms, limited R&D resources precluded complex development projects unless commercial prospects were relatively certain; for others, a history of custom orders had established a practice of developing new products only after a customer had been identified. By establishing long-term demand-side subsidies through the regulatory system, the 1990 Feed-In Law and the 2000 Renewable Energy Sources Act not only created new market opportunities in

[313] Günterberg and Kayser 2004, 8. In Germany, SMEs (*Mittelstandsunternehmen*) were traditionally defined as enterprises with less than 500 employees and less than EURO 50 million in revenue. More recently, Germany has converted to the general EU definition, which defines SMEs as firms with less than 250 employees and less than EURO 50 million in revenue.

emerging industries, but also provided the necessary investment stability and customer base to attract small-and-medium-sized firms to take advantage of these markets.[314]

In the wind energy sector, the market created as a result of the 1990 Feed-In Law attracted a wide range of component suppliers throughout the 1990s. These new suppliers included tower manufacturers such as SMB, blade producers such as SGL and SINOI; manufacturers of mechanical components, such as Eickhoff, Hansa-Flex, HAWE, HYDAC, and VEM Sachsenwerke; and firms offering electrical components and control systems, such as Stromag, OAT, and Driescher. Starting in 2004, after a revision of the Renewable Energy Sources Act provided specific subsidies for offshore installations, firms like Powerblades, PN Rotor, EEW Special Pipe Construction, and WeserWind began providing solutions specifically for wind turbine installations at sea.[315]

Firms entered the wind industry from a variety of existing industrial sectors. EEW Special Pipe Construction, for instance, was founded in 1974 as a producer of steel pipes for refineries and other industrial customers, before specializing in towers and foundations for offshore wind turbines in 2003.[316] SGL in 1926 began supplying wooden rotor blades for agricultural machines before developing capabilities in fiber-reinforced plastics that would eventually allow the firm to become a blade manufacturer for modern wind turbines.[317] Hansa-Flex, HAWE, and HYDAC were producing hydraulics and lubrication machinery for a wide range of industrial sectors before developing applications for the

---

[314] For a discussion of the role of policy stability and demand predictability in attracting firms into German renewable energy markets, see Grünhagen and Berg 2011; Lipp 2007; Mitchell et al. 2006; Vasseur and Kemp 2011. For a discussion of policy stability and renewable energy sector development more broadly, see Butler and Neuhoff 2008; Couture and Gagnon 2010; Nemet 2009.
[315 315] Ohlhorst 2009, 196. Years of industry entry compiled from company websites.
[316] For a brief background on EEW, see http://www.eew.de/about-eew. (Accessed July 12, 2013).
[317] SGL's company history can be found at http://www.sgl-rotec.com/cms/international/company/history/index.html?__locale=en. (Accessed July 12, 2013).

wind industry.[318] Stromag, founded in 1932 as a manufacturer of conductor rails and electric rail material, specialized in the production of clutches and breaks for textile machines before offering pitch controls, break systems, and gearbox components to the wind energy sector.[319] These firms' legacies in established industrial sectors were typical of a large number of suppliers which entered the wind industry during those years.

With nearly a decade delay—after the domestic solar market expanded in the early 2000s—the solar industry witnessed a similar influx of supplier firms from existing industries. Centrotherm, Roth & Rau, Schmid, and Singulus began producing turnkey production lines for crystalline solar cells; firms such as RENA, Decker, Von Ardenne, and Manz started manufacturing wet chemical benches, equipment for anti-reflective coating, and screen printers; Teamtechnik specialized in the development of stringers and laminators for module manufacturing; Bürkle and Leybold started offering thin film production lines; and firms like Reis Robotics, Schmalz, and Rofin began the production of automation and laser processing equipment for solar firms.[320]

As in the wind industry, many of these firms had previous experience in machinery and equipment sectors. Centrotherm, for instance, was founded in 1948, and initially specialized in the manufacturing of production equipment for microelectronics and semiconductor firms.[321] Schmid, founded in 1864, began the production of manufacturing equipment for furniture businesses in 1926, started manufacturing printers for electronic

---

[318] See http://www.hansa-flex.com/en/unternehmen/geschichte.html; http://www.hawe.de/cs/company/history/; and http://www.hydac.com/de-en/company.html. (Accessed July 12, 2013).
[319] Stromag company history: http://www.stromag.com/unternehmen/historie.html. (Accessed July 12, 2013).
[320] Timing of industry entry compiled from company websites.
[321] See http://www.centrotherm.de/en/unternehmen/geschichte/. (Accessed June 8, 2013).

circuit boards in 1965, and in 2001 entered the solar industry.[322] Bürkle supplied machinery to furniture, automotive, electronics, and glass firms for more than eighty years before supplying production equipment to thin film solar firms.[323] And Manz developed automation technology for flat panel displays before entering the solar industry in 2000 and the thin film sector in 2005.[324]

Although their backgrounds in traditional industrial sectors provided many of these firms with the type of manufacturing experience and tacit knowledge required for the production of complex machines and components, applying existing skills to emerging wind and solar industries entailed extensive learning and capability-building. Firms were able to repurpose existing technologies and production processes to take advantage of new opportunities in renewable energy sectors, but entering wind and solar sectors required substantial modification of existing product lines and technological capabilities. In many instances, such time and capital-intensive development processes were conducted in collaboration with wind and solar manufacturers and other supply firms, bringing together skills residing in a number of different firms. Although entry into renewable energy industries shared a number of common features—it entailed the modification of existing capabilities and technologies for application in new sectors; it often involved collaboration with other firms; and it was highly time and capital intensive, making it a challenging endeavor particularly for smaller firms—the process by which firms matched existing skills with opportunities in new sectors took on a number of different forms.

---

322 http://www.schmid-group.com/en/company/history.html. (Accessed March 18, 2013).
323 http://www.buerkle-gmbh.de/index.php?id=1132. (Accessed June 8, 2013).
324 http://www.manz.com/company/history. (Accessed June 8).

Modes of entry into renewable energy supply chains

In interviews, CEOs and R&D engineers described three main modes by which firms transitioned into renewable energy sectors. A first path into wind and solar supply chains through *re-engineering*, at the core a process of modifying and repurposing existing technologies for new applications in renewable energy industries. Future customers, more than simply ordering a product with use in wind turbine or solar module manufacturing, in many cases played an active role in the re-engineering process by encouraging industry entry, providing product specifications, and participating in product testing activities. Re-engineering of existing technologies occurred in the wind industry, for instance, when Hedrich Vacuum Systems—a firm with decades of experience in the production of casting equipment—repurposed its cast resin technology for application in the manufacturing of wind turbine blades from epoxy resins.[325] Similarly, SHW Werkzeugmaschinen, a firm with more than 70 years of history in the machine tool production, applied its experience in the manufacturing of production equipment for large engines to the wind industry by reusing its core technology, a milling head, in machines for the production of turbine housing and nacelles.[326] However, re-engineering was particularly prevalent in the solar sector, where the similarity between microelectronics (semiconductors) and crystalline photovoltaic cells—two silicon-based technologies—encouraged numerous firms to utilize their capabilities in semiconductor manufacturing as a platform to enter the solar sector. The resulting production machines shared many technological principles with their ancestors

---

325 http://www.hedrich.com/products/equipment-for-reactive-resin-insulation/cast-resin-technology-for-wind-energy.html. (Accessed, July 17, 2013).
326 See company website at www.hedrich.com and de Vries 2011.

in the microelectronics industry but were using these principles in different product applications.

The entry of supply firms into renewable energy sectors was in many cases prompted by solar manufacturers which had borrowed production equipment from the semiconductor industry. While these improvised production lines—often made up of novel equipment combinations borrowed from various industries—showed that semiconductor production equipment could in principle be used for the production of solar cells and modules, in practice manufacturing quality varied and experimental lines were unsuitable for mass production.[327] An integrated solar manufacturer, for instance, originally began development and production in the fab of a previously state-owned Eastern German semiconductor firm that had been broken apart and sold off in separate pieces after German unification. As the firm's CTO explained, in the late 1990s there simply was no commercial equipment available for large scale production of photovoltaic cells.[328] Off-grid, defense, and space applications had required specialized, small-scale production on experimental lines, yet scaling production and reducing costs to bring solar modules to a mass market now required the development of new production methods.

In order to bring the technology from lab to mass production, the firm decided to build on the microelectronics industrial base—which already had a history of large-scale production—by repurposing existing knowledge and machinery for the budding solar industry. While the production requirements for solar cells were less demanding than integrated circuits with regard to particulate contamination—permitting the use of scrap silicon from the microelectronics industry—in other ways using equipment from the

[327] Palz 2011.
[328] Author interview, CTO, German solar PV manufacturer, May 17, 2011.

microelectronics industry presented enormous challenges. Wafers twice as thin as those used in the microelectronics industry, for instance, required a re-design of all handling aspects of the production line to prevent breakage, and higher material purity requirements necessitated the introduction of new production and testing processes to isolate impurities. After successfully experimenting with production lines retained from the semiconductor plant, the solar firm contacted some of the original equipment manufacturers and persuaded them to formally collaborate on the development of specialized solar production equipment. The product development process took more than a year and resulted in an entirely new production layout, a new process design, and new-to-the-world manufacturing equipment.[329]

Although many manufacturers of production equipment were initially reluctant to invest resources in product development for such young and emerging industries, the need for professional automation and manufacturing machinery in the solar industry ultimately presented a market opportunity too good to pass up. A manufacturer of wet benches for the semiconductor industry described how maintenance calls from solar firms that were experimenting with semiconductor wet benches ultimately convinced the company to develop a product line specifically for the solar sector. This process not only entailed the design of a new product on the basis of principles borrowed from the microelectronics industry, but also necessitated new manufacturing strategies to increase production speed while simultaneously allowing a greater degree of customization than was common in the semiconductor sector. The company eventually designed a modular production system that

[329] Author interview, CTO, German solar PV manufacturer, May 17, 2011.. On the differences between microelectronics and solar PV in early mass production, see Crane et al. 1996; Green 2001; Morris 2012, VI..

permitted higher manufacturing volumes while also offering customers individual solutions with regard to cell size and wafer thickness. It took the firm a year to develop the first prototype to enter the solar sector, and a further seven years to re-design the product so that it could be mass produced. In this process, the firm not only relied on collaboration with solar cell manufacturers to make sure its products would meet customer expectations, but also worked closely with the Fraunhofer Institute for Solar Energy Systems (ISE) to further improve its technology.[330]

A second group of firms entered wind and solar industries through a process of *integration*, in which firms borrowed principles from different industrial sectors and applied them in an original way to new products and industries. Integration often occurred through cooperation between firms with different core skills and capabilities, yet occasionally it took place through the integration of technologies and skills within the same firm. Although principles from the original application of technologies and processes were repurposed in this process, the combination of different technologies resulted in the development of a new-to-the-world product designs.

In a fairly typical example, a small supplier of automation equipment combined its core skills in the production of automation and testing machines for the auto sector with capabilities from other industries through strategic learning and hiring. Trying to reduce exposure to a single industry, the firm decided to diversify into solar module assembly, since very little automation technology for module assembly was on the market and much of the existing automation technology originally developed for the auto sector could be re-applied. While the firm reused about 70 percent of the technologies it had previously

---

[330] Author interview, CEO, solar PV equipment manufacturer, May 10, 2011.

applied in the auto industry, it integrated infrared and laser welding processes from other industrial sectors. This allowed the firm to process cells contact-free, which increased speed, reliability, and production efficiency, particularly in the handling of ever-thinner wafers prone to breakage.[331]

In addition to hiring engineers with skills in laser welding and setting up training programs for existing R&D staff, the firm worked closely with laser and robotics suppliers during product development. The head of research and development pointed out that "a lot of these suppliers are just down the road. In that sense, we benefit from being in the silicon valley of the machine tool industry. They send engineering teams that can come for days, weeks, or months, and work on site with our engineers until the product works. It's very different from working with global software firms, for instance, from whom we purchase testing and measuring software. If we have a problem there, we can call a call center, but those people don't really know any more than our own staff."[332] All in all, it took two years for the development of a prototype and another two years until the first products were being delivered to customers; a lengthy process that occupied almost all of the R&D sources of the firm.

In a different case, a supplier of robots and coating machines discovered that the necessary skills to enter the solar sector were present within the firm, but required reorganization of the R&D and integration of different technologies in the same process to develop a fully automated module assembly robot. Seeking to produce automated module production lines, the firm combined engineers from its laser processing, gluing, and coating divisions to develop this new product, using technologies from the glass, automotive, and

[331] Author interview, managing partner, solar PV equipment manufacturer, May 10, 2011.
[332] Author interview, head of R&D, solar PV equipment manufacturer, May 11, 2011.

plastics industry. Although the firm was used to going through resource-intensive R&D processes for custom-designed robots, in the robot business customers generally paid for development expenses up front. Entering the solar industry, the firm for the first time had to bear the risk and cost of product development itself.[333]

In a number of instances, solar manufacturers used similar approaches to commercialize new technologies. A manufacturer of thin film solar cells, for instance, was founded as a joint venture between a former semiconductor producer and a glass company. The semiconductor firm had developed the technological principles for a potential thin-film solar technology, yet was unable to master the manufacturing process which required depositing delicate coatings on glass. The glass company was selected as a joint venture partner during a relatively early stage of technology development and contributed capabilities to design the product for manufacturing and to establish the production process itself. As the CTO explained, "imagine a sheet of glass flowing through a factory, being heated, cooled, coated with different layers. There are more than 20 steps in this process. The order in which the material flows through these steps determines much of the module efficiency but is constrained by the physical limits of the material. Without the expertise of [the glass company], we would have been unable to balance physical constraints and technology optimization."[334]

A third mode of industry entry, *resizing*, was particularly prevalent in the development of the German wind power sector. Resizing occurred when the application of an existing technology to a new industry required a radically different scale not just of production but of the product itself. Especially with mechanical parts, resizing often

---

333 Author interview, engineer, robotics manufacturer, May 13, 2011.
334 Author interview CTO, solar PV manufacturer, May 23, 2011.

necessitated a complete redesign of the product and the production process, as structural loads and forces changed exponentially as the size of the product increased. As a consequence, computer models had difficulty developing adequate specifications for new components, and trial-and-error approaches dominated product development.[335]

A manufacturer of gearboxes for wind turbines, for instance, originally produced gearboxes for tunnel drilling machines in the mining sector. Although the core principles of gearboxes in both sectors are similar—both need to withstand strong forces, high operating temperatures, and, unlike cars, almost continuous operation for years or even decades—gearboxes for large wind turbines required a completely new design to accommodate the structural requirements of the new gearbox size, new control software, a new logistics system to run operations, new measuring and testing procedures, and the use of different kinds of materials to prevent corrosion in off-shore wind applications. Since gearboxes need to fit the particular requirements of a wind turbine design, they almost always are developed in close cooperation with a future customer. Hence, for the firms' initial gearbox and subsequent product generations, a wind turbine manufacturer supplied specifications for interfaces, noise levels, vibration tolerances, and other parameters. The gearbox manufacturer subsequently developed a prototype, which was tested and slowly ramped up to volume production together with wind turbine manufacturer. Although the firm had decades of experience in the gearbox industry, the development process for the first wind turbine generation lasted more than four years, with slightly shorter development times for subsequent product generations. [336]

---

[335] Author interview, plant manager, gearbox manufacturer, May 16, 2011.
[336] Author interview, plant manager, gearbox manufacturer, May 16, 2011.

A generator manufacturer described a similar process of bringing generator technologies from the shipbuilding and railways industries into the wind energy sector. In this case, space constraints and more stringent weight requirements inside the turbine prompted a redesign of the product and production line, a process repeated every time a larger turbine generation required exponentially larger components. The plant manager explained that for some components, the firm was able to reuse parts from its railway and industrial engine business, while for others, the greater importance of small and light-weight structures and different climate conditions in wind turbine applications required the use of different materials and construction methods. In adapting existing technologies to the requirements of the wind turbine industry, the firm benefitted greatly from the proximity to its suppliers, which worked closely with the firm's engineers on adapting parts and components. As the plant manager explained, "we work with a local iron caster on making a part. Even with something as simple as iron casting we have to be careful. These firms make parts for all sorts of machines, so they don't know what's relevant and important in our business. For the first 100 parts or so we have to have an engineer work on site with them to make sure the part is optimized. For a small company like us, it's much easier if the supplier is around the corner, because we can jump in the car and meet with them to discuss tolerances and fits."[337] In spite of its extensive experience in building engines and generators for a range of industrial applications, it took the firm two years to build the first prototype, after which a new factory with new production equipment had to be installed to bring the prototype to mass production.

[337] Author interview, plant manager, German generator manufacturer, May 17, 2011.

As these examples illustrate, the entry of firms from Germany's traditional manufacturing sectors into wind and solar supply chains entailed complex transformations of existing technologies, capabilities, and production processes. In both wind and solar power sectors, these processes necessitated large investments in time and capital, even if they allowed the utilization of existing knowledge in some form. Product development times of 2-4 years were standard among the majority of firms interviewed for this project, with an almost equally lengthy development time for each new product generation. For small and medium-sized suppliers, moving into wind and solar sectors commanded the vast majority of firms' research and development resources, preventing firms from working on product alternatives for different industrial sectors. As one manager put it, "success depends on whether we can predict how the market develops or whether we get it wrong".[338]

For many of the smaller firms, however, failure was not an option. Having spent all their resources on a long-term development projects to enter a new industrial sector, they often did not have sufficient resources to revise their strategy should circumstances change. The CEO of producer of assembly equipment summarized this point: "Stability is extremely important [to our decision to enter a particular sector]. We spend years developing a product and if the circumstances in a market change, we lose a lot of money and may run out of cash before we can develop a product for an alternative sector."[339]

When entering wind and solar supply chains during the 1990s and 2000s, Germany's small and medium-sized supply firms were attracted as much by the stability of Germany's renewable energy legislation as they reacted to growing market demand.

---

338 Author interview, engineer, robotics manufacturer, May 13, 2011.
339 Author interview, managing partner, solar PV equipment manufacturer, May 10, 2011.

Although short-term demonstration programs in both sectors created domestic demand for wind turbines and solar panels prior to the introduction of long-term feed-in-tariffs, suppliers entered both industries only after government support had switched to long-term demand stimulation by passing the 1990 Feed-In-Law and the 2000 Renewable Energy Sources Act. The consistency with which demand-side subsidies were maintained across government administrations—not least because of the increasing political clout of wind and solar industries themselves—further assured firms in their investment decisions. As steadily growing markets for wind turbines and solar panels created the need for specialized equipment and component suppliers to make possible large-scale production, the continuity with which these markets were supported ensured that firms from existing machinery and equipment sectors were willing to respond to new opportunities in emerging industries.

4. Tools for Transition

Although the 1990s Feed-In Law laid the foundation for the development of renewable energy industries in Germany, it was not primarily intended to serve industrial policy goals. Neither environmentalists among the Greens and Social-Democrats nor Christian conservatives, the main groups behind the original legislation, envisioned the creation of large industrial sectors as a consequence of the law. Environmentalists were instead concerned with creating alternatives to Germany's fossil fuel and nuclear-based energy sector, while Christian conservatives were seeking to secure re-election by protecting a politically important, but economically marginal group of hydropower generators in the South. As a result, the legislation did not specifically target any particular groups of firms to benefit from the markets it created, nor did it include any provisions that could have helped specific types of firms take advantage of these new opportunities. Subsequent changes to the Feed-In Law and its successor, the Renewable Energy Sources Act, focused on adjusting tariffs for different sources of energy to account for technology improvements. Consequently, specific industrial policy measures were absent from later generations of renewable energy legislation as well. Neither the original Feed-In Law nor the Renewable Energy Sources Act included any local content requirements or loan programs for German wind and solar manufacturers and their suppliers.

Just as demand-side legislation provided little concrete assistance for firms seeking to enter renewable energy sectors, government R&D funding for energy technologies initially bypassed small and medium-sized firms. A series of federally-funded energy research programs (*Energieforschungsprogramme*), which ran between three and ten years and each had a specific substantive focus within the field of energy technologies, dispensed Euro 1.81 billion for renewable energy research between 1990 and 2005.[340] However, these programs, while successfully promoting advanced wind and solar research in Germany, were primarily targeted at large firms and research institutes such as the Fraunhofer centers. A 1993 evaluation of research funded through the third Federal Energy Research Program, which ran from 1990 until 1996, included projects conducted by industrial laboratories at Siemens, Bayer, Wacker Chemical, and Deutsche Aerospace, but was lacking participation from smaller firms.[341] Similarly, projects in the wind sector were

---

[340] The third energy research program (1990-1996) allocated Euro 878.7 million for renewable energy R&D projects, the fourth energy research program (1996-2005) dispensed Euro 537 million in funds, and the fifth energy research program (2005-2008) distributed Euro 461 million. See Bundesministerium für Wirtschaft und Arbeit 2005, 22; Prognos AG et al. 2007, 14; Sandtner et al. 1997, 260.

[341] Forschungszentrum Jülich 1993.

conducted by established turbine manufacturers like Tacke (later GE) and large utilities such as RWE.[342] The Federal Research Ministry expected new technologies to automatically diffuse into industry, while the Ministry of Economics, which was in charge of technology transfer between research and industry, argued on principle that new technologies should not need subsidies to get to market.[343] Until the late 1990s, no programs were established to transfer the results of government R&D programs to small and medium-sized supply firms, even though smaller firms often had limited resources to absorb new technologies, making them less likely to benefit from publicly funded research and development projects.[344]

The situation improved by the time the 2000 Renewable Energy Sources Act created large-scale demand for solar energy products. The fourth Federal Energy Research Program, which ran from 1996 until 2005, shifted the focus from basic research in large industrial laboratories and universities to bringing new technologies closer to commercialization. Over the duration of the program, 627 research projects were supported with a total of Euro 537 million, a modest sum compared to the Euro 4.5 billion in demand-side subsidies charged to rate payers in 2005 alone.[345] Although more than half of all projects related to wind and solar energy were conducted by universities and research institutes, among firm-based projects a growing number was carried out by small and medium-sized enterprises. By 2005, three quarters of firms participating in federally funded R&D projects had 249 employees or less.[346]

---

[342] Hoppe-Kilpper 2003, chapter 2.
[343] Bruns et al. 2011, 55-56.
[344] Belitz et al. 2012, 51.
[345] Frondel et al. 2011, 200; Prognos AG et al. 2007, 196.
[346] Prognos AG et al. 2007, 204.

Technologies under investigation in R&D projects supported between 1996 and 2005 were relatively close to commercialization or were incremental improvements of existing products. Thirty-eight percent of firms were funded for projects with the goal of developing a completely novel product or technology for renewable energy sectors, compared to 21 percent of projects which sought to improve existing designs. Nineteen percent of projects focussed on developing new production processes and 11 percent centered on enhancing existing process designs.[347] The firms carrying out these research activities now reflected the diversity of suppliers in wind and solar sectors. Among manufacturing firms that received federal R&D funding for renewable energy research, the two largest groups were machine tool producers and manufacturers of electrical equipment (*Elektrotechnik*), which made up 13 percent and 11 percent of firms, respectively. Other firms had backgrounds in the production of medical equipment, measuring technology, glass and metal products (*Metallerzeugnisse*), and components for car manufacturers. Only 4 percent of firms were primarily manufacturing energy generation equipment.[348]

Despite the shift in federal research programs to include small and medium-sized suppliers, federal R&D funds played but a small role in helping firms enter wind and solar industries. More than 70 percent of firms receiving federal funds for renewable energy R&D stated that they were already active in renewable energy sectors prior to participating in the programs. Forty percent of firms indicated that federal R&D funds were used to

[347] Prognos AG et al. 2007, 224.
[348] Prognos AG et al. 2007, 204-06.

bolster existing R&D activities or had no influence on firm strategy at all. Less than 30 percent of firms used federal funds to enter new industries and markets.[349]

For the majority of firms, federal R&D support thus at best supplemented existing R&D infrastructures and resources. Rather than solely relying on research programs targeted at wind and solar industries, supply firms made extensive use of resources, networks, and industrial practices familiar to them from prior activities. Broad macroeconomic institutions established long before the emergence of wind and solar industries further affected firms' strategies as they entered renewable energy supply chains.

Institutions for Skills, Training, and Employment Protection

Three sets of institutional resources were of particular importance in determining how firms from traditional manufacturing sectors took advantage of opportunities in emerging renewable energy sectors.

Firms interviewed for this project highlighted the importance of collaboration between their R&D engineers and their manufacturing workforce in developing technologies for wind and solar industries. For many products, such collaboration and bi-directional exchange was not just critical to improve the manufacturability of new designs, but at the core of trial-and-error based development processes that could not easily be modeled using computer-aided design (CAD) technologies. To foster collaboration between R&D and manufacturing staff, a number of firms located their R&D teams inside or in close proximity to manufacturing operations. Almost all German wind and solar supply firms

[349] Prognos AG et al. 2007, 262.

retained production activities close to their headquarters.[350] The CEO of a solar equipment manufacturer explained that "I couldn't imagine a situation in which our R&D didn't occur in the same building as production, or at least very nearby. These machines are not developed on a computer. There is a lot of tacit knowledge about what works and what doesn't work, which is why we expanded [from automobile supplies] into industries where we could apply knowledge we already had, while combining it with something new."[351]

In the opinion of executives, skills and training of their employees—R&D engineers as well as manufacturing staff—was at least as important to product development as the co-location of such activities. The recruitment of highly-skilled production workers and their continuous development were essential to allow them to identify problems in product development processes, suggest appropriate technical solutions, and implement these solutions together with R&D engineers. So closely linked were production and research activities in many of the small firms, that some did not formally differentiate between R&D teams and their manufacturing staff. According to the Director of R&D for the solar equipment supplier mentioned above, all production staff had gone through industry-specific training in Germany's vocational training system, but engineers had in most cases also completed an apprenticeship before entering university. Despite such rigorous practical training for production workers and R&D engineers, tacit knowledge acquired on the job was critical. "CAD and similar programs are unable to simulate the conditions that we find in our machines. So what we do instead is to build the machine and then test it, tweak the parameters, and then test it again. And so on. A lot of this process is tacit

[350] Germany Trade and Invest, 2011, "Photovoltaics—made in Germany." Berlin. Germany Trade and Invest, 2010, "Wind Energy Industry in Germany - A Sustainable Business in a Stable Environment." Berlin.

[351] Author interview, managing partner, solar PV equipment manufacturing, May 10, 2011.

knowledge. Our capital is the experience of our staff, and they didn't gain this [experience] in university, they learned it on the job."[352]

In finding, training, and retaining skilled workers, firms benefitted from broader labor market institutions. Firm collaboration through inter-firm networks and industry associations had maintained programs for highly industry-specific vocational training in the form of apprenticeships and, increasingly, dual degree programs (*duales Studium*) offering joint practical training and a university education at vocational universities (*Berufsakademie*). Together, firms ensured that individual companies continued to contribute to such programs by offering traineeships and extracted financial support from Länder and federal governments.[353] Although these skills and training institutions were not without challenges—firm participation in collaborative efforts declined over time, leading to calls for an 'apprenticeship tax' (*Ausbildungsplatzabgabe*) for firms unwilling to contribute, and growing numbers of high-school graduates were shut out of the vocational training system altogether as demand for apprenticeships continued to outstrip supply—from the perspective of manufacturing firms, the vocational training system continued to work well.[354] In a 2012 survey of more than 14,000 firms conducted by the Association of German Chambers of Commerce and Industry (DIHK), manufacturers in machinery and equipment sectors planned to offer permanent positions to 80 percent of their apprentices;

---

[352] Author interview, head of R&D, solar PV equipment manufacturer, May 11, 2011.

[353] Culpepper 1999; Ebner et al. 2013; Minks et al. 2011, III-V. On dual degree programs, see Ebner et al. 2013; Graf 2013; Streeck 1989, 37-38. For a history of the vocational training system with examples specifically from the metal-working industry, see OECD 1994.

[354] On changes in collaborative institutions, see Streeck 2009, esp. chapter 4. See also "Handwerk fürchtet Ausbildungsplatzabgabe." *Handelsblatt*, Feburary 27, 2004. "Betriebe flüchten aus der Ausbildung." *Handelsblatt*, March 12, 2013.

84 percent of firms indicated that ensuring access to skilled labor was their principal motivation to contribute to the vocational training system.[355]

At the same time, strong worker representation and employment protection legislation slowed employment turnover, even as a series of labor market reforms allowed for more flexible employment contracts.[356] Barred from organizational restructuring through large-scale hiring and firing, German manufacturers instead invested in training of their existing workforce to meet the skill requirements of new R&D and production activities.[357] To retain experienced production staff during recessions and seasonal downturns, federal short-time labor policies (*Kurzarbeit*) subsidized wages through policies akin to part-time unemployment support.[358] During the 2008-2009 economic crisis, for instance, a survey conducted by the German Engineering Federation (VDMA) showed that despite a 25 percent drop in orders, employment among VDMA member firms only shrunk 5 percent, in large part due to short-time labor subsidies.[359] In 2009 alone, the federal government spent Euro five billion on short-time wage subsidies for more than one million employees.[360]

By offering resources for sector-specific training and by ensuring long employment tenures, labor market institutions established long before the emergence of large-scale renewable energy industries had a lasting impact on the type of research and development activities firms could and sought to pursue as they entered wind and solar sectors.

---

[355] Deutscher Industrie- und Handelskammertag 2012, 29-30. For similar results reported in a broader survey across industries, see Wenzelmann et al. 2009.
[356] OECD 2012, 43.
[357] Culpepper 2001; Estevez-Abe et al. 2001.
[358] Bosch 2011; Eichhorst and Marx 2009; OECD 2012, 47.
[359] Author interview, VDMA Stuttgart, May 31, 2012.
[360] "Kurzarbeit rettet mehr als 300 000 Arbeitsplätze." *Handelsblatt*, October 1, 2010.

Financial Institutions and Firm Ownership Patterns

Just as research and development practices were influenced by labor market institutions that provided industry-specific workforce training and encouraged long employment tenures, financial institutions and firm ownership patterns shaped firms' strategies for competing in wind and solar industries. Germany's bank-based financial system offered few opportunities to fund the commercialization of new technologies through venture capital funds. Government attempts to create a venture capital sector had failed repeatedly, as funds suffered financial losses and were reluctant to invest in new firms and technologies.[361] Of venture capital invested in Germany in 1996, for instance, only 7 percent was spent on seed and start-up funding, and more than 60 percent of venture capital was invested in large established firms.[362] Even though the federal government injected nearly Euro 1.5 billion in venture capital funds between 2005 and 2006, overall venture capital activity remained at 0.06 percent of GDP, compared to 0.8 percent in the United States.[363] In 2011, a little more than a third of venture capital financing came from (mostly government-funded) organizations headquartered in Germany.[364] Not surprisingly, a number of studies identified the financial system as the main obstacle to research and development activities of young, innovative firms in high-technology industries.[365]

However, the scarcity of venture capital funding presented fewer barriers to existing firms seeking to diversify into wind and solar supply chains. Although wind and

361 Becker and Hellmann 2003; Mayer et al. 2005.
362 Giesecke 2000, 215.
363 Röhl 2010.
364 Zademach and Baumeister 2013. For 2011, the Zademach and Baumeister report even lower venture capital activity in Germany than Röhl, at 0.028 percent of GDP.
365 See, for instance, Kreditanstalt für Wiederaufbau 2006; Zimmermann and Hofmann 2007.

solar suppliers indicated in interviews that financial constraints prevented them from engaging in some high-risk activities and precluded them from conducting several R&D projects at once, they were able to fund multi-year research and development projects required to enter renewable energy supply chains. Because the development of wind and solar components for most firms presented a variation on existing R&D practices, firms were able to rely on funding sources they had used in the past. In doing so, some firms benefitted from long-term relationships with local credit unions (*Sparkassen*), which were willing to provide loans after demand-side subsidies had created stable market conditions for renewable energy sectors. Other firms reported either supplementing such loans with retained earnings or completely relying on internal funds for research and development activities. Among the firms interviewed for this project, the CEO of only one firm indicated floating a bond in order to finance the construction of a new production facility, adding that "financing has never been an issue for us."[366] Wind and solar suppliers reflected broader trends among small medium-sized businesses: a 2010 survey among firms that had received federal R&D assistance found that nearly 69 percent of R&D activities were funded through earned income or retained earnings. Only 6 percent of R&D funds came from bank loans, with the rest funded through grants and subsidies.[367]

Although loans and retained income provided relatively modest sums for R&D projects, particularly when compared to venture capital financing available to high-technology firms in the United States and Israel, these funds had few constraints attached to them and allowed firms to pursue long-term development strategies. Because development times of up to 4 years for a prototype were not uncommon for complex

[366] Author interview, CEO of solar equipment manufacturer, May 20, 2011.
[367] Belitz et al. 2012, 102.

components and production equipment, many firms could not generate revenue from investments in renewable energy R&D until years after the initial decision to enter wind and solar supply chains. Local credit unions were familiar with firms' R&D practices and thus willing to finance long-term development projects, and income generated from activities in other sectors could be used to cross-subsidize such activities in ways not possible for newly established firms.

The high share of family-controlled firms in Germany, particularly among small and medium-sized businesses, further assisted firms seeking to diversify into new sectors through complex, long-term research and development projects. Over the past 25 years, the share of family-controlled businesses among Germany's 100 largest firms remained relatively stable at around 20 percent, with significantly more family control among smaller businesses.[368] A survey by the German *Institut für Mittelstandsforschung* indicated that in 2002 more than two thirds of firms with fewer than 500 employees were sole proprietorships.[369] In interviews, managers of wind and solar suppliers repeatedly emphasized how owners' commitment to preserving the businesses for future generations both motivated diversification into emerging industrial sectors, while also making possible such development strategies by allowing firms to reinvest profits in R&D projects. The plant manager at a German generator supplier, for instance, explained that the family owners had not withdrawn funds from the business since the early 1990s, allowing the firm to reinvest its profits into diversifying from ship building into the wind turbine sector.[370] The CEO of an automation equipment manufacturer discussed entering the solar

---

[368] Lubinski 2011, 705.
[369] Günterberg and Kayser 2004, 12.
[370] Author interview, plant manager, generator supply firm, May 17, 2011.

business to reduce overexposure to the automobile industry by investing retained earnings when he took over the family business from his father.[371] Long-term planning horizons created a willingness to forgo immediate profits in favor of future returns, differing sharply from short-term strategies driven by maximization of shareholder profits.[372]

Resources for Collaborative Industrial Research

In contrast to training programs, firm ownership patters, and financial institutions, which influenced the resources firms could deploy internally to develop new technologies for wind and solar sectors, a third set of institutional tools helped firms access capabilities and resources outside the firm.

The development of new technologies, components, and production equipment for wind turbine and solar PV industries posed challenges particularly to small and medium-sized firms with small R&D teams and narrow technical capabilities. Limited R&D resources, which had long prevented smaller firms from absorbing new technologies generated by publicly funded R&D programs, constrained small firms' ability to develop new technologies, components, and equipment for emerging industrial sectors.[373] For all the capabilities such firms had historically acquired through activities in diverse industrial sectors—capabilities in the application of core technologies as well as competencies in managing long-term, complex, and trial-and-error-intensive R&D processes—the development of products for wind turbine and solar PV supply chains required the use of

[371] Author interview, CEO, solar equipment manufacturer, May 10, 2011.
[372] For an analysis of the impact of financial markets and shareholder value considerations on American manufacturing firms, see Davis 2009. For a discussion of long-term planning horizons of German family-owned manufacturing firms, see Berger 2013, chapter 5.
[373] Belitz et al. 2012, 51; Bruns et al. 2011, 55-56.

new materials, components, production processes, and industry standards. Particularly among smaller, more specialized firms seeking to compete in wind and solar industries, the capabilities required to master such product development processes could not all be found or maintained within the four walls of the firm.

The importance of external capabilities was most obvious in the process of *integration*, in which firms strategically chose new technologies and associated capabilities to complement existing skills. However, albeit less visibly, other modes of industry entry and subsequent product development processes equally required capabilities that firms did not possess in-house. In order to master specifications for new components, find materials capable of withstanding the stresses of new applications, and utilize novel production processes, firms turned to external partners. As I introduced in chapter 2, for small and medium-sized suppliers in renewable energy industries such partners in many cases were larger wind turbine and solar PV manufacturers, both domestically and abroad. Other firms turned to universities, research institutes, and contract researchers for help. However, in a situation somewhat unique to Germany, many small and medium-sized firms —in renewable energy industries and the manufacturing sector more broadly—also collaborated with each other, pooling resources and sharing capabilities across sectoral boundaries to meet product development challenges.

In their reliance on external capabilities, small and medium-sized German firms in wind and solar sectors built on a long tradition of collaborative research and development activities in German industry. Starting in the late 19th century, German manufacturing firms had begun organizing themselves in research networks to find suitable partners for joint R&D projects. By 1939, just prior to World War II, 19 such research networks had been created; by 2011, 101 industrial research associations were facilitating collaborative research activities amongst member firms.[374] Because these research associations were often set up through industry associations, the vast majority were organized along sectoral lines. Of the 101 research associations active in 2011, 91 focused on a single industry, including machinery and equipment manufacturing; chemicals, plastics and rubber sectors; and the production of energy generation equipment. Ten research associations had an interdisciplinary focus. By 2011, a total of 50,000 firms were directly or indirectly (through branch organizations) organized in research associations.[375]

Although research associations relied on industry associations to find members, set up collaborative research projects, and at least partially fund research through member dues, the state played a critical role in encouraging joint research efforts. In 1954, a Federation of Industrial Research Associations (*Arbeitsgemeinschaft industrieller Forschungsvereinigungen)* was established to facilitate interdisciplinary projects across sectoral boundaries and to represent the interests of research associations to the government. In the same year, the Federal Ministry of Economic Affairs began supporting collaborative research projects through subsidies and research grants.[376] Initially, the main justification for federal support for industrial collaborative research (*Industrielle Gemeinschaftsforschung*) was to level the playing field for SMEs, which were assumed to suffer from a competitive disadvantage in an economy increasingly populated by large diversified companies. Over the years, however, as SMEs were no longer regarded as

---

374 Rothgang et al. 2011, 398.

375 Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 79; Rothgang et al. 2011, 400-01.

376 A number of *Länder* governments later began to also fund collaborative industrial research, complementing federal policies. Rothgang et al. 2011, 398.

structurally disadvantaged legacies but rather understood as integral parts of Germany's innovation economy, the reasoning behind continued support for collaborative research shifted to the creation of spillovers and other positive externalities from encouraging R&D in SMEs.[377]

Despite the shifting motivation for state involvement in collaborative research, the policies and institutional resources provided to foster such collaboration remained relatively stable over time. At the core, state support for industrial collaborative research (ICR) entailed R&D funding for research projects that involved partnerships between several firms and research institutes.[378] Among firms, both SMEs and large diversified businesses were allowed to participate in order to foster supportive relationships between large firms and their smaller, specialized suppliers. Participating research institutes included universities, industry research institutes funded by industry associations, as well as non-university institutions such as Germany's large number of Fraunhofer and Max Planck Institutes. Funded projects were by definition pre-competitive: in order to quality for funding, projects could not target the development of commercializable products, but needed to focus on the development of technologies and materials with multiple potential applications in a range of future products. Results of ICR projects were shared among all

---

[377] For a full discussion of the motivation behind such programs and changes in the justification of subsidies for collaborative research over time, see Eckl and Engel 2009; Rothgang et al. 2011.

[378] In addition to the programs for industrial collaborative research, other government R&D programs provided bonus funding for projects involving several partners. For instance, ZIM (*Zentrales Innovationsprogramm Mittelstand*), which provided R&D funding targeted specifically at SMEs, dispensed R&D grants to individual firms, but increased funding for projects that involved multiple partners or entire clusters of firms. Author interview, department head, Federal Ministry of Economics and Technology, May 24, 2012.

members of participating research associations, although direct involvement in the project was in many cases necessary for firms to be able to utilize research findings.[379]

In contrast to other federal R&D funding schemes, such as the energy research programs (*Energieforschungsprogramme)* introduced above, ICR projects were developed by firms without thematic requirements.[380] As members of research associations, firms could suggest ideas for new projects at association meetings, find partners for collaboration, and identify research institutes with expertise in solving the particular problem at stake. In finding partners for R&D collaboration, firms explicitly targeted partners with different technical capabilities, R&D resources, and priorities in product development.[381] A planning group of participating firms was formed for each project, which subsequently defined the exact scope of the R&D undertaking, and jointly submitted applications for federal funding under one of the ICR programs. In addition to government grants, associations funded projects through membership fees, and individual firms were expected to contribute funds, R&D staff, and equipment. In some cases, donations by larger firms made possible more costly R&D projects.[382] Industry contributions allowed relatively modest sums of federal government support—in 2008, Euro 123 million in federal subsidies were spent on ICR funding and a total of Euro 2.6 billion have been dispensed since the inception of ICR programs in 1954—to initiate much larger R&D efforts.

---

[379] Author interview, director of research association in the machinery and equipment sector, May 25, 2012

[380] Eckl and Engel 2009, 4.

[381] For detailed results of a survey of R&D intensive firms engaged in collaborative projects, see Windolph 2010, 7. For results specifically for the PV industry, see Seemann 2012, 353.

[382] Author interviews: director of research association in the machinery and equipment sector, May 25, 2012; department heads, Federal Ministry of Economics and Technology, May 24 and June 4, 2012. See also Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, chapter 3.

Estimates suggest that as little as 15 percent of funds spent on ICR projects came from government coffers.[383]

The long history of federally-funded collaborative research and the institutional infrastructure of research associations covering virtually every part of the manufacturing industry made joint research efforts a common occurrence in German industry. In two surveys conducted by Rothgang, Peistrup, and Lageman, firms indicated that participation in ICR projects not only served short-term R&D needs, but also provided information about long-term technical developments and established relationships with firms from a variety of industries and research institutes with different disciplinary backgrounds.[384] Between 2005 and 2009, some 500 funded ICR projects were started annually, with more than 1500 projects conducted at any one time. In addition to the 50,000 firms organized in Germany's research associations, some 700 research institutes participated in ICR projects during that time.[385]

As firms from Germany's traditional manufacturing sectors began to develop products and components for rapidly growing wind and solar industries, they relied ICR programs to solve concrete technical challenges and benefitted from relationships with other firms and research institutes that had been established through previous participation in collaborative projects. Even in the absence of research associations established specifically for renewable energy sectors, firms were able to access federal ICR funding and enter interdisciplinary research networks through participation in one of the

383 Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 399.
384 Rothgang et al. 2011, 408.
385 Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 28-29.

many associations set up for existing industrial sectors. Within the open, bottom-up structure for research collaboration that was in large part shaped through the input of individual member firms, collaborations in wind and solar sectors manifested in a wide range of forms.[386] For some firms, collaboration simply meant working closely with end-customers for products and components.[387] As I introduced in chapter 2, such relationships initially focussed on wind and solar manufacturers in Germany, but increasingly involved international partners as sizable renewable energy industries emerged in China and elsewhere. Other firms used ICR networks to fund collaboration with research institutes or used contacts from past collaborative projects to independently facilitate collaboration with external research centers. The CEO of a manufacturer for production equipment for solar modules, for instance, recalled using such ties to establish a cooperation with the Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg.[388]

In some cases, firms participated in projects set up by associations from other sectors. For example, the director of a research association for the machinery and equipment sector established by the German Engineering Federation described how small suppliers and a multinational wind turbine manufacturer participated in interdisciplinary projects on the development of new alloys that none of the partners could have created in-house.[389] In yet other cases, firms formed larger clusters, seeking funding both through regional development programs for high-tech clusters set up by the Federal Ministry of

---

386 Bouncken 2004; Rheinisch-Westfälisches Institut für Wirtschaftsforschung and WSF Wirtschafts- und Sozialforschung Kerpen 2010, 75; Seemann 2012.

387 This form of collaboration was especially common in Germany, where SMEs were not formally tied to larger conglomerates and could freely pick partners among their customers. For a comparison of innovative collaborations in German and Japanese machinery and equipment firms, see Braun 2001.

388 Author interview, CEO, solar module equipment manufacturer, May 10, 2011.

389 Author interview, director of research association in the machinery and equipment sector, May 25, 2012

Education and Research and through traditional ICR programs for individual projects conducted within the group. For instance, Solarvalley Mitteldeutschland, a cluster comprised of 29 firms, nine research facilities, and four universities, received federal cluster funding and individual support for some 98 collaborative projects conducted by members along the entire solar PV supply chain.[390]

The reliance on external capabilities through research and development collaborations was not a novel strategy for small- and medium-sized firms seeking to enter wind and solar sectors, but rather the continuation of existing practices from Germany's traditional manufacturing industries. Wind and solar firms were able to utilize a vast infrastructure for facilitating and funding precisely this type of collaboration, through participation in one of the many industrial research associations, and by receiving government support for collaborative R&D efforts. By requiring multiple research partners for a number of government R&D programs, the state encouraged firms not only to maintain existing collaborative practices, but motivated new firms to take advantage of external capabilities. In a survey of 60 firms in the solar PV industry, 72 percent of firms which had received public support for collaborative research stated that they would not have participated in the absence of government subsidies. Seventy-four percent of all respondents had partaken in collaborative R&D efforts.[391] Active research associations for a wide range of industrial sectors and government subsidies for collaborative R&D both encouraged and maintained collaborative research and development practices in

[390] Author interview, CEO, solar PV supplier, May 18, 2011. See also: Florian Vollmers, "Im Osten Detuschlands geht die Sonne auf." *Handelsblatt*, June 2, 2008. For information on individual projects conducted within the cluster, see http://www.bmbf.de/en/20870.php [Accessed September 10, 2013].

[391] Seemann 2012, 355-59.

Germany's manufacturing industries—practices which particularly small and medium-sized firms retained as they entered emerging wind and solar sectors.

Rather than depend on R&D funding specifically targeted at renewable energy sectors, wind and solar suppliers largely relied on resources and institutional structures from existing industrial sectors, and, in doing so, retained research and development practices characteristic of Germany's broader manufacturing industries. Although firms were developing new-to-the-world products and components for emerging industrial sectors, resources and institutional structures encouraged continuity with existing industrial practices. Complex, long-term, and trial-and-error intensive research and development practices prevalent in Germany's machinery, equipment, and automobile supply industries thus became common in Germany's emerging wind and solar supply chains as well.

5. Conclusion

The establishment of Germany's dense supply chains in wind and solar industries cannot be understood as a direct outcome of sectoral industrial policy. As I have discussed in this chapter, federal subsidies for renewable energy markets encouraged firms to enter wind and solar sectors and to mobilize in protection of legislative support. However, demand-side subsidies did not determine which firms were taking advantage of new opportunities in renewable energy industries and what industrial capabilities they built in the process. At the core, it were entrepreneurial firms in Germany's existing industrial sectors that shaped the development of wind and solar supply chains by applying their industrial capabilities to opportunities in emerging industries. Policy-makers neither anticipated the large-scale response on part of existing firms, nor did R&D funding and other policies specifically targeted at renewable energy sectors provide much support for existing firms seeking to apply their skills to wind and solar sectors. Instead, firms utilized public resources and institutions intended to support traditional sectors in the course of entering renewable energy industries. Although the stability of domestic markets was an important factor in persuading small- and medium-sized suppliers to respond to new opportunities in renewable energy sectors, it were the existing institutional infrastructure and public resources provided for the broader manufacturing economy that ultimately allowed these firms to enter in large numbers.

Stable markets alone, these findings suggest, are insufficient to create dense wind and solar supply chains, as sectoral industrial policies are only able to achieve such outcomes only by building on existing industrial legacies. Labor market and training institutions, the banking system, firm ownership structures, and Germany's infrastructure for collaborative industrial research did not result from sectoral policy interventions intended to facilitate the creation of specific industries. However, as resources created for the manufacturing industry more broadly, they supported firms through the process of industrial transformation and encouraged firms to bring with them existing industrial practices into emerging renewable energy sectors. Often regarded as obstacles to the creation of new, high-technology industries in Germany, these institutions became critical tools for the establishment of dense wind and solar supply chains.

In recent years, Germany's large manufacturers of solar cells and panels have come under growing pressure from Chinese competitors, which have built up vast manufacturing capacity and have flooded German solar markets with low-cost solar panels. The increasing technical proficiency of Chinese wind turbine suppliers has reduced cost for standard wind turbine components, making it difficult for German manufacturers to succeed with a focus on customization and small-batch production. This has led to a string of bankruptcies in German renewable energy sectors, especially in the solar industry, where most large manufacturers of cells and modules went out of businesses between 2011 and 2013, unable to compete head-on with Chinese manufacturers that had many times the production capacity of those in Germany.

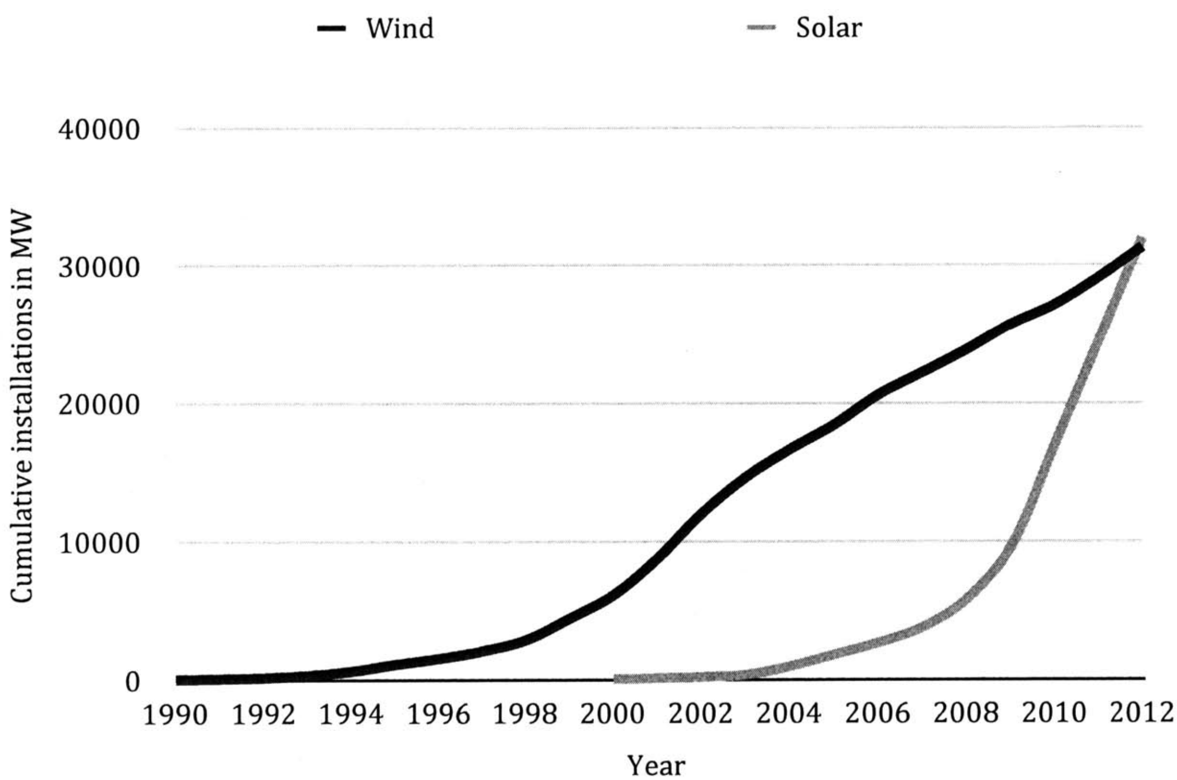
By contrast, Germany's small, specialized suppliers of custom components and production equipment have been remarkably resilient, with many working with and benefitting from China's growing wind and solar manufacturers. In the shadow of high-profile bankruptcies of solar manufacturers such as Q-Cells—precisely the type of firms that government R&D policy supported through a focus on lab-based innovation in early R&D funding programs—suppliers of production equipment for solar fabs were able to further expand their production through exports to Asia. In the wind sector, suppliers have shifted their focus to complex off-shore applications as competition increased in the market for standard componentry. Although specialized suppliers have not been immune to industry crises such—in particular the global decline in demand for renewable energy products after governments froze subsidies in the wake of the global financial crisis in 2008—their ability to repurpose core strengths for new applications and the opportunity to work with global partners on product development has lent them remarkable flexibility. The fragmentation of production and the decline of the vertically integrated firm allowed these suppliers to contribute their skills to a wide range of product development processes with partners from around the world, making them increasingly independent from the fate of local assemblers. Here, too, previous experience in export-intensive industrial sectors may have been beneficial.

Without doubt, Germany's densely populated supply chains of highly specialized firms were critical elements in the evolution of global wind and solar sectors from niche production to mass manufacturing. As I have outlined in chapter 2, German suppliers brought much needed manufacturing experience to renewable energy industries beginning in the early 1990s, at a time when manufacturers of wind turbines and solar panels were relying on experimental production techniques using equipment and components borrowed from other sectors. The specialized capabilities of German suppliers were a key ingredient in the professionalization of production not just in German wind and solar industries, but affected the development of these sectors globally.

The state played an important role in establishing these dense supply chains, not least by creating local markets for wind turbines and solar panels, and through resources provided for small and medium-sized firms in the broader manufacturing industry. As this chapter has shown, however, the state did not deliberately create the supply chains structures and firm capabilities that ultimately proved so important to global renewable energy industry development. Rather, rich fabrics of existing networks, resources, and supportive institutions made it possible for small and medium-sized firms to enter wind and solar supply chains. By determining both which firms could respond to new opportunities in wind and solar sectors and how these firms chose to compete in renewable energy industries, industrial legacies were critical in shaping the process of industrial transformation set in motion by Germany's renewable energy legislation. Ultimately, it were small, entrepreneurial firms in traditional industrial sectors that used their existing industrial capabilities, creatively utilized and repurposed government support, and applied themselves not just to German wind and solar industries, but quickly found opportunities for collaboration in global renewable energy supply chains.

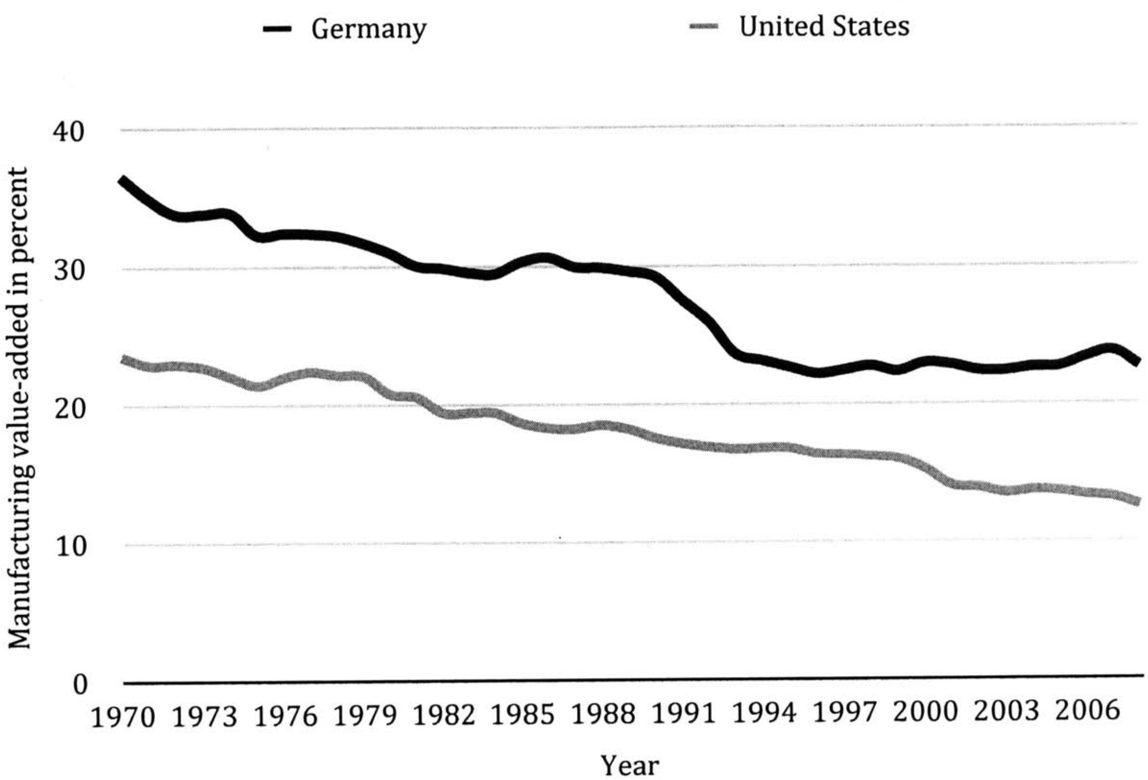
Figures and Tables

Figure 1: Wind and Solar Installations in Germany, 1990-2012 (in MW)



Source: Earth Policy Institute, 2014.

Figure 2: Manufacturing Value-Added as Share of GDP, Germany and the United States, 1970-2008 (in percent)



Source: OECD STAN Indicators Database, 2014.

Chapter 4: Innovative Manufacturing in China's Wind and Solar Sectors

1. Introduction

China is an unlikely location for the development of innovative industrial capabilities in renewable energy sectors. Literatures on economic development, particularly those based on the experience of other East Asian economies, have long described the process of industrial upgrading as one of replication and imitation of firms in more advanced economies.[392] According to such theories, the establishment of knowledge-intensive capabilities is a process of learning from technological leaders by emulating their practices from the shop floor to advanced R&D. Despite its status as a middle-income economy, however, China's wind and solar firms have not emulated technological leaders, but have specialized in innovative capabilities unique to Chinese firms. These contributions of Chinese wind and solar firms to the development and commercialization of high-technology products in global production networks break with patterns set by firms in other East Asian economies, which long produced cheap replicas of established products before catching up to the technological leaders in the West.

Amidst an industrial transformation that led China to overtake the United States as the world's largest emitter of greenhouse gases in 2007, China has also become the location of the world's largest wind and solar energy industries.[393] Over the course of the past 15 years, China's renewable energy firms have launched manufacturing facilities capable of producing more wind turbines and solar panels than the rest of the world combined—outcompeting firms in Western Europe and the United States, which dominated renewable

---

[392] This point is most explicitly made by Amsden 1989; Amsden 2001; Kim 1997.
[393] For a breakdown of the drivers of China's greenhouse gas emissions see Guan et al. 2009.

energy sectors during previous decades. As shown in Figure 1, between 2000 and 2010 alone, China increased the domestic production of solar modules from 3 megawatt (MW) to 10,852 MW, while wind turbine manufacturing grew from 80 MW to almost 19,000 MW annually.[394] China's gains in wind and solar manufacturing exceeded the rapid growth of China's overall manufacturing sector, whose combined share of global manufactured output nearly quadrupled over the same period and made China the largest manufacturing economy in the world.[395]

Even more remarkable for firms from a middle-income economy entering emerging high-technology industries, however, has been the ability of China's wind and solar manufacturers to participate in the development and commercialization of new-to-the-world wind and solar technologies. As I have introduced in Chapter 2, the engineering capabilities of China's renewable energy firms at the intersection of lab-based R&D and manufacturing have contributed to the maturation of global wind and solar industries from niche production to mass manufacturing. These capabilities in innovative manufacturing have allowed Chinese firms to rapidly prepare complex technologies for mass production, through changes to the manufacturing process itself, but also through the improvement of product designs. As a consequence of such expertise in bringing complex technologies to market, foreign innovators have come to China not just to access the domestic market, but also to learn from and partner with Chinese firms on the commercialization of renewable energy technologies. Many recent technological advances in wind and solar energy technologies—including selective emitter solar cells and gear-less wind turbine designs—

---

[394] Data compiled by Earth Policy Institute, 2013. Available from www.earth-policy.org/data_center.
[395] See UNIDO 2011. Peter Marsh, 2011. "China noses ahead as top goods producer." *Financial Times*, March 13.

were first brought to market through collaboration with Chinese firms.[396] China's renewable energy firms succeeded in contributing innovative capabilities to global networks for the development and commercialization of wind turbines and solar panels, much unlike firms in other developing economies, which have often failed to enter global supply chains in emerging industries altogether.[397]

In the global policy community, where China's rise in wind and solar industries has been observed with trepidation, many have pointed to government subsidies as the reason why Chinese firms were so rapidly able to climb the ranks of wind and solar supply chains. Regardless of whether such subsidies originate in central or local government coffers, these observers contend, they have allowed Chinese firms to license foreign technologies, invest in large manufacturing plants, and outcompete foreign competitors in global markets.[398] China's wind and solar firms have indeed received extensive government subsidies, most importantly in the form of loans from state-owned banks. Estimates suggest that the China Development Bank (中国开发银行) alone provided loans totaling USD 29 billion to 15 solar and wind companies at the request of the Chinese central government.[399] Even if interest

396 Berger 2013, 149; Nahm and Steinfeld 2014.

397 With the exception of India, where one main firm, Suzlon, has become a global player in the production of wind turbines, few firms from developing economies compete in global wind and solar markets. However, some states, such as Malaysia, have attracted manufacturing plants for solar panels, others, such as Brazil, have established supplier industries for global wind turbine producers. See Lewis 2007; Lewis 2011; Lewis and Wiser 2007.

398 Bergsten 2010; U.S. International Trade Commission 2012. See also Keith Bradsher, 2010. "On Clean Energy, China Skirts Rules." *New York Times,* September 8.

399 For journalistic reports on Chinese lending, see Sally Bakewell, 2011. "Chinese Renewable Companies Slow to Tap $47 billion in Credit." *Bloomberg,* November 16. "JinkoSolar Gets $1 Billion Infusion from Chinese Development Bank." *Sustainable Business News,* December 12, 2012. The issue of subsidies to Chinese renewable energy firms is also raised in Deutch and Steinfeld 2013, 4. For a discussion of subsidies to Chinese industries more broadly, see Haley and Haley 2013.

rates involved in such transactions are rarely publicized, it is safe to assume that many of these loans have been provided at below-market rates.[400]

Reducing the process of industrial upgrading entirely to government subsidies is problematic, not least because China has hardly been the only economy where governments have attempted to spur the growth of renewable energy sectors with government handouts.[401] For all the subsidies provided to wind and solar sectors around the world, few locations have developed renewable energy industries as rapidly as China, and virtually none have developed the same skills in innovative manufacturing as Chinese firms. More broadly, beyond the immediate context of renewable energy industries, subsidies have been part of nearly every economic development endeavor, but have rarely been associated with learning and the establishment of true capabilities. Scholars have warned that subsidization can breed complacency among firms, preventing precisely the type of learning that occurred among China's wind turbine and solar panel producers.[402] High levels of subsidization alone, therefore, are insufficient to explain the development of knowledge-intensive capabilities in emerging industrial sectors.

Yet even from the perspective of statist literatures on economic development, which have provided a more nuanced perspective on the role of the state in fostering industrial upgrading, the development of innovative capabilities in Chinese wind and solar firms is unexpected. In contrast to the East Asian developmental states, in which centralized and hierarchical planning bureaucracies orchestrated targeted policy interventions to support

[400] Goodrich et al. 2013, 2814.

[401] In the United States, the federal loan guarantee program alone provided USD 13 billion of low interest financing to renewable energy firms between 2009 and 2011. Platzer 2012a, 24.

[402] For this reason, Alice Amsden emphasized the importance of disciplinary mechanisms in post-war Korea, under which government support to firms was contingent on meeting performance and upgrading requirements. Amsden 1989, 145-47; Amsden 2001, 8-12.

technological learning and industrial upgrading, China's industrial policy framework has been highly dispersed.[403] Although the central government in Beijing has provided various incentives for technology transfer and the establishment of advanced R&D capabilities in Chinese firms, responsibility for policy-making has spread across numerous ministries and administrative levels. Particularly at the provincial and municipal level, governments have followed divergent policy goals, often in blunt contradiction of central government directives. Localities have supported local manufacturing businesses, resorted to regional protectionism, and resisted central government calls to facilitate the creation of national champion firms through industry consolidation.[404]

Why were China's wind and solar firms able to beat the odds of late development by establishing knowledge-intensive capabilities in emerging high-technology sectors? In this chapter, I propose that neither subsidies nor strategic industrial policy alone can fully account for China's upgrading outcomes. My findings suggest that Chinese firms responded to opportunities for collaboration with foreign partners on the rapid commercialization of wind and solar technologies by building on existing capabilities in mass manufacturing. In doing so, firms utilized government resources, including subsidies, provided both by the central government in Beijing and subnational administrations at the provincial and municipal level. Although the state enabled firms to participate in collaborative product development and commercialization by supplying the type of resources and institutional infrastructure that firms required in the process of technological learning, it did not fully determine how firms specialized and which resources they utilized in doing so. Firms used

[403] On strategic government intervention among the East Asian developers, see Amsden 1989; Amsden 2001; Evans 1995; Johnson 1982; Wade 1990.
[404] See, for instance, Huang 2002; Thun 2006, 52-60.

the state as a platform on which to pursue individual upgrading strategies, by drawing on institutions, policies, and incentives provided by a wide range of government agencies far beyond the domain of renewable energy policy and by connecting them to upgrading opportunities in global production networks. It were entrepreneurial firms themselves that identified opportunities in global supply chains and deployed the tools available to them in China's industrial ecosystem to build on existing skills in mass manufacturing.

The data presented in this chapter suggest that three factors jointly enabled the incremental establishment of capabilities in innovative manufacturing among China's wind and solar firms. First, Chinese government industrial policies and new opportunities in global wind and solar energy markets created incentives for entry, mobilized domestic interests in support of renewable energy industries, and encouraged the establishment of innovative capabilities among domestic firms. Such policies comprised subsidies and utility regulations to create a domestic market demand for wind turbines, but also included a host of programs intended to foster the development of independent research and development skills among Chinese firms, often summarized under the rubric of China's "indigenous innovation policies."[405] At the same time, the attraction of foreign direct investment, a central component of China's development strategy, brought global partners for collaboration to the vicinity of domestic firms.[406] Incentives for technology transfer encouraged relationships with local firms. In addition, subsidies for solar PV markets provided by foreign governments, particularly in Western Europe, created commercial

[405] On China's indigenous innovation policies, see Cao et al. 2006; Ernst 2011a; Liu and Cheng 2011.
[406] The attraction of FDI into Chinese development zones was a key policy strategy not only to create local economic growth, but was also tied to expectations about technology transfer to domestic firms. Roughly 70 percent of FDI in China has been in manufacturing, increasingly focused on the production of high-technology products. See Naughton 2007, Chapter 17.

opportunities for Chinese firms even for solar manufacturers, which did not benefit from domestic demand-side subsidies until recently.[407]

Second, the existing industrial landscape of manufacturing industries determined the range of actors who were able to respond to new opportunities in wind and solar sectors and the kinds of specializations, skills, and templates for competitiveness that firms brought with them when they did so. Whether firms spun off state-owned heavy machinery conglomerates, as was common in the wind energy sector, or were founded by foreign-trained returnees, as were many of China's solar firms, the legacy of mass manufacturing influenced hiring practices, templates for interaction with global supply chains, and the range of capabilities available to firms among local suppliers.

Third, in entering renewable energy industries, wind and solar firms repurposed resources from China's rich institutional ecosystem for the manufacturing economy, which was in large part maintained by provincial and municipal administrations. Historically rooted in a set of fiscal reforms that created incentives for local governments to promote local economic development throughout the 1980s and early 1990s, many of these resources—including land grants, tax breaks, training institutions, and production infrastructure such as test centers and certification bodies—were not targeted specifically at renewable energy industries, nor were they fully compatible with the emphasis on indigenous innovation and autonomous technology development prevalent in central-level policy-making.[408] For wind and solar firms seeking to compete in global renewable energy

---

[407] An overview of German and U.S. subsidies for solar PV markets can be found in Grau et al. 2012; Laird and Stefes 2009.

[408] For a discussion of fiscal decentralization and its effect on economic policy-making at the subnational level, see Oi 1995, 1137-45; Oi 1999, chapters 2-4; Wong 1991, 707-08. For examples of the role of China's subnational governments in fostering local industrial development, see, for example, Segal 2003; Segal and Thun 2001; Thun 2006.

industries, however, these resources were easily accessible in local development zones, familiar from past activities, and permitted incremental layering of new, innovative capabilities on past industrial practices.

The remainder of the chapter is structured along a discussion of these three factors, showing how for each of them, entrepreneurial firms repurposed resources, policies, and institutions—provided not just for renewable energy sectors, but for the broader manufacturing economy—to compete in wind and solar supply chains.

2. China's National Framework for Wind and Solar Sectors

China's central government took an early interest in renewable energy technologies as a way to meet the rapidly growing energy demand caused by population growth and industrialization. Relative to the size of its population, China possesses few natural resources; coal reserves, the one exception, are located far from the centers of industrial activity. Already during the course of the 1980s, after the onset of economic reforms fueled of flurry of economic activity in both urban areas and among town and village enterprises in rural districts, frequent energy shortages were of concern.[409] Trade ties to foreign oil and coal producing countries had withered during decades of isolation and economic self-sufficiency and the cost of imported resources was high.[410] Domestically, the heavy use of firewood as a source of fuel had caused deforestation, desertification, and widespread soil erosion.[411] As a consequence, renewable sources of energy were explored in China as a near-term option to electrify rural areas not yet connected to national electric grids; in the long term, China's leadership was investigating renewable sources of energy as means to power China's industrial aspirations.[412]

From the first technical trials of imported wind turbine technologies in the mid-1980s, central government policies to support domestic renewable energy industries were guided by a desire to create energy technologies that were both affordable and

[409] On town and village enterprises (TVEs), which drove much of China's economic growth during the early post-reform era, see Naughton 1994, 267-68; Oi 1992, 115-17. Although China remained a net exporter of oil throughout the 1980s and had sufficient coal reserves, the geographical distribution of reservers and limited infrastructure caused regional shortages. Hu 1991, 5-7. For a broad overview of energy supply and security issues during the 1980s and early 1990s, see Wu and Li 1995; Zha 2006.
[410] Wu and Li 1995, 170-71; Zha 2006, 179-80.
[411] Zhang et al. 2009a, 2815.
[412] Hu 1991, 5-7.

indigenous in the sense that they were developed and produced by Chinese firms. Unlike in Germany, where the federal government somewhat unintentionally enacted a legislative framework to mobilize domestic interests in support of renewable energy industries, China's central-level policy framework openly promoted such opportunities for domestic firms. This was case in the wind industry, which received government support to build domestic technological capabilities since the mid-1980s, including local content regulations and incentives for technology transfer for foreign-invested firms. Yet even in the solar sector—once it was subject to central government policy-making beginning with the 11th five-year plan in 2006—the goal of technology independence guided central-level policy-making.[413] In that sense, China's central-level policies for wind and solar industries were primarily industrial policies targeted at building technological capabilities in domestic firms, not climate or energy policies.

The policy framework for renewable energy technologies thus mirrored broader government goals to catch up with technological leaders in the West, first by importing technologies, then by promoting foreign direct investment, technology transfers, joint ventures and other learning opportunities through commercial collaboration with foreign partners, and, ultimately, by supporting indigenous innovation among domestic firms.[414] Table 1 summarizes these shifting government priorities, using as an example the National Torch Program, which established for high-technology zones for startups based on

[413]Although the central government had paid little attention to mostly privately-founded solar firms during the early 2000s, it declared solar PV production a strategic emerging industry (SEI) in 2010, shortly before it began prioritizing the domestic development of production equipment, which solar firms had long sourced from foreign firms. See National Energy Administration 2011; State Council 2010.
[414] OECD 2008, chapter 8.

domestic technologist starting in the late 1980s. The remainder of this section traces the shifts in science and technology making through the reform era.

Science and Technology Reforms and Technology Imports, 1978-1995

Apart from small-scale wind turbines for off-grid use and solar panels for space applications, China had invested little in renewable energy technologies in the postwar decades. The shutdown of its science and technology institutions during the turmoil of the cultural revolution had further increased the gap between renewable energy research conducted in the West and China's domestic capabilities. The onset of far-reaching economic reforms starting in 1978 spurred a renewed interest in China's domestic science and technology capabilities, which had languished under the institutional rigidity of the planned economy. In the early 1980s, the central government began reforming China's science and technology institutions, which had previously emulated the Soviet model of central state control, central planning, and complete absence of private sector participation in research and development.[415] In 1985, the State Council issued its first of three main decisions to update science and technology practices to keep up with ongoing market reforms. Funding systems were improved and programs for R&D funding among startups initiated. A "key technology R&D program" now provided funding for university research in technology areas of broad societal importance, including new energy technologies and solutions to environmental pollution.[416] Universities and research institutes were encouraged to spin off promising developments into independent companies and urged to focus on applied, commercializable technologies in their research. In March 1986, the

[415] OECD 2008, 383-84.
[416] OECD 2008, 443. The program was formally launched in 1982.

government launched the National High Technology Research and Development Program, also referred to as 863 Program, which to this day provides competitive grants for applied research in research institutions and enterprises, including in the energy sector.[417] The Torch program, initiated in 1988, began offering incubator services for start-ups in dedicated high-tech development zones.[418]

Although these reforms improved China's infrastructure for research and development and sowed the seeds for emerging technology markets, in the short term they provided few incentives for state-owned firms to develop new technologies or commercialize existing ones. S&T funding levels remained low and technology imports continued to substitute for domestic capabilities. In the energy sector, trials with grid-connected wind power generators relied on imported turbine technologies rather than improvements of smaller domestic designs that were already used for remote applications.[419] As part of international development programs established by European governments, a first batch of Vestas turbines was imported from Denmark in 1985; models produced by Denmark's BONUS and small UK and Belgian firms were tested in China in the following years.[420] All in all, some 23 cooperative projects on renewable energy technologies were set up under the Seventh Five-Year Plan (1986-1990) between foreign partners and Chinese organizations.[421]

---

417 Gabriele 2002, 335-36; OECD 2008, 386, 455-56.
418 Suttmeier and Cao 1999, 164. See also Heilmann et al. 2013.
419 He and Shi 1991, 56-57.
420 He and Shi 1991, 56-57; Xia and Song 2009, 1968.
421 Hu 1991, 6.

High-Tech Industrialization with Foreign Partners, 1995-2006

As part of China's renewed commitment to economic reform in the early 1990s, the improvement of domestic science and technology capabilities also took on new urgency. By 1993, under China's strategy of "walking on two legs"—reforming it's domestic S&T institutions while sourcing key technologies abroad— China had spent USD 70 billion on technology imports.[422] Such purchases of foreign technologies, particularly of production equipment and machine tools, improved productivity and product quality in the domestic manufacturing sector, yet they were of little help to the establishment of improved technological capabilities among domestic firms. Beginning in the mid-1990s, a second set of initiatives aspired to use foreign technologies more instrumentally for the improvement of domestic capabilities and shifted China's developmental model "to reliance on scientific and technological progress and improvement of the quality and skills of the labor force."[423] The *1995 Decision on Accelerating S&T Progress* set a target of increasing gross expenditures for R&D from 0.57 percent in 1995 to 1.5 percent of GDP by 2000 and called for a greater proportion of R&D activities to be carried out in enterprises rather than research institutes.[424]

At the same time, the central leadership's focus on high-tech industrialization and the aspiration to compete in the global knowledge economy began to be viewed as a potential alternative to the predicament of smoke-stack industrialization, as ever more visible levels of environmental degradation sparked debate about the need to find a path toward sustainable development. According to Suttmeier and Cao, the debates indicated

---

[422] Suttmeier and Cao 1999, 158.
[423] OECD 2008, 387.
[424] Gabriele 2002, 337.

that "China sees its 'train' to the knowledge economy as a ride to a green future as well."[425] The shifting priorities in science and technology policy where accompanied by changes in the governance of the energy sector, as policy-making was centralized in the State Development Planning Commission and the former industrial ministries were dismantled and turned into state-owned enterprises. In 1998, the State Environmental Protection Agency was set up along with a State Electricity Regulatory Commission to oversee the growing number of enterprises in the electricity sector.[426] China's first central-level industrial policies for the renewable energy sector were established in this context of weak domestic technological capabilities, dawning environmental awareness, and aspirations to build domestic high-technology industries.

Throughout the 1990s, energy policy prioritized the establishment of a domestic wind industry over other emerging renewable energy technologies, as wind turbines had already been tested in large-scale installations in California during the 1980s and were far more affordable than solar power at the time.[427] In encouraging the development of an indigenous wind industry, the government pursued a three-pronged strategy of creating domestic markets, supporting R&D efforts by local enterprises and research institutes, and providing incentives for foreign firms to localize manufacturing and transfer technology to local partners. Already in 1994, the Ministry for Electric Power had mandated the purchase of wind-generated power from turbines installed on demonstration sites. Under the Ninth Five Year Plan (1996-2000), designated funds for wind turbine R&D were added to China's

[425] Suttmeier and Cao 1999, 170.
[426] Karplus 2007, 8-9.
[427] China had extensive installations in hydropower, which had been used for rural electrification during the Mao years. In 1984, more than half of China's counties had small-scale hydro dams for local power generation. Technically, wind was China's second renewable energy industry. China Yeh and Lewis 2004, 443.

863 program for applied research, a 40 percent local content requirement for new wind power projects was introduced, and a loan program for wind farm development created by the State Development Planning Commission and the Ministry of Science and Technology (MOST).[428] In 1997, the State Council lowered value-added tax and import tax on foreign wind technologies and provided preferential tax treatment to joint ventures between Chinese and foreign firms.[429] A first localization program, *Ride the Wind*, offered financial incentives for the production of 600 kW turbines to two joint ventures, one set up between the Spanish company Made and China's Yituo, a second between Nordex of Germany and Xi'An Aero Engine Company.[430] Although the program ultimately failed to reach its target of installing 1,000 MW of wind turbines within three years due to unrealistic local content requirements and complications in approving turbines for installation on the grid, it established a pattern of working with foreign firms on establishing domestic capabilities in a far more comprehensive manner than during demonstration programs a decade earlier.[431]

Funds available for renewable energy research in universities and enterprises continued to increase over the following years. Overall R&D appropriations by China's central and local governments increased from RMB 70.3 billion in 2001 (USD 11 billion) to RMB 168.9 billion in 2006 (USD 26 billion), a sizable portion of it reserved for applied research. Between 2001 and 2005, the centrally funded 863 program for applied research dispensed RMB 20 billion (USD 3 billion) to research institutes and enterprises, including

---

[428] For an detailed timeline of wind power policy, see Lewis 2012, 68-74.
[429] State Council 1997.
[430] Lew 2000, 282. See also Nordex, 2005. *Nordex Establishing Joint Venture in China* [Press Release]. Retrieved from www.nordex-online.com. March 25, 2013.
[431] Lewis 2013, 51-53; Xia and Song 2009, 1969.

to startups such as Suntech and Goldwind, which would ultimately rise to become some of China's largest producers of wind turbines and solar PV technologies.[432] Overall funding for the 863 program rose nearly fifty-fold between 1991 and 2005.[433] However, more central to the improvement of China's domestic capabilities were the creation of large-scale markets for wind turbines through a *Wind Power Concession Program* in 2003, which provided subsidies for large-scale wind turbine installations through a government-run, tender-based bidding system. The program was coupled with stringent domestic content regulations of up to 70 percent and tax incentives to attract foreign turbine manufacturers and their suppliers to China.[434] More than 3,350 MW of turbines—many of them produced by foreign turbine manufactures in China—were installed through the *Wind Power Concession Program* between 2003 and 2007, rapidly turning China into one of the largest wind markets in the world.[435] Local content rates for wind turbine components increased from 12 percent to 62 percent between 2002 and 2008 (see Figure 4).

Indigenous Innovation and the Development of Autonomous Capabilities since 2006

In 2006, China's science and technology policy framework again shifted gears, and with it the conditions for domestic renewable energy industries. After technology imports had given way in the 1990s to encouraging domestic production of foreign technologies and fostering technology transfer to Chinese firms, the central government declared the pursuit of 'indigenous innovation' (自主创新) as a central goal of 11th five year plan

[432] Campbell 2011, 3; Karplus 2007, 23-24.
[433] Evan Osnos, 2009. "Green Giant." *The New Yorker*, December 21.
[434] Ru et al. 2012b, 65; Wang 2010a, 705-06.
[435] Ru et al. 2012b, 65.

(2006-2010).[436] China's strategy of trading market access for technology transfers had not achieved the desired results among domestic technology firms, and the leadership—informed by a caucus of more than 2000 scientists, engineers, and corporate executives—decided that the nation was ill-equipped to independently solve challenges in areas critical to China's future development, including energy, environmental protection, and health.[437] Two documents issued by the State Council in January 2006—the "Medium- and Long-term Strategic Plan for the Development of Science and Technology" (MLP) and the "Decision on Implementing the MLP and Improving Indigenous Innovation Capability"—laid out the central leadership's intention to place indigenous innovation at the core of China's developmental strategy.[438]

As is often the case with central government directives in China, the MLP only loosely defined indigenous innovation, leaving open to interpretation the exact nature of the relationship between domestic scientific and technological progress and advances in other parts of the world. The MLP described indigenous innovation as having three components: new-to-the-world innovation, innovation through integration of new and existing technologies, and re-innovation through the adaptation of global technologies for domestic applications.[439] Nevertheless, it is unclear whether the goal of indigenous innovation indeed equaled self-sufficiency and fully autonomous technology development and whether agreement on such matters even existed within the leadership circle in

---

[436] State Council 2006. The term 自主创新 (*zizhu chuangxin*) has most frequently been translated as indigenous innovation, though 'endogenous innovation' and 'independent innovation' have also been used in news reports and academic publications alike.
[437] Cao et al. 2006, 38-39.
[438]OECD 2008, 389; Schwag Serger and Breidne 2007; State Council 2006. See also: Xinhua, 2006. "China outlines strategic tasks for building innovation-oriented country." http://english.people.com.cn/200601/09/eng20060109_233919.html, [Retrieved December 15, 2013.]
[439] Cao et al. 2006, 40; State Council 2006, Chapter 2, Section1.

Beijing. Beyond doubt is the fact that the State Council wished for a greater role for domestic capabilities in technological innovation and less reliance on technology transfers and other forms of technology 'imports' from abroad.[440] Regardless of the central government's intentions, the prospect of China's desire to reduce reliance on foreign technologies registered with concern among global executives and policy makers alike, which rallied to protest discrimination against foreign firms and possible violations of commitments China had entered when jointing the World Trade Organization (WTO) in 2001.[441]

Apart from setting targets to further increase R&D spending to 2.5 percent of GDP and reducing reliance on foreign technologies, the MLP selected a range of core industrial sectors and research areas for special treatment, energy among them.[442] The MLP supplied a list of government instruments for achieving such goals, including government procurement of domestic technologies, development of domestic technology standards, a range of tax benefits and subsidies for research and development activities, improvement of intellectual property rights practices, the improved use of technology standards, and international collaborations to accelerate learning among domestic firms.[443] Central S&T programs, including the 863 program for applied research, received increased funding as a result, and funds for core research areas were adjusted according to the guidelines for the MLP. The 863 program, for instance, now included ten focus areas, including energy

440 For an overview of the MLP and the technological challenges it sought to address, see Cao et al. 2006.

441 See, for instance, Liu and Cheng 2011; U.S. International Trade Commission 2011.

442 Specifically, the MLP called for a reduction of reliance on imported technology from 50 percent to 30 percent by 2020, measured as spending on technology imports as part of the overall spending on domestic R&D and foreign technology purchases. Ernst 2011b, 24.

443 A short overview of the MLP guidelines for implementation can be found in OECD 2008, 390. Annex F (*China's Policies for Encouraging Indigenous Innovation of Enterprises*) of the same volume lists policies in more detail. OECD 2008, 613-30.

technologies, and sought to further increase the proportion of funds supplied to enterprises, rather than universities and research institutes which had long won the majority of grants.[444]

In renewable energy policy-making, the indigenous innovation guidelines were reflected in a combination of aggressive expansion of renewable energy markets and continued support for domestic R&D activities. In 2006, the central government passed China's first renewable energy law, which provided a framework for introducing feed-in-laws similar to those in effect in Germany and set up the legislative basis for cost-sharing mechanisms to retrieve the cost of renewable energy subsidies through rate-payer surcharges. The Medium- and Long-Term Plan for Renewable Energy Development issued in 2007, which fixed targets for renewable energy markets in China first announced in the renewable energy law, mandated that 15 percent of energy demand must be met from renewable sources by 2020.[445] It called for the installation of 30 GW of wind turbine as well as 1.8 GW of solar PV by the same year (both 2020 targets have since been revised to 200 GW for wind and 20 GW for solar, respectively).[446] By 2009, the central government had eliminated individual feed-in-laws set up in various provinces in the wake of the renewable energy law and had established China's first national, unified feed-in-tariff for wind energy. China was now the world's largest market for wind turbines, having doubled its cumulative wind power capacity from the previous year.[447]

At the same time, a first nation-wide feed-in-tariff of USD 0.16 per kWh for solar energy created a small but growing domestic market for solar PV technologies, with

---

[444] Tan and Gang 2009, 2-4.
[445] Lewis 2013, 53.
[446] Campbell 2011, 6-8; Lewis 2013, 53.
[447] Data compiled by Earth Policy Institute, 2013. Available from www.earth-policy.org/data_center.

additional subsidy programs available to support both residential customers and developers of utility-scale solar PV installations. For smaller installations, the Golden Roofs initiative provided a subsidy of USD 2.63 per watt, covering up to half of total installation cost. The Golden Sun Program reimbursed up to 70 percent of installation cost for utility--scale installations.[448] These subsidies for a domestic solar PV market followed after the global financial crisis had led many European governments to drastically reduce support for local solar installations, slowing global market development and causing overcapacity among China's solar producers.[449] Cost reductions in solar PV technologies made these technologies more attractive for domestic use after decades during which wind turbines had been at the center of local renewable energy markets.[450]

Although the period of the 11th Five Year Plan saw an unprecedented expansion of domestic demand for renewable energy technologies in China as a result of the renewable energy law and its accompanying regulations, market opportunities and resources provided by the central government were increasingly restricted to domestic firms. Even though local content requirements for wind turbines were removed in 2009 and no formal nationality requirements were part of China's feed-in tariffs, foreign wind turbine manufacturers complained about being systematically excluded from government tenders and undercut by local competitors.[451] Despite having established local manufacturing facilities in China, foreign manufacturers argued that central and subnational governments were making use of the government procurement clauses included in the indigenous

---

[448] Campbell 2011, 8.
[449] For an overview of the effects of the global financial crisis on the solar PV industry, see Bartlett et al. 2009.
[450] Goodrich et al. 2013, figure 1.
[451] See "China Shuts Out Foreign Businesses From Its $14 Billion Plan." *Business Insider*, June 4, 2009. Keith Bradsher, 2010. "On Clean Energy, China Skirts Rules." *New York Times*, September 8.

innovation legislation to purchase from domestic firms.[452] Many foreign firms ceased to participate in public tenders and subsequently scaled down planned investments in China-based manufacturing facilities.[453]

New government policies implemented after the release of the indigenous innovation guidelines aimed to close remaining technology gaps between foreign firms and Chinese suppliers by building up domestic capabilities rather than collaborating with foreign firms. Government programs for international science and technology collaborations on wind and solar technologies, for instance, increasingly focused on academic exchange between universities and research institutes, rather than firms, and no longer traded access to local markets in exchange for technology transfers.[454] Direct subsidies for renewable firms were now tied to the successful commercialization of new technologies. Since 2008, for instance, Chinese turbine manufacturers were eligible for significant financial support for the first 50 turbines of 1 MW capacity or more, as long as they were indigenously developed, certified, and connected to the grid.[455] To consolidate the industry and increase technical standards among turbine producers, the Ministry of Industry and Information Technology (MIIT) in 2010 restricted the operation of turbine manufactures that could not produce wind turbines of 2.5 MW or more and failed to meet a series of R&D and quality requirements.[456]

---

[452] Liu and Cheng 2011, 25-26.

[453] Author interviews: Head of China Operations, Foreign Wind Turbine Manufacturer, August 17, 2011; General Manager, Foreign Wind Turbine Manufacturer, August 30, 2011.

[454] See Zhao et al. 2011. The International Science and Technology Collaboration Program on New and Renewable Energy set up by NDRC and MOST in 2007 resulted in 103 collaboration agreements with institutions 97 countries. See Tan and Gang 2009, 5.

[455] Lewis 2013, 72.

[456] Kang et al. 2012, 1913; Lewis 2013, 73.

In the solar sector, which had only received direct government subsidies since the beginning of the 11th year plan, central government policies now emphasized the domestic manufacture of production equipment, which most Chinese solar firms sourced in Europe and the United States. In 2010, when the State Council released a list of seven 'Strategic Emerging Industries' (战略性新兴产业) to replace the old pillar industries that had long structured industrial policy, not only were renewable energy technologies included, but so was advanced manufacturing equipment.[457] The emphasis on equipment manufacturing subsequently pervaded the 12th Five Year Plan for the solar PV industry, released in 2012, which called for 80 percent of solar production equipment to be manufactured domestically by 2015.[458]

By the beginning of China's 12th Five-Year Plan in 2011, industrial policies for wind and solar industries had traced the shift of China's broader framework for science and technology from catching up through technology imports to learning through collaboration with others, and, ultimately, to closing technological gaps to enable indigenous technology development. China's national renewable energy policies had created a range of opportunities for firms in emerging industrial sectors, yet these opportunities were not as unconditional as they had been in Germany. Rather, demand-side subsidies were combined with policies that urged the newly created renewable energy firms to make efforts toward becoming independent from foreign partners.

[457] State Council 2010; US-China Business Council 2013.
[458] Ministry of Industry and Information Technology 2012; National Energy Administration 2011.

3. From Mass Production to Innovative Manufacturing in China's Wind and Solar Sectors

Although central government science and technology policy sought to create high-technology startups and national champion firms with indigenous capabilities in early stage R&D, entrants to renewable energy industries focussed largely on building skills in the manufacturing of wind turbines and solar PV technologies. As I discuss in this section, China's manufacturing economy determined the range of firms that were able to respond to new opportunities in growing domestic markets for wind turbines and rapidly expanding markets for solar PV technologies in Europe. It also shaped the kinds of technological specializations, skills, and templates for competitiveness that firms brought with them when they did so. Whether firms spun off state-owned heavy machinery conglomerates, as was common in the wind energy sector, or were founded by foreign-trained returnees, as were many of China's solar firms, the legacy of mass manufacturing influenced hiring practices, templates for interaction with global supply chains, and the range of capabilities available to firms among local suppliers. The responses of entrepreneurial firms growing out of China's existing industrial ecosystem determined how central government incentives for industrial upgrading were implemented in practice. China's wind and solar firms, instead of building early-stage R&D capabilities, chose to focus on engineering skills in scale-up and mass manufacturing instead.

This section proceeds by tracing the development of China's production economy through the attraction of foreign-direct investment and incentives for subnational governments to invest in manufacturing. It then discusses how firms collaborated with foreign partners to access technology and repurposed central science and technology policy and establish engineering capabilities in mass production, rather than replace collaboration in global supply chains through the establishment of autonomous capabilities in early-stage R&D. The section concludes by discussing three types of capabilities in mass manufacturing that Chinese firms contributed to global processes of technology development.

Wind and Solar Firms in China's Manufacturing Economy

By the time China's first domestic producers entered the wind and solar industries in the late 1990s, two decades of economic reform had turned China into a large manufacturing economy. Between 1978 and 1998, China's per capita GDP had expanded nearly eighteen-fold, from RMB 381 to RMB 6,796, and it would double again within six years.[459] New rules on private ownership enabled a gradual restructuring of the state-owned sector. In the countryside, economic liberalization and fiscal decentralization during the 1980s had created incentives for rural governments to aggressively intervene on behalf of local township and village enterprises (TVEs), setting off a golden age of rural industrialization that ended with large-scale privatization in the mid-1990s.[460] Along the coast, special economic development zones proliferated, offering tax breaks, land deals, and development assistance to foreign investors and domestic manufacturers. What had started with four special economic zones (SEZ) to experiment with economic liberalization during the early 1980s, by 2003 had grown to 54 national-level economic and technological development zones (ETDZs), 53 national high-technology industrial zones (HTZs), depicted in Figure 2, and hundreds of economic development zones (开发区) managed by local governments, all of which were competing to attract investment in

[459] *China Statistical Yearbook* 2007, chapter 3-1.
[460] Naughton 2007, 271-94; Oi 1995, 1136-38.

manufacturing and, increasingly, high-technology industries.[461] Manufacturing in China's development zones initially focussed on consumer goods, textiles, and shoes—both Nike and Rebook sourced nearly half of their athletic shoes from Chinese factories in the late 1990s. By 2004, however, China had become the world's largest producer of electronics and communication equipment.[462] Nearly two thirds of the world's laptop computers were manufactured in China in 2005.[463]

Much of the functional upgrading to high-technology manufacturing occurred at the hands of foreign firms, which flocked to China's economic development zones in large numbers in response favorable investment policies. Between 1979 and 2000, China attracted USD 346 billion in foreign direct investment (FDI). Over the course of the 1990s, it was second only to the United States on the list of the largest FDI recipients; 70 percent of FDI targeted the manufacturing industry.[464] By far the largest sources of foreign direct investment were manufacturing firms in Taiwan and Hong Kong, which used China's opening to foreign investment during the reform years to move labor-intensive export production to low-cost manufacturing locations in China's coastal development zones. Between 1985 and 2005, 60 percent of FDI arriving in China originated in Hong Kong, Taiwan, and Macau.[465] Eighty-eight percent of high-technology exports during the 1990s were manufactured by foreign-invested enterprises. Of the 10 largest high-technology exporters in 2003, four were Chinese subsidiaries of Taiwanese electronics firms. Four

---

[461] Naughton 2007, 304, 409-10.
[462] Tomas Meri,"China passes the EU in Hightech exports", in *Eurostat: Statistics in Focus*, 25/2009. Shoe manufacturing statistics cited in Landrum and Boje 2002, 84.
[463] In 2005, Taiwanese companies produced more than 70 percent of the world's notebook computers, 85 of which were manufactured in facilities in mainland China. Yang 2006, 7-12.
[464] Huang 2003, 6; Naughton 2007, 419.
[465] Naughton 2007, 413.

belonged to U.S.-based multinationals—Intel, Seagate, Dell, and Motorola—which followed on the trails of Taiwanese and Hong-Kong based firms that had moved to China in great numbers during the early 1990s.[466]

As a consequence, China's industrial base in mass production evolved rapidly in the post-reform era. It included a substantial contribution on the part of foreign firms, which brought decades of manufacturing experience to China as they set up subsidiaries in China's economic development zones. Although empirical studies have found mixed evidence of direct technology transfers to local firms as a result of China's FDI-led development regime, foreign-invested firms provided training opportunities for staff in economic development zones, pushed local governments to continue to provide incentives for mass production in China, and attracted large supplier industries for materials, production equipment, export logistics, and other complementary capabilities required for large-scale manufacturing.[467] In parallel to the central government's push to encourage domestic firms to develop indigenous R&D capabilities, China's FDI-led development strategy over the course of the 1990s was a critical enabler of Chinas industrial base in high-technology manufacturing.

China's domestic renewable energy firms were established in the context of manufacturing expansion and functional upgrading in economic development zones in the 1990s. Even before the emergence of domestic wind energy markets and market demand for solar PV technologies in Europe, China's national science and technology policies—in

[466] Naughton 2007, 417.

[467] Huang has argued that China's FDI-led development strategy has crowded out local firms, by providing investment incentives and favorable tax policies predominately to foreign-invested enterprises. See Huang 2003. For a discussion of training and other benefits provided by foreign-invested firms, see Naughton 2007, Chapter 17. Others have found mixed statistical evidence for direct technology transfer from foreign investors to local firms beyond their Chinese subsidiaries. See, for instance, Hu et al. 2005; Lemoine and Ünal-Kesenci 2004; Liu and Buck 2007.

particular the encouragement of technology spin-offs, funding for high-tech R&D, and start-up support in High-Technology Zones set up under the Torch Program—created incentives for firms to enter wind and solar PV industries. Domestic demand for wind turbines resulting from China's 2003 *Wind Power Concession Program*, subsequent feed-in tariffs, and rapidly growing export markets for solar PV technologies caused additional waves of industry entry.

Although new wind and solar firms were located in the same manufacturing environments in China's economic development zones, they had different backgrounds and entered renewable energy sectors on different paths. Like Goldwind, China's first domestic wind turbine manufacturer, many wind turbine producers were spin-offs from research institutes or subsidiaries of state-owned or formerly state-owned enterprises. Goldwind, for instance, was founded in 1997 as a spin-off from Xinjiang's Wind Energy Research Institute in response to 863 program funding offered for the development of wind turbines with 600 kW capacity.[468] Huayi, a conglomerate producing mining equipment and transformers, entered the wind industry in 2002.[469] After domestic markets expanded as a result of the *Wind Power Concession Program,* Dongfang Electric in 2004 began producing wind turbines based on a license from German REpower. Dongfang was a subsidiary of China Dongfang Electric Corporation (中国东方电气集团), a centrally-owned enterprise with a wide product portfolio that included power generation equipment, transformers,

[468] Evan Osnos, 2009. "Green Giant." The New Yorker, December 21. See also Chen Lei, 2011. "Goldwind : From Follower to Leader [金风科技：从追风到引领]." http://www.goldwind.cn/web/news.do?action=detail&id=201103310223342852 (accessed January 19, 2014). In Chinese, Goldwind is named 新疆金风科技股份有限公司, or simply 金风科技.
[469] See http://www.heag.cn/aboutheag.html (accessed January 20, 2014).

railway engines, and power converters.[470] Sinovel, a start-up backed by Dalian Heavy Mechanical and Electrical Equipment Engineering company, began producing 1.5MW turbines in 2006 with a license from Germany's Fuhrländer and began offering a 3MW turbine a few years later, at a time when European producers were still testing their 3MW technology.[471] As the renewable energy law created the prospect for long term growth in domestic markets in 2006, Mingyang, a privately-owned producer of switch-gears, high-low voltage frequency converters, and pitch control equipment supplied to wind turbine manufacturers, began the production of its own 1.5 MW wind turbine. Its technology was based on a joint development agreement with the German design firm Aerodyn and funded through 863 Program grants.[472] In 2007, China Guodian Corporation, one of five state-owned power companies, established it's own wind turbine manufacturer, Guodian United Technology (国电联合动力技术有限公司).[473]

In contrast to the wind energy sector, in which most of the firms had ties to state-owned or formerly state-owned enterprises and backgrounds in the production of power equipment and heavy machinery, the solar industry was almost entirely made up of start-up firms. As I introduced in Chapter 2, many of the solar firms were founded by Chinese scientists educated in solar PV research laboratories abroad, in particular at the School of

---

[470] Dongfang Electric Corporation was originally founded in 1956. See company website at http://www.dongfang.com.cn/index.php/business/ (accessed January 19, 2014).
[471] Qin 2013, 598. See also: Pu Jun and Wang Xiaocong, 2011. "Boom, then Blowdown for Wind Energy's Sinovel." *Caixin Online*, November 21.
[472] China Ming Yang Wind Power Group Limited 2011. See also http://www.mywind.com.cn/English/about/index.aspx?MenuID=050101 (accessed January 19, 2014).
[473] http://www.gdupc.com.cn/publish/gdlhdl/1/12/index.html (accessed January 19, 2014).

Photovoltaic and Renewable Energy at the University of New South Wales in Australia.[474] Research funding dispensed through the 863 and Torch Programs and the support for high-technology startup firms in China's High-Technology Development Zones attracted these scientists back to China, where many of them returned to their hometowns to open solar PV firms around the same time as manufacturers sprung up in Europe and the United States. Trina Solar, today one of China's largest producers of solar wafers and modules, was established as a solar PV installer for demonstration projects in 1997.[475] Yingli Solar followed in 1998, setting up its first facility in Baoding's High-Tech Industrial Zone (HTZ) established under the Torch Program in 1993.[476] Suntech opened its first production plant in Wuxi in 2001, with USD $6 million in funding from the local government in return for a 75 percent equity stake.[477] Canadian Solar was founded in the same year and opened its first manufacturing facilities in Suzhou.[478] In 2004, after global demand for solar panels increased as a result of improvements to Germany's domestic subsidy regime for renewable energy, a number of additional firms entered the industry. China Synergy, also referred to as CSUN (中电光伏), was established in 2004 in Nanjing as a subsidiary of China Electric Equipment Group (中电电气集团), a manufacturer of electrical transformers and advanced composite materials. JA Solar (晶澳太阳能) began manufacturing wafers in

---

[474] See Cathy Alexander, 2013, "Carbon Cutters." *Crikey,* March 7. Other solar firms recruited Chinese citizens from elsewhere in the world. Wan Yuepeng, CTO of Trina Solar, for instance, completed a PhD at Aachen University and worked for New Hampshire-based equipment manufacturer GT Solar prior to returning to China. See http://www.ldksolar.com/com_team.php. (Accessed March 27, 2013).

[475] Trina Solar, 2013. "TSL: Company Milestones." http://media.corporate-ir.net/media_files/irol/20/206405/milestones.pdf (accessed January 19, 2014).

[476] For a list of all national-level high-tech industrial zones established under the Torch Program, see Cao 2004, 648. http://www.yinglisolar.com/en/about/milestones/ (accessed January 19, 2014).

[477] Ahrens 2013, 2-3.

[478] http://www.canadiansolar.com/about_us.aspx?id=1 (accessed January 19, 2014).

Shanghai in 2005.[479] In 2006, LDK was founded in Xinyu by Peng Xiaofeng, who had previously made a fortune by mass-manufacturing protective equipment such as gloves and now saw a market opportunity in producing solar wafers.[480]

With the exception of firms such as CSUN and LDK, which had links to existing manufacturing firms, the majority of solar PV startups did not share the same direct connections to manufacturing businesses that were common in the wind industry. Nevertheless, even just a cursory glance at company websites and annual reports reveals that the majority of executives at China's solar PV firms came from existing manufacturing industries, in particular electronics and semiconductor production. In a fairly typical case, the chief technology and financial officers at LDK Solar, Wan Yuepeng and Lai Kunsheng, had previously worked for a range of semiconductor, glass, and solar manufacturers, including GT-Solar and Saint Gobain, before joining LDK in 2007 and 2006, respectively. At JA Solar, the CEO and chief technology officer, Fang Peng and Liu Yong, had managed factories for semiconductor firms such as SMIC and NEC before joining JA in 2008 and 2010. The chief technology officer of Yingli from 2006 until 2009, Yao Guoxiao, worked in chemical manufacturing before entering the solar industry.[481]

Accessing Technology Abroad: Collaboration with Foreign Partners

From the beginning, producers of wind turbines and solar PV technologies took advantage of a publicly funded R&D infrastructure that prioritized new energy

---

[479] JA Solar Holdings 2007, 6.

[480] Andrew Farrel, 2008. "In Pictures: Asia's Youngest Billionaires." *Forbes,* September 3. http://www.forbes.com/2008/09/03/asia-billionaires-wealth-biz-billies_cx_af_0903youngasiabillies_slide_4.html (accessed December 13, 2013).

[481] Information compiled from company websites and annual reports.

technologies as early as the mid-1990s. Although China's wind and solar firms used such government grants to set up internal R&D departments, they did not have to be self-sufficient: technologies were available to them through multiple global pathways, even as they continued to improve their own technical capabilities. Despite their diverging paths into renewable energy sectors, China's wind and solar firms thus shared the ability to access the technological capabilities of external firms, both in China and abroad.

In the wind industry, Chinese firms had access to foreign wind turbine technologies through licensing agreements and joint development agreements with foreign manufacturers. Wu Gang, the founder of Goldwind, reportedly reasoned that there was no need to replicate existing technologies, so when government programs encouraged domestic turbine development, Goldwind licensed a design from Germany's Jacobs Energie and used R&D funds to solve production challenges instead.[482] The vast majority of Chinese wind turbine manufacturers entered similar relationships with foreign partners to access global technologies. Sinovel signed joint development agreements for a 1.5 MW turbine with Fuhrländer of Germany in 2003, followed by agreements with Austria's Windtec for 3 MW and 5 MW turbines in 2007. Dongfang Electric purchased a license for a 1.5 MW turbine from Germany's REpower in 2004 and entered a joint development agreement for a 2.5 MW turbine with the German wind engineering firm Aerodyn in 2005.[483] Nordex entered a joint venture with Ningxia Electric Power Group and REpower set up a joint venture turbine assembly firm with North Heavy Industrial Group in 2006.[484] Among the 31 largest wind turbine manufacturers in China, sixteen entered license agreements with

---

482 Evan Osnos, 2009. "Green Giant." The New Yorker, December 21.
483 See Zhang et al. 2009b, 559.
484 Company websites. See http://www.nordex-online.com and http://www.repowernorth.com.

foreign firms, fourteen entered joint-development contracts, six autonomously developed wind turbine technologies, and three were joint venture operations. Seven firms both had joint-development and licensing agreements with foreign firms.[485]

The second source of technology for China's domestic turbine manufacturers were global suppliers, many of which eventually established production facilities in China as foreign turbine manufacturers attempted to meet strict local content requirements. The Swiss multinational ABB; the German firms Euros, Bachmann, Jake, and VEM; the Danish blade manufacturer LM; and the Austrian control systems firm Windtec (now part of U.S. based AMSC) were among the early foreign suppliers to Chinese turbine manufacturers.[486] FAG/Schaeffler of Germany, a bearings manufacturer, opened a facility in China in 2006; Bosch Rexroth, a gearbox manufacturer, and SKF, a Swedish bearings multinational, followed in 2008. Over time, domestic suppliers became additional sources of advanced technologies. As foreign firms set up facilities in China to meet local content requirements, they not only brought suppliers with them, but also trained local firms. Gamesa of Spain opened its first facilities in China in 2005, Vestas opened a blade factory in Tianjin in 2006, the same year that GE began the assembly of turbines in Shenyang. Nordex of Germany and Suzlon of India opened plants in Dongying and Tianjin in 2007. Many foreign firms began sourcing from local suppliers such as NTC, a generator producer, and Nanjing Highspeed Gear, a gearbox manufacturer, and in turn helped these suppliers meet global technical standards.[487]

---

485 List complied from Lewis 2012, 136-37; Wang 2010b, 197-203.
486 Wang 2010b, 197-203.
487 Information retrieved from company websites, the China Wind Power Center database (http://www.cwpc.cn), Windpower Monthly, and Li 2011a.

Unlike China's wind turbine producers, which entered the industry from a position of technology lag, many of the original solar companies were founded by returning scientists trained at the world's top solar laboratories. The technological skills and training of foreign-trained returnees obviated the need for technology licenses and joint development agreements common in the wind industry, but solar firms still tapped into global technology networks, in particular for production equipment. Centrotherm, a German manufacturer of cell and module production lines, began selling its products to China's solar firms as early as 2000. Other foreign equipment manufacturers quickly followed and set up sales networks in China, particularly as European and U.S.-based solar manufacturers only slowly expanded production facilities.[488] The small and highly specialized suppliers of production equipment were relatively unchallenged by domestic competitors: as late as 2009, virtually no producers of full (turnkey) production lines existed in China, though a number of Chinese firms offered equipment that solar manufacturers could modify and connect to construct their own production lines.[489] Since solar producers from around the world sourced from and cooperated with the same producers of manufacturing equipment on incorporating new technologies into production machinery, sourcing equipment from external firms was not just a way to access instruments and machinery that could not be produced in-house. Sourcing from suppliers offered access to global technological developments and pooled knowledge that solar producers risked loosing when relying on production equipment developed in-house.[490]

---

488 Nussbaumer et al. 2007, 109.

489 de la Tour et al. 2011, 765.

490 de la Tour et al. 2011, 764. Author interview, CTO of solar PV manufacturer, May 23, 2011.

Innovative Manufacturing in China's Wind and Solar Sectors

Foreign partners provided access to key technologies, capabilities, and components that Chinese wind and solar manufacturers were not able to establish in-house, yet they were less capable of helping Chinese producers scale new technologies to mass production. In the late 1990s, foreign producers of wind turbines were not manufacturing at scale, or had done so only very recently. In the solar industry, foreign producers of manufacturing equipment had no experience running large-scale manufacturing operations, nor where they particularly trained at rapidly integrating new technologies into production lines that were already operating in Chinese solar facilities. The decline of vertically integrated enterprises and the shift of manufacturing to Asia over the course of the 1990s had generally reduced engineering capabilities in mass production in advanced industrialized economies. As demand for wind and solar technologies grew rapidly in the early 2000s—as a result of China's domestic subsidies for wind turbines and European funding for solar PV installation—foreign partners were reliable sources of technology, but, as I discussed in Chapter 2, scale-up to mass production was a challenge that they themselves were struggling with.

When the first Chinese firms entered wind and solar sectors in the late 1990s, production technologies for wind turbines and solar PV technologies had not fully matured, yet low production volumes still allowed for improvisation and experimentation in bringing new technologies to market. Although engineering challenges in the commercialization of wind and solar technologies already existed at the time, they became particularly acute with the onset of demand spikes in 2003, when increasing production volumes no longer permitted trial-and-error approaches to scale up and mass manufacturing. Advanced manufacturing capabilities and tacit knowledge around the large-scale manufacture of complex technologies were critical to commercialization of new technologies in highly competitive industries, yet Chinese firms had to establish such skills in-house.

The growing importance of engineering capabilities in scale-up and commercialization in wind and solar sectors coincided with an increased emphasis on the development of domestic innovative capabilities in China's national science and technology policy framework. Between 2000 and 2006, China's domestic spending on research and development activities increased from RMB 89.6 billion to RMB 300 billion; R&D intensity, still below the targets set in the tenth Five-Year Plan, grew from 0.9 to 1.4 percent of GDP over the same period.[491] Both the 863 Program and a second research program, the 973 Program named after its inception in March 1997, dispensed increasing funds for technology development and both had designated budgets for energy technology research. China's 863 Program budget for energy technology doubled in 2001, providing funding mainly for R&D on low-carbon energy technologies.[492] The 973 Program provided RMB 8.2 billion in funding for basic research between 1998 and 2008, 28 percent of which went to projects that targeted technologies in the fields of energy, resource conservation, and environmental protection.[493] Additionally, centrally funded state key laboratories, which since the beginning of the 1980s had existed for strategic research topics in universities, could be located within enterprises starting in 2007, and firms were encouraged to seek state key laboratory accreditation for their R&D programs.[494] Overall, central government

[491] Ministry of Science and Technology 2007a, 2-3.
[492] Evan Osnos, 2009. "Green Giant." The New Yorker, December 21.
[493] Tan and Gang 2009, 4.
[494] Ministry of Science and Technology 2007b; OECD 2008, 462.

R&D appropriations for renewable energy research increased from RMB 21.1 billion in 1996 to RMB 104.8 billion in 2008.[495]

Almost all of China's leading wind and solar producers at some point participated in central-government R&D programs. Goldwind, for instance, received central government funding for almost every generation of wind turbine it developed, including gearless turbine technologies accessed through licensing, collaboration, and the subsequent purchase of Germany's Vensys. Under the 9th and 10th Five Year Plans, Goldwind participated in national science and technology programs for R&D and commercialization of 600 kW, 750 kW, and 1 MW-scale turbine systems. It also received direct funding from the Ministry of Science and Technology for the improvement and optimization of its 1.2 MW turbine as well as support from the provincial-level department of science and technology for R&D and commercialization of 1.5 MW, 2.5 MW, and 3 MW turbines.[496] Other wind turbine manufacturers, such as Mingyang and Sinovel, similarly received support from the 863 Program for turbine development. [497]

Albeit more recently, solar manufacturers also took advantage of central government funding. LDK Solar, for instance, participated in a national project under the 863 Program to develop environmentally friendly solar PV production processes and took part in two Torch Program initiatives to improve solar wafers and reduce industrial waste in wafer cutting.[498] EGing solar received a National Torch-Plan High-Tech Company

[495] Cao and Groba 2013, 12.
[496] CRESP 2005, 27-30; Tan 2012. See also: Ministry of Science and Technology, 2007. "Breakthrough in 1.2MW Direct Drive Permanent Magnet Wind Generator." http://www.most.gov.cn/eng/pressroom/200703/t20070306_41930.htm (Accessed January 18, 2014).
[497] See, for instance, "Sinovel Wind's Wind Turbine Passed 863 Program Review". SinoCast Daily Business Beat. November 18, 2011. "Ming Yang Wind Power Company Profile." http://www.mywind.com.cn/English/about/index.aspx?MenuID=050101 (Accessed January 17, 2014).
[498] LDK Solar, 2014. "R&D Achievements." http://www.ldksolar.com/inn_rd.php (Accessed January 19, 2014).

designation.[499] CSUN (China Sunergy) received 863 funding to develop mono-crystalline solar cells, ultimately achieving record-breaking conversion efficiency with the cells developed under this project.[500] When central-government policy allowed the establishment of state key laboratories in enterprises in 2007, Trina Solar, Yingli, and United Wind Power were among the firms that opened such nationally-accredited and centrally-funded research laboratories on site.[501]

Although China's central-level science and technology policies pursued the goal of creating technological capabilities that would reduce reliance on technology imports and allow domestic firms to compete in global markets, China's wind and solar firms did not utilize program funds to become independent from foreign partners. Most firms maintained collaborative relationships with foreign firms, jointly developing and commercializing new renewable energy technologies even as they received central government support under the umbrella of China's indigenous innovation policies.[502]

Instead, China's wind and solar firms focused a large part of their research and development efforts on building niche capabilities that could not be accessed in global production networks: they specialized on building capabilities in scale-up and mass

---

[499] EGing Solar, 2014. "Corporate Overview." http://www.egingpv.com/english/about_company.htm (Accessed January 19, 2014).

[500] China Synergy, 2013. "China Sunergy's High-Efficient Mono Cells Achieve Certified New Conversion Efficiency Record of 20.26%." http://investors.csun-solar.com/phoenix.zhtml?c=211846&p=irol-newsArticle&ID=1851207 (accessed January 19, 2014).

[501] See Trina Solar, 2013. "Trina Solar's State Key Laboratory of PV Science and Technology Receives Ministry Accreditation. "http://ir.trinasolar.com/phoenix.zhtml?c=206405&p=irol-newsArticle&ID=1874706&highlight=" (Accessed January 19, 2014). United Power, 2013. "Company Profile" http://www.gdupc.com.cn/publish/gdlhdl/1/12/index.html (Accessed January 19, 2014). Yingli Solar, 2010. "State Key Laboratory of PV Technology to be Established at Yingli Green Energy's Manufacturing Base." http://ir.yinglisolar.com/phoenix.zhtml?c=213018&p=irol-newsArticle&ID=1375499&highlight= (Accessed January 19, 2014).

[502] As recently as 2010, Harbin Electric and General Electric entered a joint venture agreement to develop gearless turbines for offshore use. Although the joint venture only operated for three years, it nevertheless shows that partnerships and global collaborations continue to pervade technology development and commercialization in China's renewable energy sectors. Qi 2013.

manufacturing that I refer to as *innovative manufacturing*. These capabilities in many ways built on existing manufacturing capabilities in China's economic development zones, yet they went far beyond fabrication and assembly by utilizing engineering and design knowledge to rapidly translate complex technologies into mass-manufacturable products. Innovative manufacturing included improvements to process designs long associated with manufacturing innovation, but also entailed far-reaching changes to product designs to accommodate manufacturing requirements and meet cost targets for final products. Regardless of whether advanced wind and solar technologies were developed in-house or contributed by a global partners, engineering teams in China's wind and solar firms met production and cost targets through the substitution of materials, the re-design of particular components, and the reorganization of internal product architectures to allow for better and faster manufacturability at scale.[503] As executives again and again highlighted in interviews, most firms had access to new technologies through relationships with global partners, so it were capabilities in achieving speed and cost of manufacturing that set firms apart in highly competitive market environments for wind turbines and solar PV technologies.

Many renewable energy firms thus used central government R&D programs to establish two divisions within their research and development facilities. A first group of engineers focused on applied research on new wind and solar technologies to meet and

[503] Author interviews: Senior VP global supply chains, Chinese solar manufacturer, interviewed March 13, 2011; CTO and director of R&D at Chinese solar manufacturer, both interviewed August 26, 2011; head of China operations, European wind turbine engineering firm, interviewed January 13, 2011; CEO, European wind turbine engineering firm, interviewed May 20, 2011; CTO, Chinese wind turbine manufacturer, interviewed August 29, 2011; CEO, Chinese solar cell manufacturer, interviewed August 10, 2011; president, Chinese wafer manufacturer, interviewed August 26, 2011. CEO, Chinese cell and module manufacturer, interviewed June 28, 2013. See also Nahm and Steinfeld 2014.

surpass the technological standards of foreign competitors, as intended by the central government programs. A second R&D division focused on the challenge of scale-up and mass production, and it is in this division that the most advanced Chinese wind and solar firms established unique capabilities in bringing new technologies to market. At the wind turbine manufacturer Mingyang, for instance, out of 300 R&D staff in 2010, about one third focused on the development of new technologies, while the remaining engineers worked on bringing technologies to mass production.[504] Similarly, Trina Solar reported that out of 425 employees working in its R&D devision in 2012, 79 focused on technology development and the remaining 346 engineers devised solutions to the challenges of commercialization and manufacturing.[505] The two-fold research and development activities explain why Chinese firms built strengths in bringing new technologies to market, but where not able to match the early stage R&D activities of firms in other economies and thus remained dependent on foreign partners. By 2006, for instance, some of the world's most efficient solar PV modules in mass production were made in Chinese manufacturing facilities, even as China's could not match the conversion efficiencies of foreign R&D laboratories in experimental setups.[506]

Just as manufacturing activities in China's industrial parks had different ties to global production networks—ranging from reverse engineering of foreign products, through contract manufacturing for foreign firms, to export processing of imported parts and technologies—so, too, did specializations in innovative manufacturing differ across China's wind and solar firms. Some firms focused on commercializing new versions of

---

504 China Ming Yang Wind Power Group Limited 2011, 54.
505 Trina Solar 2013, 64-65.
506 Marigo 2007, table 1.

existing products, others specialized on bringing new-to-the-world product designs to the market for the first time, while yet others integrated new components into products already produced at scale. Some firms were capable of performing several of these tasks and used them simultaneously in technology commercialization.

What these different specializations had in common was the use of engineering capabilities at the intersection of R&D and manufacturing to make contributions to product development and commercialization in global production networks—contributions that extended beyond emulation and assembly to modifications of product designs. At the core, the distinct specialization in innovative manufacturing among China's wind and solar firms was a combination of existing capabilities in mass production, which were abundant in China's industrial parks, and new capabilities in engineering and product design, which were increasingly supported through China's domestic science and technology infrastructure. As such, capabilities in innovative manufacturing where not the intended outcome of targeted government interventions, but were established at the hands of entrepreneurial firms, which identified opportunities in global supply chains and repurposed and combined a wide range of government resources to improve existing capabilities to respond to these opportunities.

Innovative manufacturing capabilities among China's wind and solar firms manifested in three different variants that resembled knowledge-intensive variations of reverse engineering, contract manufacturing, and export processing—manufacturing activities long at the center of economic development.[507] These variants of innovative manufacturing were not mutually exclusive, and wind and solar producers were often able

[507] The role of such manufacturing activities in economic development and industrial upgrading is discussed in Ernst and Kim 2002; Gereffi 2009; Lüthje 2002; Minagawa et al. 2007.

to apply their engineering capabilities in multiple ways to solve the challenges of commercialization, yet for analytical purposes it is helpful to distinguish between the three.[508]

Backward design and the reengineering of an existing product

The first variant of knowledge-intensive capabilities in innovative manufacturing, backward design, resembled traditional processes of reverse engineering. By creating versions of existing products that were simpler and cheaper to manufacture at scale, Chinese entrants were outcompeting foreign incumbents by undercutting them on price. In contrast to conventional reverse engineering, however, in which mature technologies are simply copied and cost advantages stem from differences in factor prices and scale economies, Chinese firms were cutting costs through changes to product designs.[509] Although backward design led to products that resembled the original archetypes, the new product versions could be scaled at lower cost and faster speed due to the use of simplified components, cheaper materials, and better design for manufacturability. While backward design thus retained core features of reverse engineering, firms created new products with distinct characteristics, rather than attempting to simply reproduce the original template,

Backward design was particularly prevalent in the wind industry, where the large number of mechanical components and advanced materials used in wind turbines offered many opportunities for manufacturing-oriented design improvements. In a typical

[508] The discussion of the three variants of innovative manufacturing over the following pages draws heavily on a collaborative project with Edward Steinfeld, a version of which has previously been published. See Nahm and Steinfeld 2014, 294-98.
[509] For a discussion of reverse engineering in economic development, see Amsden 1989; Amsden 2001; Kim 1997; Kim and Nelson 2000.

example, a Chinese wind turbine supplier was granted a license by a German firm to produce a generator, one of the core turbine components. Due to engineering constraints, the German firm had previously been unable to incorporate the most cost-effective fan model in the generator design. The Chinese licensee, however, in the process of scaling production of the licensed generator, was able to redesign the original model to accommodate the cheaper fan. It were the backward design capabilities of the Chinese firm that permitted it to realize a product alternative that the German firm had dismissed as unworkable. Once the alternative was demonstrated to be feasible, the German firm was willing to pay for this proprietary information through reverse licensing.[510]

In the above example, the Chinese firm was able to contribute production knowledge within a formal contractual relationship. In many other cases, however, Chinese firms used backward design skills to develop cheaper, mid-level products that competed directly with the product archetypes and their originator firms.[511] Particularly in the Chinese domestic market, many established multinationals were unable – and to some extent unwilling – to engage in such processes of cost-driven design, and lost market share to cheaper alternatives as a result.[512]

The large number of mechanical components, the importance of product architecture for the manufacturing process, and the sophisticated material needs of advanced wind turbines made wind turbine technologies particularly suitable for design

---

[510] Interviews: plant manager, German generator manufacturer, May 17, 2011; executive, Chinese generator manufacturer, August 26, 2011.

[511] This phenomenon has occurred in other industrial sectors, see Ge and Fujimoto 2004; Thun and Brandt 2010.

[512] Head of China operations at foreign wind turbine manufacturer, interviewed August 30, 2011; executive, foreign wind turbine manufacturer, interviewed November 11, 2011. Head of China operations, foreign wind turbine manufacturer, interviewed August 17, 2011.

improvements through backward design. Out of twelve Chinese wind turbine manufacturers interviewed for this project, nine reported having either improved licensed turbine technologies through backward design or observed such improvements in technologies licensed by local partners and competitors. However, even in the solar sector, where products have far fewer components and are fabricated using non-mechanical production processes, manufacturers used backward design strategies. A Chinese manufacturer of solar cells and modules, for instance, reported buying a foreign equipment manufacturer to access technology and then re-engineering parts for its production lines to save cost and time over equipment available domestically.[513] A competitor expressed frustration with the lack of speed of some of its foreign suppliers in adapting production lines to changing technology applications, switching to local suppliers who could more quickly— and cheaply—improve equipment designs for new manufacturing needs.[514] Although such instances of backward design in the Chinese solar sector focused on rapid customization rather than scale, they retained the core feature of improving on existing technologies through knowledge-intensive manufacturing innovation.

Translating designs into new products

The ability of Chinese firms to rapidly move complex products toward commercialization was also manifested in a second variant of innovative manufacturing, here referred to as "making designs come true." Rather than re-engineer an existing product, in this variant of innovation manufacturing Chinese firms deployed engineering capabilities at the intersection of R&D and manufacturing to prepare new-to-the-world

[513] Senior VP global supply chains, Chinese solar manufacturer, interviewed March 13, 2011.
[514] CTO and director of R&D at Chinese solar manufacturer, both interviewed August 26, 2011.

technologies for mass production. In many cases, such technologies originated from foreign partners, who either did not have in-house manufacturing capabilities, were unable to manufacture the product at a commercially viable price, or were deterred by the capital and tooling costs of commercializing new technology. In other cases, Chinese firms used such capabilities to commercialize their own product innovations coming out of the technology development divisions in their R&D facilities. What these cases had in common was their reliance on production knowledge to replace, redesign, and substitute parts until the product could be manufactured at a commercially viable price. In contrast to traditional contract manufacturing, which relies on firms in developing economies to manage only the production process of foreign-owned designs and technologies, Chinese wind and solar producers improved product designs for commercialization.[515]

The role of innovative manufacturing capabilities in the commercialization of new product designs is illustrated by a second example from China's wind energy industry. In 2009, a Chinese wind turbine producer acquired a ten-year exclusive license for the manufacturing of a groundbreaking, new-to-the-world wind turbine design from a European engineering firm. The European firm selected the Chinese manufacturer among multiple potential partners for the technology, choosing largely on the basis of manufacturing capabilities that would ensure reliability for the product, speed in commercialization, and commercial viability for the project as a whole. Although the European firm developed the turbine design—a new turbine technology which offers greater reliability and versatility through new and lightweight components—the design for manufacturability occurred during small batch production on the site of the Chinese

[515] For a discussion of non-innovative contract manufacturing in the context of the electronics industry, see Lüthje 2002.

manufacturer. Engineers employed by the Chinese firm made design changes to simplify tooling and assembly processes, and, in cooperation with other local firms, reduced costs by localizing sourcing and by introducing substitute materials. This was especially challenging in the case of this particular turbine concept, because its novel product architecture required all the components to be produced in-house. Additional design adjustments were then made during the process of scale-up to accommodate requirements for mass production.[516]

However, not all instances of "making designs come true" relied on foreign partners, as a case involving a Chinese solar PV manufacturer exemplifies. Like many innovations in the solar industry, where the conversion efficiencies of light to electricity for different processes are easily calculated but hard to achieve in practice, a high-efficiency cell developed by the Chinese solar manufacturer was based on a commonly known theoretical principle that had not yet been made to work in a commercial solar application. The Chinese firm, like many of its competitors in China and abroad, was researching ways to commercialize this principle. Ultimately, the firm's R&D center discovered a material produced by a third party vendor that allowed the firm to run the process in the laboratory, yielding cells with the desired efficiency levels after several months of trials. A key challenge, however, was to utilize existing production equipment to manufacture cells based on this new principle, and to do so very rapidly. Due to different material requirements, the new product was more expensive than traditional cell technologies, yet the high price of silicon justified the additional expense at the time. Rapid

[516] Head of China operations, European wind turbine engineering firm, interviewed January 13, 2011. CEO, European wind turbine engineering firm, interviewed May 20, 2011. CTO, Chinese wind turbine manufacturer, interviewed August 29, 2011.

commercialization was critical because the innovation had to take advantage of a potentially narrow time window during which silicon prices would remain high and competitors researching the same technology would likely not realize breakthroughs of their own.[517] Through collaboration between the R&D team and production engineers, the firm was able to adjust existing production equipment to manufacture the new product, and within months four production lines were churning out new, higher efficiency cells. By the time many competitors developed a similar product, silicon prices had already dropped so far that the original firm decided to reconvert its production to a traditional product since the cost increase to achieve higher efficiency was no longer justifiable.[518]

As these examples illustrate, the contexts in which design changes facilitated the rapid and cost-effective commercialization of innovative technologies varied widely. In some cases, licensing agreements between two firms resulted in a much more deep-seated process of cooperation, in which both sides chose each other for particular capabilities and potential knowledge transfer. In other instances, Chinese wind and solar manufacturers purchased foreign partners to access an innovative technology, but then adjusted, improved, and commercialized the technology in their facilities in China.[519] In the solar industry, where cell technologies were more easily accessible and returnees from global universities had introduced advanced R&D capabilities to Chinese firms, manufacturers were frequently applying innovative manufacturing capabilities to new technologies

---

[517] The Chinese patent office had denied patent protection since the technology is based on a commonly known principle. Interviews with CTO and director of R&D at Chinese solar manufacturer, August 26, 2011.

[518] Executive, global manufacturer of solar production equipment, interviewed August 08, 2011. CEO, Chinese solar cell manufacturer, interviewed August 10, 2011.

[519] Engineer, European wind turbine startup, June 2, 2011. CEO, Chinese solar cell manufacturer, interviewed August 10, 2011. Foreign wind turbine manufacturer, interviewed November 11, 2011.

developed in-house.[520] What these instances had in common was that manufacturability was a key constraint in commercializing an idea, and that scaling had to take place in short timeframes to take advantage of opportunities in fast-moving markets. Out of 24 Chinese wind turbine and solar PV manufacturing firms interviewed for this project, 19 discussed the importance of knowledge-intensive manufacturing capabilities in commercializing new technologies in fast-moving wind and solar markets.

Manufacturing as a platform for technology systems integration

In a third and final variant of innovative manufacturing, the presence of production know-how provided a platform for external innovators to integrate their technologies into existing wind and solar technologies that were already mass-produced in China. In such cases, the firms supplying the technology, however, were more than just high-end component vendors who sold a product at arms-length to a Chinese competitor. Rather, the vendors commercialized their technology in collaboration with a Chinese partner. The vendor contributed knowledge about a particular technology that may have applications to a product the Chinese manufacturer has already scaled up. The Chinese manufacturer, in turn, provided knowledge about production, knowledge about how the component technology can be applied at scale using existing production technology, and knowledge about how the original product will be improved as a result.

The cooperation of US-based Innovalight with the Chinese solar cell manufacturer JA Solar illustrates an interaction in which a foreign firm relied on China's manufacturing

[520] CEO, Chinese solar cell manufacturer, interviewed August 10, 2011. President, Chinese wafer manufacturer, interviewed August 26, 2011. CEO, Chinese cell and module manufacturer, interviewed June 28, 2013.

infrastructure as a platform for product development. A Silicon Valley start-up founded in 2002, Innovalight developed a nanomaterial with potential applications in products ranging from integrated circuits and displays to solar PV. With Department of Energy funding and support from the National Renewable Energy Laboratory (NREL), the firm developed an understanding of how the nanomaterial, a silicon ink, might be applied in the solar PV industry. However, while Innovalight and NREL could determine how the material might improve a single solar cell, neither had the know-how required for applying the material in a cost-effective manner in high-volume solar PV production. Outside investors certainly seemed to doubt Innovalight's know-how in this area, for the firm was unable to raise the capital needed to build a solar PV production facility.[521] In 2009, short of funds and nearly out of business, Innovalight found a partner in the Chinese cell manufacturer JA Solar. Looking for a way to gain an edge over its competitors, JA Solar was willing to invest in the collaborative development of a component that could substantially improve the efficiency of its main product. After a year of joint R&D, the two firms announced the successful production of high-efficiency solar cells using Innovalight's silicon ink technology. As a result, the two firms in 2010 signed a three-year agreement for the supply of silicon ink, as well as a strategic agreement for the joint development of high-efficiency cells.[522] The process of joint development with JA Solar for the first time verified Innovalight's silicon ink technology as a product that can contribute value in solar PV.

---

[521] Ucilia Wang. 2011. "DuPont buys solar ink maker Innovalight." Available from http://www.reuters.com/article/2011/07/25/idUS165538390720110725. (Accessed March 11, 2012).
[522] JA Solar. 2010. JA Solar Signs Strategic Agreements with Innovalight for Joint Development of High Efficiency Solar Cells. Available from http://investors.jasolar.com/phoenix.zhtml?c=208005&p=irol-newsArticle&ID=1446259&highlight= (accessed March 11, 2012).

Established as a legitimate player in the solar industry, Innovalight subsequently began licensing its technology to other solar manufacturers.[523]

Manufacturing as a platform for product development was especially common in the interaction between manufacturers and component suppliers, which relied on customers not just for demand, but also for engineering skills and product knowledge required to integrate new components and materials.[524] As China became a center for the commercialization for some of the most advanced renewable energy technologies, Chinese firms used innovative manufacturing capabilities to find applications for novel components, materials, and production equipment developed by global firms.[525] Although the intensity of collaboration differed from case to case, six out of seven solar PV suppliers interviewed for this project reported working with Chinese solar manufacturers on the commercialization of new technologies. In the wind sector, European manufacturers of complex components such as gearboxes and generators similarly described collaborating with Chinese customers on integrating their largest and most advanced technologies.[526]

The capabilities in innovative manufacturing that China's wind and solar firms layered on existing production skills presented a form of knowledge-intensive upgrading, yet they differed from the vision of indigenous innovation—however loosely defined—that permeated central-level policy making. In all three variants of innovative manufacturing,

---

523 Becky Stuart, 2012. "DuPont and Yingli sign $100 million PV materials agreement." In PV Magazine, February 14. http://www.pv-magazine.com/news/details/beitrag/dupont-and-yingli-sign-100-million-pv-materials-agreement_100005757/#axzz2rirI1NP0 (accessed January 20, 2014).

524 CEO of American nanomaterial manufacturer, interviewed October 13, 2011.

525 Neuhoff 2012.

526 Plant manager at a German gearbox supplier, interviewed May 16, 2011. Plant manager at a German generator manufacturer, interviewed May 17, 2011.

wind and solar firms continued to rely on collaboration with foreign innovators, as their capabilities, knowledge-based though they were, remained too narrow to autonomously develop and commercialize new technologies. Although some firms expanded into the production of multiple production steps and displayed different degrees of vertical integration, these were not the type of national champion firms that internally established all the capabilities to bring an idea to mass production. Central-level policy-makers at no point pursued a naive vision of complete technology autonomy in an increasingly globalized economy, however, the networked nature of innovation in wind and solar supply chains and the specialization of individual firms in niche capabilities did not support the stated goal of reducing reliance on foreign technology.

In addition to working with technology partners on product development, China's wind and solar firms differed from central government conceptions of indigenous innovation through the type of innovative capabilities that they brought to bear on global production networks. By embedding innovative capabilities in manufacturing itself, China's wind and solar manufacturers were challenging the notion that technological upgrading would somehow entail moving 'beyond' manufacturing to the higher-value added activities of product development. Although innovative manufacturing contributed to such product commercialization through changes to product designs, all three variants of innovative manufacturing defied simple categorization into product, process, or architectural innovation through their close connection to manufacturing.[527] And yet, as China's wind

[527] Although they differ from the type of innovation described here, instances of innovation in product architecture have been documented in the Chinese business ecosystem. See, for instance, Ernst and Naughton 2008b; Ernst and Naughton 2012; Ge and Fujimoto 2004. Others have identified cases in which changes in product architecture and the need to develop lower-cost adaptations of products for the Chinese market have led to new products. See Breznitz and Murphree 2011; Thun and Brandt 2010.

and solar sectors became important locations for the knowledge required to adjust, improve, and integrate product designs and individual components for mass manufacturing, it was through engineering capabilities—and technological innovation—of Chinese firms that new generations of renewable energy technologies made it from lab to market. That capabilities so central to product development could emerge within the context of manufacturing was not an option anticipated by the Beijing's science and technology planners.

4. Innovative Manufacturing and Local Government Support

China's wind turbine and solar PV producers made use of China's national science and technology infrastructure in the development of capabilities in innovative manufacturing, yet technological learning in wind and solar firms was also shaped by the manufacturing ecosystem around them. China's renewable energy producers did not just benefit from links to existing manufacturing firms, but made use of a wide range of resources and financial incentives provided for mass production in China's sprawling industrial parks.

In contrast to science and technology funding, which often entailed top-down administrative structures and directives set by China's central government ministries in Beijing, such resources for the manufacturing economy were largely provided by subnational governments.[528] For China's wind and solar firms, which could access product designs through technology licenses and collaboration but had to autonomously build capabilities in design-for-manufacturing and rapid commercialization, local policies for the manufacturing economy provided an important supplement to the central government's focus on lab-based R&D. Firms utilized local government support to build the manufacturing facilities which provided the basis for knowledge-intensive capabilities in mass production, but they also repurposed local support for establishment of engineering capabilities. Just as firms had utilized central government science and technology policies to respond to opportunities for industrial capabilities in scale-up and commercialization, entrepreneurial firms used resources for mass production provided at the local level for industrial upgrading in ways not anticipated by local government administrations.

[528] Cao et al. 2006; Kroll et al. 2008, 172-77.

The importance of local government policy for industrial upgrading in wind and solar sectors corresponds to the central role subnational administrations have played in China's political economy since the onset of economic reforms. Over the course of the 1980s, a series of fiscal and administrative reforms had made local governments dependent on local tax revenue while granting them decision-making autonomy on local economic affairs. Fiscal decentralization was intended to promote growth-enhancing economic measures at the local level while also creating room for localities to experiment on economic policy.[529] The center sought to further encourage experimentation in local policy-making by evaluating local officials on a series of development outcomes, rather than prescribing the policies to achieve them.[530] Even though fiscal decentralization was largely reversed in the course of the 1990s in order to improve the revenue situation of China's central government, local government discretion in economic governance and autonomy in the implementation of central directives remained central features of China's post-Mao political economy.[531]

In addition to experimenting with growth-enhancing policies at the local level, subnational governments carried out the implementation and financing of many national policies, including programs introduced under China's innovation-based development strategy. As a consequence, research and development appropriations of subnational governments rose in accordance with central government budget increases, growing from RMB 10.6 billion in 1996 to RMB 69.9 billion in 2006 (see Figure 3).[532] In 2004, nearly 40

[529] Jin et al. 2005; Oi 1995.

[530] Although factors such as social and environmental factors have been added to the cadre evaluation system over time, economic parameters have been paramount. For an introduction to cadre evaluation in China, see Edin 2003; Landry 2008, chapter 5; Whiting 2004, 106-12.

[531] The process of fiscal re-centralization is described in detail in Huang 2008, chapter 3.

[532] Ministry of Science and Technology 2007a.

percent of appropriations for science and technology programs came from subnational governments.[533] Local administrations shaped the details of such programs during implementation. As I will discuss in more detail below, the Torch high-tech development zones, for instance, experienced what Heilmann et al. have called "mission drift", as localities repurposed the zones from their original function as incubators for technology start-ups to a new focus on foreign investment and export-processing in an attempt to bolster economic growth.[534] Similarly, provincial implementation plans of China's 2009 decision to support seven strategic emerging industries (SEIs), reveal striking differences across localities, with local administrations picking between six and ten sectors and selecting local SEIs to match to the existing industrial base. In some provinces, such as Jiangxi, solar PV industries were included on this list, while other localities disregarded renewable energy industries in their interpretation of the original directive.[535] The implementation of central government policies thus provided an opportunity for localities to adjust such policies to match local needs.

In contrast to national policies issued in Beijing, which increasingly emphasized a broad reorientation away from mass production of standardized commodities toward an innovation-based development strategy, local administrations were primarily concerned with meeting immediate economic targets and raising local revenue. In practice, this entailed supporting manufacturing activities of local firms, often making financial support conditional on production targets and meeting tax revenue requirements. Even in the

---

533 Kroll et al. 2008, 179.

534 Heilmann et al. 2013, 903. The manufacuring orientation of high-tech zones has also been described in Cheng et al. 2013, 5; Kroll et al. 2008; OECD 2008; Sutherland 2005.

535 For details about provincial SEI implementation plans, see US-China Business Council 2013, 16-22.

implementation of central-level directives to support lab-based R&D and product innovation, local officials prioritized measures to enhance growth in the existing industrial base over policy support for innovative activities that may not yield returns in the immediate future. The designation of existing local sectors as Strategic Emerging Industries (SEIs), mentioned above, illustrates this strategy of connecting broad central government directives with the local economic requirements.[536] Not always did local economic policy produce optimal outcomes. In their emphasis on local development and rapid growth outcomes, local policy-makers also produced unintended negative consequences, most notably when localities refused to stop supporting industries already characterized by overcapacity and lack of scale economies. In the 1990s, for instance, many Chinese local governments backed independent auto-makers in blunt disregard of central directives, creating more than 120 local auto manufacturers that each produced no more than a few thousand vehicles per year. Rather than follow central directives to create a competitive national auto sector, localities were throwing good money after bad to protect enterprises that were not viable in the long-term.[537]

In this environment, wind and solar firms were able to access two sets of resources at the local level. First, they benefitted from general support for the manufacturing economy in the form of investment incentives such as tax breaks and discounted land. These financial incentives were offered relatively uniformly across China's economic development zones and industrial parks to attract foreign and, increasingly, domestic investment. Second, localities provided resources, institutions, facilities, and infrastructure

[536] US-China Business Council 2013, 16-22.
[537] Huang 2002, 542; Thun 2006, 59.

to support the existing local industrial base. Such institutions were regionally divergent, as they targeted needs of specific industrial sectors in the local economy.

Manufacturing Resources in China's High-Tech Industrial Zones

Although China's high-tech industrial zones had been established under the Torch program beginning in the late 1980s to provide incubator services for small- and medium-sized high-technology enterprises, in practice the economic constraints placed on local governments caused a reorientation towards mass manufacturing and export processing in China's high-technology zones. According to a 2013 study by Heilmann et al., out of a sample of 53 high-technology zones (HTZs), 39 deviated from their original purpose to promote domestic R&D activities and instead focused on mass production.[538] For local governments, high-technology zones had become convenient vehicles to increase economic growth and tax revenues within their jurisdiction; production, rather than innovation, appeared to many officials as the most promising use of HTZs.[539] Although the original definition of HTZs excluded production activities, China's high-technology zones became the fastest growing regions precisely because of the manufacturing facilities that they were able to attract.[540]

It is no surprise, then, that many of the preferential policies available to firms in China's HTZs supported mass production rather than the setting up of R&D labs or creating linkages to local universities and research institutes. Across most HTZs, firms were exempted from income tax for two years after becoming profitable, after which rates rose

538 Heilmann et al. 2013, 903.
539 Breznitz and Murphree 2011, 78.
540 Sutherland 2005, 91.

to a mere 7.5 percent for three years and topped out at 15 percent after that, a substantial discount on the 33 percent income tax businesses were required to pay outside such zones. Further tax benefits existed for foreign-invested enterprises and firms producing 'advanced technologies,' a category which wind turbines, solar panels, and their components were generally included under. For greenfield investors, such as the newly established wind and solar firms, HTZs cut building taxes, accelerated planning permits, waived VAT and import tariffs on imported parts and equipment, and allowed rapid depreciation for high-tech equipment.[541]

Localities further competed for investment by offering discounted land rates to firms seeking to establish manufacturing facilities.[542] The development and sale of land for urban construction became one of the most important sources of revenue for subnational governments after fiscal recentralization in the 1990s reassigned a large share of overall tax revenue back to the central government.[543] In development zones, however, local officials were willing to forgo profits on land as production facilities presented a source of future tax revenue and productive output remained an important factor in the cadre evaluation system. Because HTZ administrators had information about land (and tax) packages offered by neighboring municipalities and were willing to match their own deals to compete, land prices became relatively uniform across development zones. Moreover, mandatory compensation levels for rural farmland converted to industrial use determined by the central government set a lower price boundary of sorts. As a senior official at one of the Torch Program HTZs, Suzhou New District (苏州新区), explained

[541] Liu and Martinez-Vazquez 2013, 4; Sutherland 2005, 95.
[542] Kremzner 1998, 628; Kroll et al. 2008, 191.
[543] For a discussion of land as a source of revenue for municipal governments, see, for instance, Lin and Yi 2011; Rithmire 2013; Whiting 2011; Zhao 2011.

> "If you represent a manufacturing company and they want to come to Suzhou, you will come to different investor parks. Suzhou New District will hopefully be one of them. But Wuxi and Changzhou will compete against us. Our function is to recommend Suzhou New District and try to persuade them to put their investment here. In the Suzhou area we have at least five national level investor parks. There are more than 10 provincial and city level investor parks. So there are at least 15-20 parks which are all competing. And that's just Suzhou.
>
> The benefits that we offer are pretty much the same across industrial parks. We cannot lower the taxes because we are not allowed to subsidize that way. We can speed up approval and help firms with the bureaucracy. We cannot lower the electricity price because that's not determined by us locally. Same with water. We cannot control the price for that locally. Wuxi and Changzhou give some subsidies to recruit high-level talent employees, which is one way to attract firms.
>
> What we can do is to lower the price of land, but not indefinitely. The land is never free. That also is beyond our control. Before we transfer the land to the companies we have to relocate the farmers on the land. And that requires quite a bit of money as compensation levels are centrally determined. After they are relocated we need to tear down everything and then we need to pay fees to the provincial authorities and the central government. So there is high burden for the local government and we have to pass on that cost to some extent."[544]

As less and less agricultural land was available for industrial development in China's sprawling high-technology zones, local officials became increasingly selective about the kinds industries targeted and the types of incentives offered to firms. High-tech industrial sectors—independent of central-government guidelines that encouraged preferential treatment of high-tech firms—were particularly sought after because they promised higher returns on smaller plots than the manufacturing of consumer products that had dominated economic development zones during the 1990s.[545] To ensure that firms would rapidly contribute to the local economy, local administrations made tax breaks and land deals conditional on meeting production targets and revenue requirements. At times, firms were contractually obliged to build facilities with pre-determined manufacturing capacity by a

[544] Interview, senior official at Suzhou New District HTZ, January 9, 2012.
[545] Interview, senior official at Suzhou New District HTZ, January 9, 2012.

particular date or risk losing government grants, tax reductions, and discounts on land prices. In other cases, local governments informally exerted pressure on firms to rapidly scale production. The CEO of a European wind turbine engineering firm reported that a Chinese collaborator "constructed a 25,000 square meter facility practically over night, because local officials had provided financial support and wanted to see results."[546] A President of a solar startup disclosed that steeply discounted land prices required meeting tax revenue targets, otherwise fines equal to the land discount would have to be paid.[547]

Most of China's wind and solar firms were established in one of the growing number of HTZ's created under the Torch Program, building manufacturing capabilities in an environment that not only offered investment incentives firms, but encouraged rapid scale up and mass production. Goldwind set up its first manufacturing facilities in a high-tech industrial development zone in Urumqi's Xinshi District established under the Torch program in 1994, where it participated in a tax refund program for high-tech manufacturing enterprises that returned RMB 15 Million in taxes to local firms in 1999 alone.[548] In 1998, the Baoding municipal government supported the creation of Yingli Solar in Baoding's High-Tech Industrial Zone with a RMB 166 million investment. The local administration required the establishment of 3 MW of production capacity, an ambitious goal for a single firm at a time when the United States, then the global leader in PV production, had a national production capacity of 54 MW.[549] Trina Solar relocated its operations to a Changzhou HTZ in 2002 to qualify for preferential income taxes, yet moved

[546] Author interviews: CEO, European wind turbine engineering firm, interviewed May 20, 2011; CTO, Chinese wind turbine manufacturer, interviewed August 29, 2011; senior official at Suzhou New District HTZ, January 9, 2012; CEO, European wind turbine manufacturer, August 17, 2011.
[547] Author interview, President, solar PV startup firm, August 24, 2011.
[548] *Urumqi Year Book [乌鲁木齐年检].* 2000, 116.
[549] *Baoding Year Book [保定年检].* 1999, 111.

to a neighboring zone in 2004 after its original tax discount expired.[550] Canadian Solar and GCL solar opened manufacturing facilities in Suzhou's New District HTZ.[551] Mingyang, China's largest private wind turbine manufacturer, set up its headquarters in the National Torch High Technology Industry Development Zone in Zhongshan, Guangdong province, in 2006.[552] It subsequently opened manufacturing facilities in other parts of China, including in the Jilin High-Tech Industrial Development Zone, a Torch HTZ, and Tianjin Binhai High-Technology Zone (滨海新区), a state-level HTZ that focussed on the attraction of renewable energy manufacturing.[553] In 2010, after the company was listed on the New York Stock Exchange, its annual report disclosed RMB 111.1 million in cash grants by local governments to support R&D, the improvement of manufacturing facilities, and the acquisition of land.[554]

High-tech development zones and local government officials offered a range of additional services to encourage local firms to rapidly increase production output. For firms setting up production facilities, the HTZ administrations acted as scale-up consultants of sorts, fast-tracking planning permits and navigating the Chinese bureaucracy, not just for foreign investors, but also for domestic ones.[555] More importantly, however, local governments offered access to financing, channelling bank loans and other forms of funding to firms in development zones. Local science and technology offices were often willing to invest directly in new energy firms, if only to demonstrate a commitment to central government directives to support technological innovation. The grants and

[550] Trina Solar 2008, 36.
[551] Author interview, senior official at Suzhou New District HTZ, January 9, 2012.
[552] Guang Dong Mingyang Wind Power Technology Co. Ltd 2007.
[553] *Tianjin Yearbook [天津年鉴].* 2010, 241-42.
[554] China Ming Yang Wind Power Group Limited 2011, 53.
[555] Sutherland 2005, 95-96.

incentives described above are illustrative of this kind of investment. For larger sums, however, local officials connected firms to banks. The special focus on new energy sectors in national science and technology plans made China's state-owned financial institutions more willing to lend to wind and solar companies, but particularly when the first wind and solar firms were founded, local governments were critical brokers in such deals. The city of Wuxi, for instance, invested USD 6 Million in return for a 75 percent equity stake in the solar PV producer Suntech in 2001, after its founder, Shi Zhengrong, had compared offers from a number of local high-tech development zones. To fund the rapid expansion of Suntech in the following years—by 2006, Suntech was the world's third largest producer of solar panels—local officials subsequently brokered a series of bank loans for the company.[556] For a single 68,0000 square meter production facility launched in 2005, a RMB 200 Million investment was financed through such connections.[557]

Access to large-scale financing of course provided no guarantee for upgrading to innovative capabilities, yet it was a precondition for the construction of the type of capital-intensive manufacturing facilities required for the commercialization of new energy technologies. As such, local financing provided the basis for engineering capabilities in innovative manufacturing, as it made possible the infrastructure on which such skills could be applied in ways that limited central-government R&D funding alone could not. Recent media reports suggest that the China Development Bank alone extended USD 29 billion in credit to 15 solar and wind companies; others have calculated that China's publicly listed wind and solar companies took out some USD 18 billion in loans with loan guarantees from

---

[556] Ahrens 2013, 3-4. See also, Kevin Bulls, 2011. "The Chinese Solar Machine." *MIT Technology Review*, December 19.

[557] *Wuxi Yearbook [无锡年检].* 2006, 293.

municipal governments.[558] Although there is little reliable information on what interest rates such deals entailed, it is safe to assume that at least some of these loans were provided a sub-market rates.[559] While firms could not fund their way to know-how and engineering skills in commercialization, the availability of such funding for production facilities enabled the specialization in innovative manufacturing in China's most capable wind and solar firms. In interviews, foreign partners of solar firms frequently praised the R&D conditions in Chinese manufacturing facilities, where access to capital allowed firms to dedicate entire production lines to testing and experimentation of new technologies under production conditions. Meanwhile, in Europe and the United States, R&D engineers struggled to obtain adequate time slots during which tests could be conducted on regular production lines.[560]

High-tech development zones not only provided access to the financial capital required to build capabilities in mass production, but also attracted the human capital necessary for know-how in rapid-commercialization. Between 1990 and 2006, China's science and technology personnel—defined in China as staff who spend at least 10 percent of their time in activities "closely related to the production, development, dissemination, and application of knowledge in natural sciences, agricultural science, medical science, engineering and technological science, humanities and social sciences"—nearly doubled, from 23 million to 41 million.[561] More than two thirds of S&T personnel were scientists and

[558] "Chinese Renewable Companies Slow to Tap $47 Billion Credit." *Bloomberg*, November 16, 2011. "JinkoSolar Gets $1 Billion Infusion from Chinese Development Bank." *SustainableBusiness.Com*, December 12, 2012. Keith Bradsher, 2012. "Glut of Solar Panels Poses a New Threat to China." *New York Times*, October 4.
[559] Deutch and Steinfeld 2013.
[560] Author interviews: CEO, Chinese solar manufacturer, August 20, 2011; CTO and director of R&D at Chinese solar manufacturer, August 26, 2011; CEO, German equipment manufacturer, May 10, 2011; CTO, German equipment manufacturer, May 11, 2011.
[561] Simon and Cao 2009, 67-68.

engineers.[562] The share of such workers with university degrees increased from 10 million in 2000 to 14.5 million in 2005, with a growing percentage of science and technology workers employed by enterprises, rather than universities and research institutes.[563] By 2006, nearly half of science and technology employes worked in large and medium-sized enterprises, up form 36 percent during the early 1990s.[564] A disproportionate amount of this young and educated workforce gravitated to high-technology development zones. In 2000, for instance, when the first wind and solar firms were just beginning to engage in the commercialization of new technologies, enterprises in China's Torch Program HTZs jointly employed a workforce of 7.5 million, a third of which held university degrees. Although the Ministry of Science and Technology estimated only 30,000 staff with masters degrees and 4,000 graduates of doctoral programs at work in HTZ enterprises that year, the figures far exceeded average Chinese educational levels at the time.[565] For wind and solar firms, HTZs thus presented a rich environment within which to recruit engineering staff who not only had above-average levels of educational achievement, but who had work experience in mass production in a wide range of other sectors, including many foreign-invested firms that had come to China during the 1990s and settled in high-tech zones.

Local Government Resources for Industrial Upgrading

Political economists have long documented differences across China's regional political economies, yet the local conditions in high-tech development zones were relatively uniform in terms of the basic resources offered to attract investment and the

---

[562] Simon and Cao 2009, 75.
[563] Simon and Cao 2009, 72.
[564] Simon and Cao 2009, 79.
[565] Ministry of Science and Technology data cited in Sutherland 2005, 96.

stipulations of scale-up and mass production attached to government support.[566] Once localities had successfully attracted firms, however, a second set of policies and institutions supported the activities of local firms in a more target way. Such resources, policies, and institutions differed depending on the make-up of the local economy; what they had in common was support for rapid commercialization and mass production through the creation of new capabilities in the local economy, rather than the financing of ever larger production facilities.

Municipal governments themselves were active agents in the composition of the local economy, interpreting central directives to promote strategic industries in ways that were compatible with the existing industrial structure. Although many of the early wind and solar firms were simply established in the proximity of their parent companies or near the hometown of their founders, municipalities later attracted supplier firms and companies from related industrial sectors to create cluster effects and synergies. Wuxi, the city where Suntech was founded in 2001, attracted a large number of suppliers, including glass manufacturers, producers of production equipment, and firms supplying silicone and other materials required for PV production. Semiconductor firms, which rely on a production process in many ways similar to that of a solar cell, also settled in local HTZs.[567] Baoding, where Yingli had started the domestic solar PV industry in 2001, ultimately branded itself as a 'green city,' attracting a wide range of renewable energy firms and suppliers with complementary capabilities to its local industrial parks. The local government additionally targeted foreign equipment manufacturers and component

---

[566] A large literature has documented different regional political economies in China, emphasizing differences in institutions, training of local officials, sequencing of economic reforms, and local economic rules. See, for instance, Rithmire 2013; Segal 2003; Thun 2006.

[567] *Wuxi Yearbook [无锡年检].* 2003, 219; *Wuxi Yearbook [无锡年检].* 2006, 292.

suppliers at international conferences, including the 2004 Global Wind Power Exhibit held in Beijing, less than a 100 miles away from the city.[568] In other cases, particularly among the late entrants, domestic wind and solar firms were attracted to high-tech development zones specifically for their existing industrial base. A history of shipbuilding and the presence of related supplier industries, including bearings manufacturing, persuaded Sinovel to open its first manufacturing facilities in Dalian.[569] Tianjin, became a popular destination for domestic wind turbine producers after the city had successfully attracted a wide range of foreign wind turbine manufacturers and their suppliers, including REpower, Sinovel, and Vestas.[570] In Changzhou, where Trina Solar and EGing Solar were producing cells and solar PV modules, the municipal government counted 109 firms manufacturing products and components for power generation equipment, including transformers, inverters, electrical insulation, and switching equipment.[571]

The agglomeration economies that resulted from local government coordination promoted the type of collaboration between foreign and domestic firms and the specialization on niche capabilities that I have described in chapter 2. For domestic manufacturers seeking to upgrade their capabilities in manufacturing, however, these local economies also created supplier networks that allowed the purchase of large quantities of raw materials at short notice and they permitted close interaction with suppliers on tweaking equipment and adjusting material composition to match product designs and manufacturing processes. For engineering teams seeking to find ways to accelerate product

---

[568] *Baoding Year Book [保定年检].* 2004/2005, 155.
[569] *Dalian Yearbook [大连年检].* 2007, 130-39.
[570] *Tianjin Yearbook [天津年鉴].* 2010, 241-42.
[571] *Changzhou Yearbook [常州年检].* 2005, 173.

commercialization, regional economies thus offered a wide range of tools and partners focused precisely on large scale production of renewable energy technologies. In interviews, firms confirmed the benefits of their local environments. The president of a solar PV startup, for instance, explained their locational choice in proximity to other solar PV manufacturers with the availability of used production equipment, on which engineering teams could cheaply test the manufacturing of new product designs.[572] Others emphasized the availability of local suppliers with whom to collaborate on substitute materials or new equipment design, rapidly going through multiple configurations until the right setup was determined.[573]

Beyond the benefits that firms naturally derived from agglomeration economies, specialization in local industrial composition also permitted local governments to design more targeted institutions to support firms in the process of developing knowledge-intensive capabilities. In contrast to the broad national educational reforms that increased the number of graduates from China's engineering schools over time, local administrations created educational facilities for vocational training and continuing education that matched the needs of local firms. These local colleges were not aiming to graduate engineers with doctoral degrees; rather, they focused on creating a manufacturing workforce capable of understanding manufacturing blueprints while grasping the requirements of mass production. Regardless of whether such programs allowed firms to send existing workers for continuing education or trained high-school graduates for manufacturing jobs, many of the vocational colleges set up by local governments in China's high-technology institutes

---

[572] Author interview, president, solar PV startup firm, August 24, 2011.

[573] Author interviews: CTO and director of R&D at Chinese solar manufacturer, August 26, 2011; CTO, Chinese wind turbine manufacturer, interviewed August 29, 2011.

collaborated with local firms. For instance, the municipal government in Changzhou set up a program for technological upgrading in manufacturing firms as early as 1997, around the time that Trina solar was founded as a solar installation company. The city estimated that about 25 percent of local large- and medium-sized enterprises had employees with Computer Assisted Design training (CAD), with a total of 5000 CAD-trained workers in the city. To further increase this number and promote advanced manufacturing capabilities in the local workforce, the city set up CAD demonstration platforms, established training programs, and offered loans to local companies seeking to upgrade their manufacturing infrastructure and skill level of employees.[574] Similar programs to introduce IT capabilities in local manufacturing operations were established in other locations with sizable renewable energy industries, including in Changzhou, Baoding, and Urumqi.[575] In Wuxi, the local government founded a vocational college for science and technology training in 2003. By 2005, the school was offering applied vocational training programs for 6000 students in collaboration with Suntech, Sony, and 37 other firms with facilities in the region.[576] In some cases local enterprises themselves took the initiative to set up such programs, collaborating with local government and other firms for support. Spearheaded by Dalian Daxian Group, a supplier of electronic components, vocational training was offered in Dalian for electro-mechanical technicians, supplying workers with knowledge of mechanical components and electronic circuitry to local industrial sectors, including wind turbine manufacturing.[577]

---

[574] *Changzhou Yearbook [常州年检].* 1998, 288.

[575] *Changzhou Yearbook [常州年检].* 2004, 249-50; *Baoding Year Book [保定年检].* 2004/2005, 523; *Urumqi Year Book [乌鲁木齐年检].* 2007, 226.

[576] *Wuxi Yearbook [无锡年检].* 2006, 305.

[577] *Dalian Yearbook [大连年检].* 2007, 140.

The training of the local manufacturing workforce in Chinese HTZs occurred at the same time as wind and solar manufacturers increasingly automated their production lines to avoid the high turnover rates associated with unskilled labor, rapidly increasing average training levels of the remaining workforce. Although innovative manufacturing capabilities continued to reside in designated engineering teams and did not extend into the manufacturing workforce in the same way as advanced manufacturing capabilities in Germany, the training of manufacturing staff permitted a more rapid translation of design and process changes into manufacturing practice. Efforts to increase skill and training levels among local workers through vocational training and continuing education for the existing workforce thus complemented central government innovation policy, which focused on technology development but paid little attention to the types of skills required in commercialization and production.

In addition to promoting workforce training, municipalities supported technology commercialization of local firms by funding individual commercialization projects in firms and by improving the research and development infrastructure available in the local economy. Such R&D infrastructure included China's 800 universities and 5000 research institutes, 60 percent of which are located in close proximity to one of the high-technology industrial zones.[578] Many of these institutions set up laboratories working on technologies of importance to industrial sectors; municipal chronicles boast increasing patent activities and journal citations of local research laboratories. In Baoding, for instance, Hebei University of Technology (河北工业大学) established a School of Energy and Environmental Engineering in the early 2000s, after the arrival of Yingli and other

[578] Heilmann et al. 2013; Sutherland 2005, 96.

renewable energy companies prompted the city to promote itself as a green technology cluster.[579] In practice, however, studies have found relatively weak links between firms and local university laboratories in the commercialization of new technologies; although almost all renewable energy firms indicate some connections to research institutes, collaborative research and development activities mostly occur with other firms.[580]

More central to the specialization in innovative manufacturing were local programs focused not on laboratory research, but on the commercialization of new technologies and the transition to mass production. Almost all localities set up municipal "innovation funds," providing grants for innovation-related activities in local firms. Often these grants funded activities to overcome challenges in the commercialization of new technologies, rather than the development of such technologies themselves. Although most grants went directly to firms, localities also used such programs to public fund facilities such as test centers, providing complementary capabilities for firms in the local economy.

In Dalian, for instance, the municipal government in 2006 supported Sinovel in the commercialization of a 1.5MW turbine technology based on a license from a German firm, in the process adapting the turbine for deployment under harsh climate conditions of up to -40 degrees celsius. Two local suppliers, Dalian Tianyuan Electrical Machinery (大连天元电机有限公司) and Dalian Wazhou Group (大连瓦轴集团), supplied components for the new turbine. In the process, the local government aided Dalian Wazhou in constructing a test platform for industrial-scale precision bearings to aid the commercialization of new bearing designs. Beyond supporting the commercialization of wind turbine components,

[579] Author interview, senior official, Baoding Municipal Government, January 7, 2012.
[580] Sutherland 2005, 96.

however, the testing platform enabled the commercialization of bearings for other local industries such as shipbuilding and railway engines.[581] In collaboration with Suntech, the Wuxi government in 2006 initiated a so-called "530 Program," providing funds to attract Chinese engineering graduates back into local high-tech development zones and offering grants of RMB 1-3 million for the commercialization of promising technologies. By 2012, 876 local firms were participating in the 530 program and program funds had grown to a total of RMB 2.5 billion.[582] In Baoding, the provincial government funded the development of two public engineering centers in the local high-tech development zone, a center of virtual engineering and a engineering center of blade development, both of which offered access to advanced computer workstations and test facilities. The government emphasized the importance of industry associations in setting up these facilities to meet the needs of the local industry and enhance competitiveness of local firms.[583]

Local government policies, training institutions, and innovation support programs did not add up to a comprehensive strategy for industrial upgrading, but rather presented ad-hoc responses to the perceived needs of local industrial sectors, central government directives to promote innovation, and the desire of local officials to promote economic growth. For wind and solar firms, these policies created a broad range of resources that could be used to improve engineering capabilities and fund the expansion of manufacturing facilities. However, just as central government policies had not deliberately created institutions to support the establishment of capabilities in innovative manufacturing, local

---

581 *Dalian Yearbook [大连年检].* 2007, 130-39.

582 *Wuxi Yearbook [无锡年检].* 2008, 241. See also http://www.1000plan.org/qrjh/channel/11 (Accessed, January 28, 2014).

583 *Baoding Year Book [保定年检].* 2004/2005, 155.

governments and high-tech development zones did not strategically choose capabilities in technology commercialization as an upgrading goal. Within China's broader fiscal and administrative structures, policy-making at the local level was instead driven by the much more immediate necessity of maintaining sufficient economic growth through the encouragement rapid scale-up and mass production. It were China's wind and solar firms that utilized this manufacturing infrastructure to respond to new opportunities in global wind and solar supply chains, by laying engineering capabilities in innovative manufacturing on existing skills in mass production.

5. Conclusion

Chinese firms have competed in global wind and solar sectors with knowledge-intensive capabilities in scale-up and commercialization, which I have referred to as capabilities in innovative manufacturing. These engineering capabilities, narrow they may be, could not be accessed in global supply chains, as firms in Europe and the United States were themselves still engaged in experimental small-batch production when Chinese firms entered renewable energy sectors. While wind and solar technologies were easily accessible in global production networks through licensing and collaboration with foreign partners, it was the rapid and cost-effective translation of such technologies into mass-manufacturable products that could not be bought or learned from others. As a result, Chinese firms collaborated with foreign partners to obtain wind and solar technologies; engineering capabilities in innovative manufacturing, which permitted these technologies to be commercialized at scale, had to be established in-house.

The findings presented in this chapter suggest that China's rapid rise in wind and solar industries is not purely an outcome of factor cost advantages or government subsidies, which have attracted low-cost production activities into local development zones. Nor is China's role in renewable energy industries the result of traditional tools of industrial policy, which in other East Asian economies long channelled resources into strategic industrial activities, picked winners, and shielded domestic firms from competition to establish conglomerates with capabilities ranging from manufacturing through early-stage R&D. Instead, I find that the divergence of policy goals and resources offered at different administrative levels—with China's central government policies targeting indigenous innovation and autonomous technology development while local governments continued to support mass production—provided firms with a range of institutions and resources which could be repurposed to build engineering capabilities in innovative manufacturing. Ultimately, it were entrepreneurial firms that identified new opportunities for industrial upgrading within manufacturing and creatively deployed the tools available to them in China's industrial ecosystem to take advantage of these opportunities..

China's wind and solar manufacturers thus neither followed central government policy goals, which encouraged the emulation of advanced R&D capabilities of foreign companies through research and development funding, nor did they use local government support for mass production purely to lower production cost through expansive manufacturing facilities. Instead, Chinese firms repurposed policies and institutions provided by central and subnational governments to establish knowledge-intensive capabilities within manufacturing itself, incrementally building on China's industrial legacy of mass production. The state enabled industrial upgrading among China's wind and solar producers, not only by providing the resources required for technological learning, but also by attracting foreign-invested high-technology manufacturers into China's economic development zones, establishing an industrial ecosystem for mass production on which capabilities in innovative manufacturing capabilities could be built.

China's role in global renewable energy industries suggests that the fragmentation of global production has created new opportunities for industrial upgrading for developing economies that do not rely on the emulation of foreign partners. Instead of having to master activities along the entire trajectory from mass production to early-stage R&D, firms were able to participate in global processes of technology development with narrow engineering capabilities centered on commercialization and scale-up. This specialization in innovative manufacturing was neither anticipated by government officials, nor deliberately supported through targeted intervention. At least implicitly, the creative use of government resources was tolerated, as neither neither central nor local governments stepped in to prevent the repurposing of existing institutions and policies for new applications, even if they did not meet expectations about traditional trajectories of industrial upgrading. The behavior of the Chinese state thus contrasted sharply with that of other East Asian developers, which rewarded firms only when meeting government-defined upgrading goals and withdrew support from those that failed to comply with official targets. The use of disciplinary mechanisms to encourage firms to meet set upgrading goals, which Amsden has identified as an important factor in creating competitive firms in South Korea, would have likely prevented firms from embarking on new trajectories for industrial upgrading outside the scope of government plans.[584]

The findings presented in this chapter bode well for firms in developing economies seeking to upgrade under conditions of fragmented production. China's wind and solar firms have achieved sustained growth despite divergent—and often outright conflicting—government policies, which have not followed the hierarchical, centralized, and highly-disciplined template of the East Asian developmental states. China's renewable energy firms have avoided the main hazard associated with participation in fragmented global production systems, the possibility of getting stuck in low skill and low value activities in global supply chains.[585] Instead, capabilities in scale-up and commercialization have attracted global innovators to China, allowing Chinese firms to bring new-to-the-world

[584] Amsden 1989, 145-47; Amsden 2001, 8-12.
[585] Steinfeld 2004.

wind and solar technologies to market, even if they do not do so autonomously. At least in renewable energy industries, Chinese firms have been able to compete with knowledge, not labor cost. As a consequence, wind and solar production has not chased labor cost to cheaper manufacturing locations in the Chinese interior or neighboring economies, even as wage differentials are large and growing.[586]

At the same time, however, such upgrading-within-manufacturing has required Chinese firms and regulators to bear enormous risks. Participation in global processes of technology development has required Chinese firms to make large investments in manufacturing capacity, often funded by state-owned banks and local governments. Much in contrast to Germany's suppliers of components and production equipment, which have maintained customers in several industries despite small firm sizes, China's investments have been industry specific. In sectors such as wind and solar, in which demand continues to rely on demand-side subsidies, the fate of China's innovative manufacturers is determined not just by the ability to innovate and further reduce cost, but depends on government policy in China and abroad. The global financial crisis, which led many European governments to cut or eliminate subsidies for wind and solar products, has created overcapacity in global renewable energy sectors. Anti-dumping legislation against Chinese solar panels has further reduced exported markets.[587] In this situation, Chinese firms have been stuck with the most capital intensive part of the global innovation processes, and a number of firms have declared bankruptcy as a result. Suntech, for instance, exported 38 percent of its solar panels to Spain in 2008. By 2009, after the

---

[586] In 2009, the wage gap between urban workers in coastal provinces—where most of China's renewable energy manufacturing is located—and urban workers in interior provinces was 55%, up from 28% two decades earlier. Li et al. 2012, 62.

[587] U.S. International Trade Commission 2012.

Spanish government had all but shut its domestic support for renewable energy markets, Spanish demand accounted for less than 3 percent of Suntech's revenue.[588] By 2013, the company, once the largest solar manufacturer in China, had filed for bankruptcy protection.[589]

Ultimately, the sustainability of China's specialization in innovative manufacturing as a source of industrial development may depend on the ability of China's manufacturers to apply their capabilities in scale-up and commercialization to a wide range of industrial sectors. Breznitz and Murphree, in a study on China's electronics industry, have found that manufacturers there may have embarked on an upgrading trajectory similar to that of the wind and solar firms examined in this study.[590] Thun and Brandt find that in machine tools and automotive sectors, too, Chinese firms benefit from engineering capabilities in manufacturing.[591] That capabilities in manufacturing can in principle be the source of long-term advantage is illustrated by Germany's small- and medium-sized wind and solar suppliers discussed (Chapter 3), which have incrementally improved and adapted their core capabilities over decades and applied them to successive industrial sectors. If the experience of China's renewable energy industries is any guide, it will be up to entrepreneurial firms, not government, to identify new applications for capabilities in innovative manufacturing, in the process repurposing a wide range of resources and institutions in ways not anticipated by Beijing's central government planners.

---

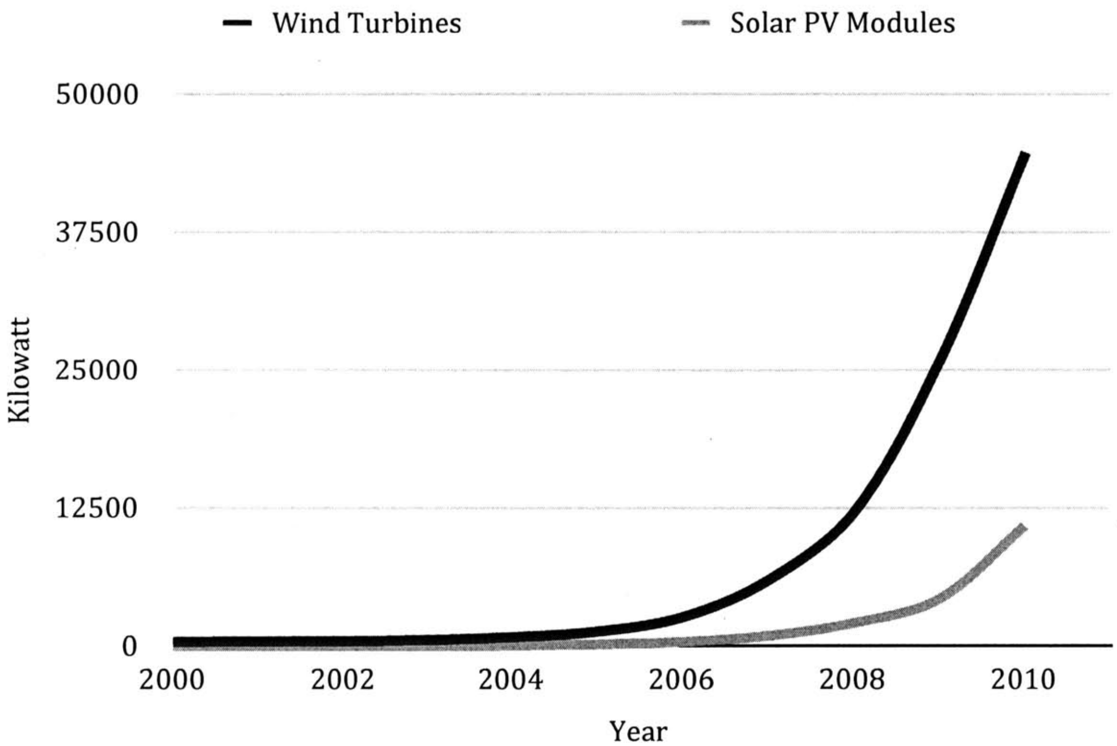
588 Ahrens 2013, 4.

589 Keith Bradsher, 2013. "Chinese Solar Giant is Tainted by Bankruptcy." *New York Times*, March 20.

590 Breznitz and Murphree 2011.

591 Brandt and Thun 2010.

Figure 1: Domestic Production of Wind Turbines and Solar Panels, 2000-2010 (in Kilowatt)



Note: Reliable data on wind turbine production is not available, so domestic turbine installations are used as an approximate value for this graph. Since the vast majority of turbine components are sourced domestically and all turbines are assembled in China, the difference between installations and domestic production.

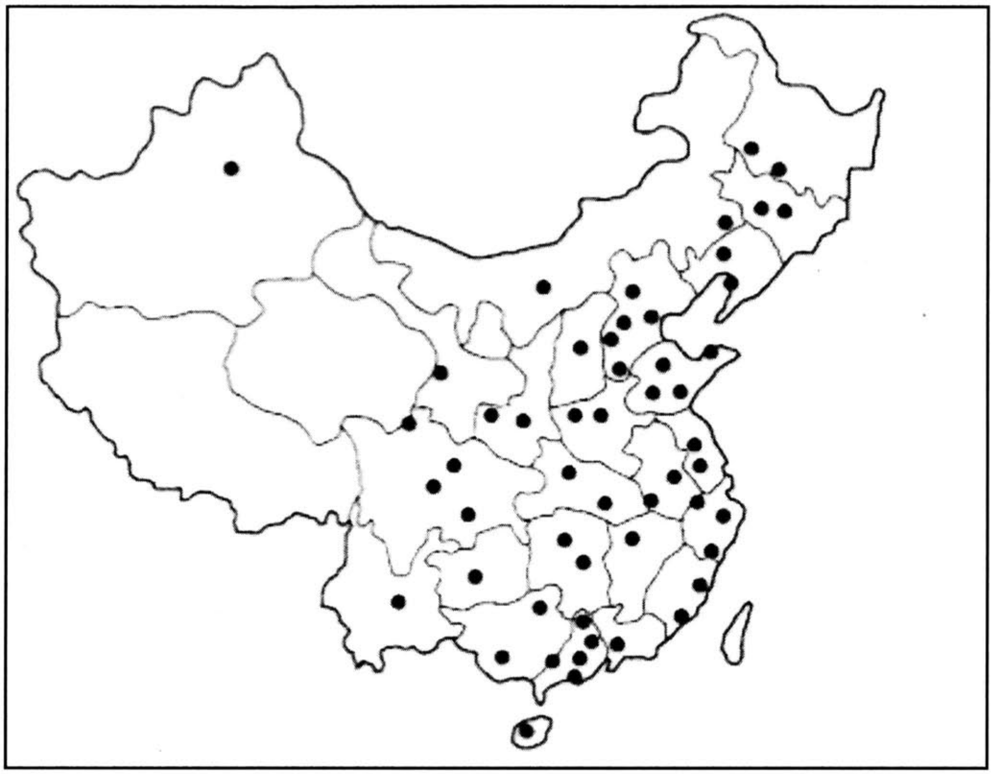
Source: Earth Policy Institute, 2013. "Climate, Energy, and Transportation Data." See http://www.earth-policy.org/?/data_center/C23/

Table 1: Shifting Priorities in the National Torch Program, 1988-2010

1988-1995 R&D investment, technology imports	**1996-2005** First increase, then reduction of FDI dependence	**2006-2010** Promotion of indigenous innovation
• Invest in R&D infrastructure • Promote university spin-offs • Promote transformation of R&D into marketable products • Promote establishment of high-technology zones in new localities • Attract research institutes to HTZs • Attract **foreign investment to HTZs** to increase competitiveness of local tech firms	•Establish production bases for high-tech industries in HTZs • Encourage new technology-based industrial sectors • Since 2001, encourage HTZs to return to original mission, **reduce FDI dependence** and promote innovation in domestic firms	• Promote "**indigenous innovation"** • Reduce reliance on technology imports • Preferred government procurement for domestically developed technologies • Encourage SME-based technology clusters • Encourage Chinese scientists and entrepreneurs to return to China from foreign universities and enterprises

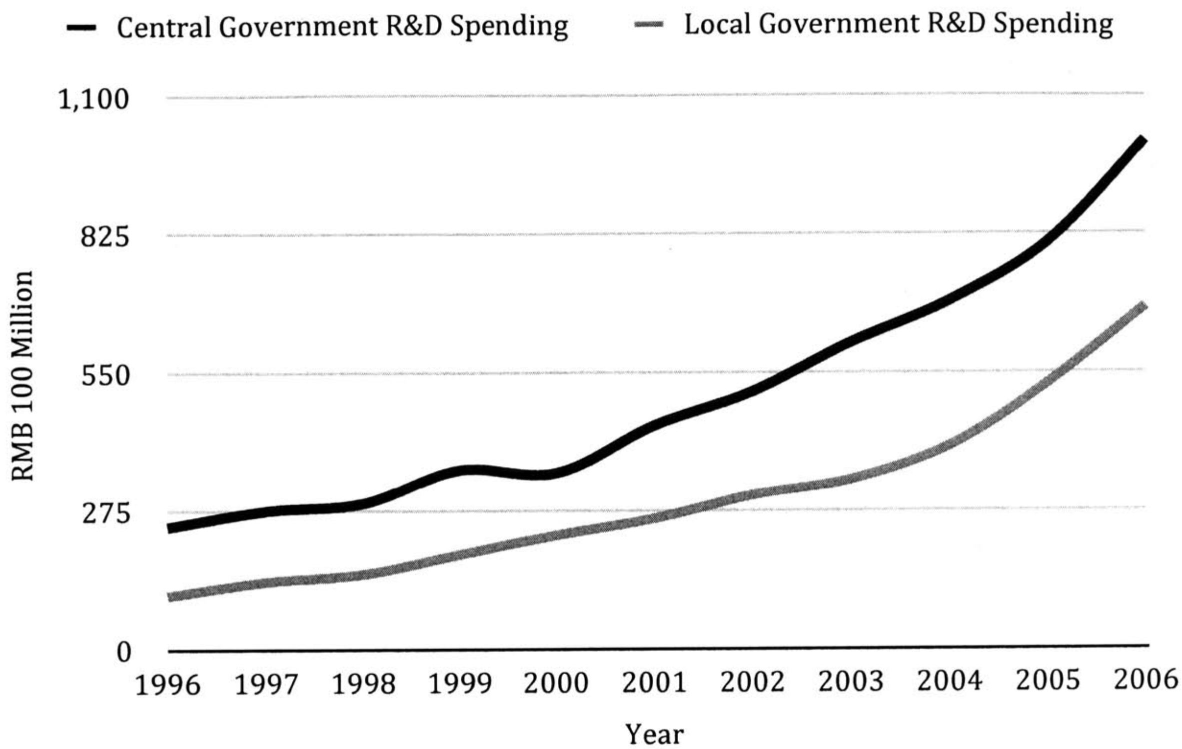
Source: Compiled from Heilmann, Sebastian, Lea Shih, and Andreas Hofem. 2013. National Planning and Local Technology Zones: Experimental Governance in China's Torch Programme. In The China Quarterly 216: 904.

Figure 2: Location of China's High-Technology Zones Established under the Torch Program



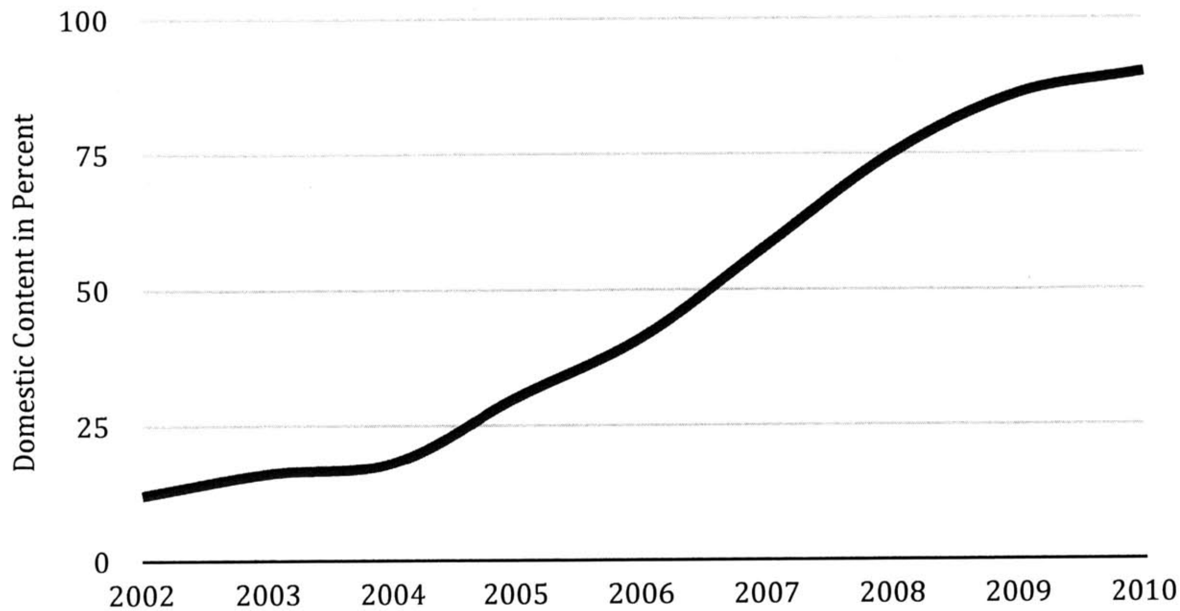
Source: Ministry of Science and Technology data, cited in Sutherland, Dylan. 2005. China's Science Parks: Production Bases or a Tool for Institutional Reform? In Asia Pacific Business Review 11 (1): 89.

Figure 3: Central and Local Government S&T Expenditures, 1996-2006 (in RMB 100 Million)



Source: Ministry of Science and Technology. 2007. China Science & Technology Statistics Data Book [中国科技统计数据]. Beijing: Department of Development Planning, Ministry of Science and Technology.

Figure 4: Local Content of Chinese Wind Turbines, 2002-2010, in Percent



Sources: Wang, Zhengming. 2010. *The Evolution and Development of China's Wind Power Industry* [中国风电产业的演化与发展]. Zhenjiang: Jiangsu University Press. Chinese Wind Energy Association (CWEA). *Statistics of China's wind power installed capacity*. Beijing: CWEA, 2005-2010.

Chapter 5: Innovation Without Production in U.S. Wind and Solar Sectors

1. Introduction

To a far greater degree than in Germany or China, renewable energy industries in the United States are populated by small and medium-sized high-technology firms that have spun-off universities and research institutes. In 2009, out of 100 solar photovoltaic firms in the United States, 73 were startups, many of which were seeking to commercialize thin-film technologies that break with the conventional use of silicon as the basic raw material for solar cell production.[592] In the wind industry, too, U.S. startup firms have developed wind turbines that have abandoned traditional designs, including gearless drivetrain concepts and small-scale turbines based on jet engine technologies.[593] Small in size and with advanced technological capabilities, these firms have built strengths in early-stage research and development, but have rarely established capabilities in scale-up and mass manufacturing. U.S. multinational companies (MNCs), which have also entered American renewable energy industries, have maintained a similar focus on the invention of new technologies in their U.S. operations, while offshoring or outsourcing much of their scale-up and production to locations abroad. As a consequence, U.S. industrial capabilities in renewable energy industries have almost exclusively focused on early stage-R&D, without establishing the full range of capabilities necessary to bring new products from lab to market. Few scale-up and commercialization activities for wind and solar technologies take place in the United States today.

---

[592] Knight 2011, 176.
[593] See Kevin Bullis, 2008. "A Design for Cheaper Wind Power." *MIT Technology Review,* December 1.

By 2008, the United States accounted for more than 61,000 renewable energy patents filed in U.S., European, and Japanese patent offices, roughly double the number of patents filed by German entities.[594] And yet, despite an overwhelming strength in R&D, local content rates for U.S. wind turbines hovered around 40 percent, as high-value components —gearboxes, metal castings and even turbine blades—were imported from abroad due to a shortage of local suppliers.[595] A 2011 study by the American Wind Energy Association (AWEA) estimated that European wind turbine manufacturers create three to four times as many jobs per megawatt of installed wind turbine capacity than their U.S. counterparts, as local supply chains obviate the need for imported components.[596] In the solar sector, where U.S. firms and research institutes have developed the foundations for virtually all of the main solar technologies in production today, U.S. firms accounted for a less than five percent of global manufacturing in 2010. New technologies were brought to market in other parts of the world and key components for domestic solar PV manufacturing—including wafers, thin film feedstock, and inverters—were imported from abroad.[597]

The singular focus on early-stage R&D in U.S. wind and solar industries is striking, particularly when compared to the diverse capabilities that have emerged in Germany and China. German and Chinese renewable energy supply chains have attracted firms with a wide range of skills, including firms specialized on component and equipment manufacturing, scale-up, and mass production. German and Chinese firms have also

[594] Bierenbaum et al. 2012, 6-7.
[595] Bolinger 2013, 18-19.
[596] AWEA Manufacturing Working Group 2011; David 2009.
[597] Data compiled by Earth Policy Institute, 2012. The U.S. maintained a positive trade balance in the production of manufacturing equipment and silicon feedstock. See GTM Research 2011.

conducted R&D and commercialized new technologies, but such activities have occurred in the context of a rich manufacturing capabilities in local supply chains. Apart from German engineering design houses, which have provided contract designs and technical consulting for Chinese wind turbine manufacturers, the majority of firms in China and Germany have retained at least some production capabilities in-house. As I have documented in chapters 3 and 4, for many German and Chinese renewable energy firms, local access to a range of industrial capabilities was necessary to commercialize new technologies, even if local capabilities were complemented through collaborations in global supply chains. The strong focus on early-stage R&D in the United States thus breaks with the patterns of German and Chinese renewable energy industries, where R&D and complementary production capabilities have been established together.

Observers have offered a range of explanations for U.S. strength in R&D and the lack of industrial capabilities in scale-up and mass production. Some have argued that theories of comparative advantage predict American strength innovation, not manufacturing. Proponents of this view have frequently cited examples like Apple, a company that has used strength in upstream R&D to generate economic benefits in the United States, even if production activities are mostly located in Asia.[598] Policy-makers and industry representatives, meanwhile, have claimed that the cost of labor in the United States has prevented competitiveness in manufacturing. This argument has often been made in conjunction with calls for trade barriers, following accusations that China and other Asian economies have lowered their production cost through subsidies and lax environmental regulations.[599] Yet for all the competition from China and other economies with low factor

[598] See, for instance, Kraemer et al. 2011; Sturgeon 2002b.
[599] U.S. International Trade Commission 2011.

prices, which have led to a series of high-profile bankruptcies of German solar PV manufacturers, Germany has retained a diverse supply chain of highly specialized small- and medium sized wind and solar suppliers. It has done so despite its high-wage environment, in which hourly compensation for manufacturing workers in 2012 was nearly 50 percent above manufacturing wages in the United States.[600] At the very least, the case of Germany suggests that high-wage economies can retain in domestic production activities. Why, then, have U.S. wind and solar supply industries built strengths in early stage R&D without the full range of complementary capabilities in scale-up and mass production?

In this chapter, I show that strong federal policies for R&D created conditions under which universities and research institutes were able to spin off large numbers of high-technology startup firms. Federal R&D support for wind and solar technologies consistently exceeded that of other advanced economies, and, beginning in the 1970s, a growing number of national laboratories created a public infrastructure for advanced energy research. A series of policy changes have since encouraged the formation of startup firms based on renewable energy research conducted in universities and research institutes, as the Bayh-Dole act of 1980 and subsequent legislations permitted licensing of federally-funded research. At the same time, however, declining domestic manufacturing sectors and a weak supplier base in adjacent industries drastically reduced the number of firms with capabilities in scale-up and mass production that could enter wind and solar supply chains. Losses were particularly strong in sectors such as aerospace, semiconductors, and machine tools—precisely the type of industries from which suppliers

---

[600] Levinson 2014, 14.

entered wind and solar sectors in Germany.[601] These structural problems in the U.S. supplier base were exacerbated by continued uncertainty over government support for domestic wind and solar markets, as tax credits and other subsidies were perpetually on the brink of elimination. As a consequence, small- and medium-sized suppliers with capabilities applicable to wind and solar sectors were deterred from industry entry. The weakness of the existing supplier base in adjacent industrial sectors also prevented the entry of export-oriented firms, which have thrived in German and Chinese renewable energy sectors without relying on local markets.[602]

The explanation offered in this chapter suggests that U.S. strength in early-stage R&D without the development of industrial capabilities required for commercialization and mass production is not the result of market forces or high U.S. wages. Rather, I propose that federal government R&D policies have not been matched by equally favorable conditions for bottom-up industrial change—the type of repurposing of existing skills and resources for application in new industrial sectors that I have identified in German and Chinese renewable energy industries. Ultimately, the absence of local firms with a diverse range of industrial capabilities in scale-up and commercialization forced U.S. innovators to look for partners with complementary skills outside of the United States.

The remainder of this chapter is organized as follows. Section two discusses the role of federal government policy in supporting wind and solar R&D activities in universities and its effect on creating high-technology startup firms with capabilities in early-stage R&D. The third section shows that structural problems in adjacent industries created a

---

601 Pisano and Shih have argued that the loss of U.S. semiconductor capabilities has eroded industrial capabilities required for the solar PV industry. Pisano and Shih 2012, 8-13.
602 The effects of policy uncertainty and volatile wind and solar markets have been documented by Barradale 2010; Bird et al. 2005; Fabrizio 2012; Platzer 2012a; Platzer 2012b; Wiser et al. 2007a.

weak supplier base and reduced the number of firms with skills in scale-up and mass production that could potentially enter wind and solar sectors. It discusses how these structural problems were compounded by policy uncertainty over public support for domestic markets, which prevented all but large multinational manufacturers from investing in U.S. production facilities. The fourth section outlines how the absence of a diverse range of firms in local supply chains forced innovators to look outside the U.S. for capabilities in commercialization and scale-up. Large firms, with strong financial backing and global ties, were able to find such complementary capabilities more easily than startups, which had fewer institutional resources to do so systematically.

2. Federal R&D Support : Universities, National Laboratories, and Startup Firms

In this section, I discuss how U.S. federal policies maintained their focus on new-to-the-world invention, even as wind and solar technologies matured and became ready for commercialization. At the federal level, the U.S. policy framework for renewable energy was guided by the notion that government involvement was required to fix market failures in R&D, but that market forces were sufficient to translate scientific discoveries into industrial outcomes. In the words of Kristina Johnson, former Under Secretary in the Department of Energy, government policies for the energy sector sought to foster technology breakthroughs "that will bring orders of magnitude improvement and accelerate commercialization of technologies" by funding high-risk renewable energy R&D.[603] Federal R&D programs were complemented by a range of policies that permitted universities and research institutes to license the results of federally-funded research—effectively enabling the creation of high-technology spinoffs—but little support was extended to commercialization and manufacturing.

Early Policies for Renewable Energy R&D

Measured purely in terms of public financial support, the United States have spent more than any other advanced industrialized economy on the development of global wind and solar industries.[604] Many of the technological advances underlying silicon-based solar cells and thin film PV applications have emerged from federally-funded R&D institutes and enterprise laboratories, making possible the spread of solar technologies from their initial application in the space industry to the grid-connected solar photovoltaic models that are

[603] Johnson 2011, 145.
[604] International Energy Agency 2008, 31.

widely available today. Even in the wind industry, where European researchers made many of the critical contributions that enabled the gradual increase of turbine capacity, research consortia led by U.S. corporations made efforts to leapfrog to the design of large-scale wind turbines in the wake of the 1970s oil shocks. These costly investments were almost entirely funded through federal government programs.[605]

The U.S. government response to the volatility in global energy markets during the 1970s was a swift and massive expansion of domestic research efforts in alternative energy technologies. Supported by bipartisan agreement on the need to diversify the U.S. energy supply, federal investment in renewable energy R&D peaked in 1980—two years after the second global oil shock—at USD 1.3 Billion.[606] The unprecedented level of R&D funding for renewable energy technologies encouraged research on wind and solar technologies in universities, but it also supported a growing governmental research infrastructure for energy technology in the form of national research laboratories. In 1974, immediately following the first oil crisis, the federal government established a Solar Research Institute (SERI) within the Energy Research and the Development Administration (ERDA), the predecessor to the Department of Energy (DOE).[607] In addition to supporting research on solar photovoltaic technologies, the Solar Research Institute, together with NASA's Lewis Research Center, also coordinated a wind power research program, which allocated USD 380 Million for the development of large-scale wind turbines between 1973 and 1988.[608] As part of the program, conglomerates from aerospace, energy, and defense industries

[605] On the contributions of European research, see Heymann 1998. The role of U.S. conglomerates is discussed in Righter 1996, 149-69.
[606] Martinot et al. 2005, 3.
[607] Loferski 1993, 74; Strum and Strum 1983, 134-47.
[608] Righter 1996, 158.

were paid to design turbine technologies that could reach generation capacities of up to 7MW, larger than the turbine technologies that are in commercial use today. General Electric, Boeing, Westinghouse, Lockheed, and McDonnell Douglas were among the firms that participated.[609]

The political climate in Washington became less favorable for renewable energy industries when President Carter lost the 1980 election to Ronald Reagan. The transition to a Republication administration averse to large government programs coincided with the stabilization of global energy markets and rapidly falling oil prices, causing a sharp decline in federal funding for energy R&D. While private sector spending on energy R&D remained relatively stable throughout the 1970s, public funding for energy research increased by a factor of three, only to be cut by half during the early years of the Reagan administration.[610] The unraveling of a bipartisan consensus on the need to shift the U.S. energy supply away from imported fossil fuels led to increased political conflict over research priorities, which in turn caused volatility in federal R&D funding from the 1980s onwards.[611] As shown in Figure 1, however, in most years federal funding for research continued at levels far above those of other countries, even as renewable energy budgets decreased during the Reagan presidency. A number of federal programs consistently supported research on components, subsystems, and technical development of wind and solar technologies.[612] In the solar sector, for instance, such programs funded experimentation with cell technologies based on Cadmium Telluride, Copper Indium Gallium Selenide, and organic semiconductors, supporting the development of thin film cell technologies that were later commercialized

[609] Gipe 1995, 77; Righter 1996, 158.
[610] Nemet and Kammen 2007, 747.
[611] Laird and Stefes 2009, 2626.
[612] Harborne and Hendry 2009, 3582.

by American firms.[613] More importantly, the national institutional infrastructure for energy research that had been created during the oil crises was left in place: SERI, the Solar Energy Research Institute, continued to advance renewable energy research throughout the 1980s in spite of budget cuts. In 1991, its broad mandate beyond solar PV earned it the designation as the National Renewable Energy Laboratory (NREL), one of seven such laboratories set up by the Department of Energy.[614] NREL subsequently established a National Wind Technology Center in Boulder, Colorado, in 1993.[615] The national laboratories provided demonstration sites, test centers, and accreditation for manufacturers, who came to rely on the highly specialized staff for technical expertise.[616]

The continuation of federal R&D funding and the maintenance and expansion of the energy national laboratories allowed the United States to maintain a global lead in renewable energy research. Technological advances that originated in the federal R&D programs of the late 1970s, for instance, decreased the cost of solar photovoltaic technologies from USD 300 per watt in 1980 to USD 4 per watt in 1992.[617] The price for wind turbine installations dropped from USD 4,040 per kW in the early 1980s to an average of USD 1,340 per kW in the early 2000s, at least partially as a result of technology improvements.[618] Between 1974 and 2008, the U.S. federal government spent USD 3.3 billion on solar PV research alone, significantly more than resource-strapped Japan (USD 2.1 billion) and Germany (USD 1.9 billion), the largest solar PV market in the world. U.S. patenting activity for alternative energy technologies also outpaced that of other advanced

---

[613] Knight 2011, 176.
[614] NREL 2002, 2.
[615] See http://www.nrel.gov/wind/nwtc.html [Accessed March 25, 2014.]
[616] Harborne and Hendry 2009, 3582.
[617] Loferski 1993, 74.
[618] Wiser and Bolinger 2008, 21; Wiser et al. 2007a, 81.

economies, roughly tracing the nation's above-average spending on R&D.[619] By 2008, the United States accounted for more than 61,000 renewable energy patents filed in U.S., European, and Japanese patent offices, a third more patents than were filed by Japanese inventors and roughly double the patents filed by German entities. Thirty-four percent of U.S. renewable energy patents were for wind turbine technologies and 26 percent of patents were for the solar PV industry.[620] Many of these patents—including those for next-generation thin film technologies—originated in research that was initially funded by the large U.S. investment in renewable energy research immediately following the 1970s oil crises, suggesting a strong link between research funding and innovation output over time.[621]

Federal R&D and High-Technology Startup Firms

Private-sector firms in the United States were able to benefit from a research and development infrastructure that encouraged universities to make new technologies—often funded through federal research grants—available to the public through licensing. As part of a series of legislative changes that eased the flow of technologies from universities to the private sector, the Bayh-Dole Act of 1980 permitted universities and research institutes to patent discoveries that resulted from federally funded research and to offer exclusive

[619] Measures for patent counts differ widely in methodology and national rankings subsequently display a large degree of variation. Patent counts are also an imperfect measure of technological innovation, since the importance and contribution of a patent is not weighted. However, by almost all of these measures, the United States has been ahead of other economies in patents counts and patent citations since the 1970s oil crises. See Bettencourt et al. 2013; Bierenbaum et al. 2012; Johnstone et al. 2010, 141.
[620] Bierenbaum et al. 2012, 6-7.
[621] Bettencourt et al. 2013, 5.

licenses to third parties.[622] These broader changes in intellectual property legislation spurred increased university patenting and licensing over the course of the 1980s. In 1965, less than 200 patents were granted to American universities; by 1988, more than 1000 patents were granted to universities annually, as universities were permitted to commercially exploit the results of their research through patents and licensing. By 1993, many U.S. universities and research institutes had established designated technology transfer and licensing offices and jointly held more than 4000 active license agreements with firms, jointly generating USD 375 million in royalties.[623]

The infrastructure for technology transfer allowed wind and solar industries to access technologies developed as a result of vast public investments in renewable energy research. Even before state-level legislation created the first domestic markets for wind turbines or solar panels, a number of firms spun off from universities and government research institutes to commercialize recent discoveries. In contrast to the aerospace and defense conglomerates that had begun working on large-scale wind turbines through a series of federal programs beginning in the 1970s, these firms were small and specialized, growing directly out of publicly funded research. In 1974, for instance, entrepreneurs Stanley Charren and Russell Wolfe founded U.S. Windpower Inc. as a spinoff from MIT's Lincoln Lab. The MIT laboratory provided the core technology and the company's chief engineer. U.S. Windpower, later named Kenetech, began building a demonstration wind farm on Crotched Mountain in New Hampshire, long before the first large wind markets

---

[622] Patents could be licensed, but private sector firms could not purchase the patents. Mowery et al. 2001, 102. The Bayh-Dole act was just one of many legislative changes that encouraged university patenting. For a discussion of the extensive legislative changes that transformed university-private sector knowledge transfer during the early 1980s, see Mowery et al. 2004.
[623] Henderson et al. 1998, 120-21.

were created in the U.S.[624] Six years later, ESI, another turbine manufacturer, was established by two government engineers working at a wind turbine testing site set up as part of the national wind energy program in Rocky Flats, Colorado. The engineers left government to set up their own company and took the technology with them.[625] FloWind, founded in 1982, obtained a license to a technology for vertical wind turbines from Sandia National Laboratories in Albuquerque.[626] Windtech, another small startup firm, commercialized a technology developed by Berkeley's United Technology Research Center as part of the small wind turbine program set up by the Department of Energy.[627]

In the solar sector, a number of small solar firms produce solar PV cells for niche applications and benefitted from state funding for utility-scale demonstration projects.[628] Former employees of Spectrolab, a firm that since the 1950s had supplied solar modules for space applications, founded Solec International in 1976. It was located in proximity to Caltech and NASA's Jet Propulsion Lab in Pasadena and collaborated with both institutions on the improvement of terrestrial solar technologies throughout the 1980s.[629] Solar Technology International, which had also been founded by former Spectrolab employees, also participated in joint research with Caltech and the Jet Propulsion Lab to improve its solar PV technologies.[630]

---

[624] Jeff Ackerman, 1981. "Putting the Wind to Work; Breeze Power Is Serious Business For Founds of Farm in N.H." In *The Boston Globe*, May 03. See also: MIT Lincoln Lab, "Spin-Off Companies." http://www.ll.mit.edu/about/TechTransfer/spinoffs.html (Accessed March 27, 2014).
[625] Gipe 1995, 71.
[626] Righter 1996, 182.
[627] Gipe 1995, 181-82.
[628] West 2013, 7.
[629] Colatat et al. 2009b, 5.
[630] Solar Technology International was purchased by the oil firm ARCO in the late 1970s and changed its name to ARCO Solar. Colatat et al. 2009b, 5; West 2013, 6.

With the exception of a brief period in the early 1980s, during which a combination of federal and state-level subsidies created short-lived demand for wind power installations in California, renewable energy startups were unable find large markets for their technologies. Even though California's wind energy boom was not replaced by new domestic markets for renewable energy technologies until the early 2000s, new wind and solar firms continued to be founded based on technologies originating in federally-funded research. While the first generation of terrestrial solar PV firms was specialized on traditional silicone photovoltaic modules that were derivative of earlier products for space applications, a second generation of solar firms began commercializing new types of solar technologies in the early 1990s. First Solar (then named Solar Cells Inc.) was founded in 1990 in Toledo as the first commercial manufacturer of thin film solar cells, a technology that reduced the use of silicon by depositing a thin layer of photovoltaic material on alternate substrates. Its first facilities were located on the campus of the University of Toledo, where collaboration between First Solar and university laboratories was funded by federal and state-level research grants.[631] SunPower was founded in 1991 by a Stanford University engineering professor, Richard Swanson, to commercialize a new approach to creating high-efficiency solar cells that used all-back contacts to increase energy output. The research for the core technology at Stanford had been funded by the Department of Energy and the National Renewable Energy Laboratory. SunPower's first facility was financed with grants from Department of Energy, the Electric Power Research Institute, and venture capital financing.[632] In 1994, MIT professor Emanuel Sachs established Evergreen Solar to commercialize a new manufacturing technology for solar wafers.

[631] American Energy & Manufacturing Partnership 2013, 12.
[632] Swanson 2011, 537-38.

Evergreen employed a so-called string-ribbon technology to manufacture thin solar wafers without cutting them from large silicon blocks, thereby preventing material loss from wire-sawing prevalent in traditional wafer manufacturing.[633]

Over the course of the 1990s, the absence of subsidies for the large-scale deployment of renewable energy technologies in the United States made it difficult for startup firms to generate revenue from their products. Financial institutions, in particular venture capital funds, were reluctant to fund long-term research and development activities without a clear prospect of market demand—without government subsidies, even advanced wind and solar technologies would not be cost-competitive with fossil fuels for decades.[634] To stay afloat, some attempted to use their technologies for niche applications. SunPower, for instance, provided high-efficiency solar cells for solar-powered cars competing in the World Solar Challenge car race in 1993. It subsequently collaborated with NASA to develop a solar-powered airplane.[635] Others, such as the wind turbine manufacturer Zond, worked with utilities on building small demonstration facilities.[636] The majority of startup firms continued to rely on government research grants for funding and few were able to invest in capital-intensive production facilities. Between 1991 and 2008, DOE invested USD 289 million in R&D for new solar technologies as part of the so-called PVMaT program. Throughout the 1990s, a wide range of solar firms participated, including Evergreen and Solarex.[637] A separate program for thin film cell technologies was heavily

---

[633] For an explanation of Evergreen's string-ribbon technology differs from conventional solar cell manufacturing practices, see Wallace et al. 1997.

[634] Moore and Wüstenhagen 2004, 243.

[635] Swanson 2011, 539-45.

[636] Department of Energy, 2003. "Wind Power Pioneer Interview: Jim Dehlsen, Clipper Windpower." http://www.windpoweringamerica.gov/filter_detail.asp?itemid=683 (Accessed March 27, 2014).

[637] O'Connor et al. 2010, 3-11.

utilized by First Solar. In the wind sector, too, federal funds remained critical.[638] Zond, one of two wind turbine manufacturers that had survived the end of California's wind power subsidies in the mid-1980s, received Department of Energy funding for research on large wind turbines in 1995.[639]

In the early 2000s, both California and Texas passed renewable portfolio standards that required utilities to meet ambitious renewable energy targets, leading to large local markets for wind turbine installations.[640] Fueled by regional investments in renewable energy in addition to federal production tax credits, the United States soared to become the largest market for wind turbines in 2005.[641] A federal solar investment tax credit of 30 percent was passed as part of the 2005 Energy Policy Act and renewed in 2006 and 2008; together with state-level policies such as the 2007 California Solar Initiative, it led to a surge in U.S. domestic demand for solar PV after decades of stagnation.[642] By then, the introduction of generous subsidies for solar PV installations had created the world's first large solar market in Germany. Other nations, most notably Spain and Italy, bolstered domestic solar demand in the following years.[643]

Few financial institutions had been willing to invest in wind and solar startups in previous decades, yet the prospect of global renewable energy markets for the first time motivated venture capital funds to support renewable energy startups, particularly in the solar sector. The percentage of government R&D funding as a share of overall investment in

---

[638] O'Connor et al. 2010, 3-14.
[639] Department of Energy, 2003. "Wind Power Pioneer Interview: Jim Dehlsen, Clipper Windpower." http://www.windpoweringamerica.gov/filter_detail.asp?itemid=683 (Accessed March 27, 2014).
[640] Bird et al. 2005, 1401-02.
[641] Wiser et al. 2008, 4.
[642] Colatat et al. 2009b, 7; Solar Energy Industries Association 2014.
[643] Campoccia et al. 2009, 290-91.

solar energy technologies dropped from 90 percent in 2001 to less than 10 percent in 2007 as private investment increased exponentially.[644] Global venture capital investment in clean energy technologies multiplied from USD 200 million in 2000 to USD 2.5 billion by 2007; U.S.-based venture capital funds investing in U.S. startups accounted for 82 percent of overall VC investment in renewable energy.[645] In 2011, U.S. venture capital firms invested USD 11 billion in American clean technology businesses, compared to USD 9 billion globally.[646] Figure 2 summarizes VC investment in renewable energy firms over time.

The combination of global markets and venture capital prompted a new wave of industry entry, particularly in the solar sector, where cumulative federal R&D funding had continually surpassed investments in wind turbine research and new technologies were ready for commercialization.[647] New entrants were clustered in proximity to major research institutions and venture capital firms, with California and Massachusetts emerging as two main centers of startup activity. In the solar sector, many of the new firms focussed on the commercialization of thin film solar cells. Although thin film cells promised to replace costly silicon as the basic raw material in solar cell production, complex manufacturing processes had kept thin film technologies prohibitively expensive. Firms such as Nanosolar and Nanosys, both founded in California in 2001, were testing alternate deposition technologies that could potentially reduce the cost of thin film manufacturing. Heliovolt, established in Austin, Texas, in 2001, and Day Star, founded in Halfmoon, New York, in 2006, were attempting to solve the same problem. In Massachusetts, Konarka was

[644] Jennings et al. 2008, 8.
[645] Jennings et al. 2008, 9.
[646] Mazzucato 2013, 127.
[647] Jennings et al. 2008, 8.

founded in 2001 as a spin-off from the University of Massachusetts, Lowell, to fabricate solar cells from flexible plastics.[648] Scientists from the National Renewable Energy Lab in 2005 founded Solyndra, a company that used a deposition technology developed by NREL to build cylindrical, higher efficiency cells.[649] In 2007, Emanuel Sachs, the MIT professor who had started Evergreen Solar in the 1990s, spun off a new company, 1366 Technologies, to introduce new production processes for solar wafers.[650] By 2009, at least 46 solar PV startups were operating in California alone.[651]

In the wind sector, too, the industry saw a number of startups as a result of growing domestic markets. In 2001, former employees of the legacy wind turbine manufacturer Zond founded a new turbine manufacturer, Clipper Windpower, in California. Clipper proposed replacing a singe turbine generator with several smaller generators to increase efficiency and reliability.[652] In Florida, AML Energy, a manufacturer of superconducting magnets, diversified into the wind energy business in 2002 and began the development of gearless wind turbines.[653] FloDesign, a spin-off from the aerospace sector, in 2008 began the development of new wind turbine technology by borrowing principles from jet engines to increase turbine efficiency.[654] In 2009, NREL employees founded Boulder Wind Power to commercialize an alternative gearless wind turbine technology.[655]

---

648 Morton 2006, 21.
649 David R. Baker and Carolyn Said, 2011. "Solyndra: Energy superstar's rapid rise and fall." *San Francisco Chronicle,* September 18.
650 Kevin Bullis, 2010. "Making More Solar Cells from Silicon." *Technology Review,* March 4.
651 Colatat et al. 2009b, 6.
652 Goudarzi and Zhu 2013, 199.
653 Angela Lazazzera, 2009. "New Innovations in 19th Century Technology." *Spacecoast Business Magazine,* May.
654 Jon Gertner, 2013. "FloDesign's Jet-Engine turbine Will Change the Way You Think about Wind Power." *Fast Company Magazine,* September.
655 See www.boulderwindpower.com. (Accessed March 29, 2014).

In addition to venture capital investment and growing domestic markets, wind and solar startups continued to benefit from R&D programs and other federal subsidies. ARPA-E, a federal program to support the commercialization of high-risk energy technologies, provided USD 130 million to 66 startup firms and university labs in its first round of funding, including the MIT spin-off 1366 Technologies (USD 4 million) and the wind turbine manufacturers FloDesign (USD 8.3 million).[656] Clipper, AML, and Boulder Wind Power received grants and technical assistance from NREL and the Department of Energy.[657] NREL supported development of a turbine for low wind speeds by Clipper between 2002 and 2006, covering half of the USD 19 million in R&D expenses to develop a prototype.[658] DOE's Thin-Film Partnership program, first established in the 1990s, funded pilot production of thin film modules through 2008; First Solar was one of the grant recipients.[659] Finally, the American Recovery and Reinvestment Act provided USD 1.282 billion in loan guarantees to four solar startups—Solyndra, 1366 Technologies, Abound Solar, and SoloPower—to help fund investments in production facilities.[660]

Although venture capital funds played a critical role in allowing startup firms to test and improve their early-stage products once they had left universities and research institutes, the basic technologies of most startup firms sprung from federally-funded research. Federal government R&D support not only funded the development of new

---

[656] ARPA-E, 2009. "ARPA-E Project Selections." http://www.energy.gov/sites/prod/files/edg/news/documents/ARPA-E_Project_Selections.pdf (Accessed March 29, 2014). Matthew L. Wald, 2011. "Energy Firms Aided by U.S. Find Backers." *New York Times,* February 2.

[657] NREl, 2012. "DOE Funds Advanced Magnet Lab and NREL to Develop Next-Generation Drivetrains." http://apps1.eere.energy.gov/wind/newsletter/detail.cfm/articleId=105 (Accessed April 10, 2014). Tyler Hamilton, 2011. "Building Bigger, Better Wind Turbines." *MIT Technology Review,* July 6.

[658] U.S. Department of Energy, 2006. "Wind Energy Program Portfolio." http://www.nrel.gov/docs/fy06osti/37937.pdf (Accessed April 10, 2014.)

[659] O'Connor et al. 2010, 3-17.

[660] Brown 2011, 4.

renewable energy technologies, but federal research grants also provided an important source of revenue for startups that were yet unable to find markets for their technologies. For further testing and improvements to their technologies, firms relied on resources and technical expertise provided through national laboratories. Investments in the most risky technologies—very early research in fields with no clear market application—were thus made by the state. Venture Capital funds were neither willing to invest in high-risk early stage R&D, nor in the capital-intensive manufacturing facilities required for scale-up and mass production, instead funding technologies that had achieved sufficient maturity to leave the university and had an established path toward commercialization.[661] Ultimately, the large number of startups that entered U.S. wind and solar sectors were a product of federal government policies—policies that funded scientific discovery, encouraged technology transfer into the private sector, and provided technological expertise and research funding for nascent wind and solar firms.

[661] Mazzucato 2013, 127-29.

3. Manufacturing Decline, Volatile Market Support, and Local Supply Chains

The large number of startups with strength in early stage R&D that populated U.S. wind and solar industries were not accompanied by equally strong capabilities in scale-up and mass manufacturing. In contrast to Germany and China, where large numbers of domestic suppliers entered renewable energy industries in response to growing global markets, U.S. wind and solar sectors were sparsely populated by small and medium-sized domestic suppliers with diverse industrial capabilities. U.S.-based MNCs, such as the multinational equipment manufacturer Applied Materials, the silicon producer Hemlock, and the global bearings manufacturer Timken, faced little competition from domestic entrants from other industries. Out of 10 blade manufacturing facilities located in the United States in 2009, only three were operated by independent U.S. suppliers, with the majority of blade plants run by European wind turbine manufacturers.[662] Although more than 10,000 metal casting firms existed in the United States in 2010, not a single firm had retooled its manufacturing facilities to supply metal castings for wind turbines, requiring turbine manufacturers to source castings for turbine hubs in Europe and Asia.[663] Only two American firms were manufacturing wind turbine generators.[664] Likewise, in the solar sector, the majority of suppliers were multinational corporations which had diversified into renewable energy industries. In addition to Applied Materials, which had entered the solar sector through a series of acquisitions beginning in 2006, one firm, GT Solar, offered domestically manufactured turnkey production equipment.[665] Suppliers were more

[662] Rogowsky and Laney-Cummings 2009, 11.
[663] Spada 2010. See also Brian Rogal, 2012. "Foundries twisting in breeze over wind tax credit." *Midwest Energy News*, March 27.
[664] Baker 2010; Rogowsky and Laney-Cummings 2009, 9-10.
[665] Platzer 2012a, 7.

abundant in glass manufacturing, wire production, laser technology, and other areas in which products required little or no customization for the solar PV sector. Local content rates for U.S.-manufactured wind turbines—even though they were gradually increasing over time—remained below 50 percent, far less than the rates of 80 or more achieved in Germany and China.[666] In the solar PV sector, the U.S. trade balance for component manufacturing was positive only because of silicon exports, which a small number U.S. producers supplied to China, and exports of manufacturing equipment, almost all of which was produced by the U.S. multinational Applied Materials.[667]

U.S. Manufacturing in Decline

The weakness of U.S. wind and solar supply chains in scale-up and R&D was rooted broader structural changes in the U.S. economy. Beginning in the 1970s, the decline of manufacturing sectors in the United States reduced the number of domestic firms that possessed technological capabilities with potential application in wind and solar industries. Between 1999 and 2010 alone, the number of manufacturing establishments in the United States declined by 14 percent.[668] The number of manufacturing plants that employed more than 1000 workers dropped by half between 1977 and 2007.[669] Losses were particularly strong in sectors such as aerospace, semiconductors, machine tools, and automotive components—precisely the type of industries from which suppliers had entered wind and solar sectors in Germany.[670] Between 1998 and 2010, nearly 1,200 plants closed in the

[666] AWEA Manufacturing Working Group 2011; David 2009; Nahm and Steinfeld 2014, 292.
[667] See GTM Research 2011.
[668] U.S. Census Data cited in Yudken 2010, 2.
[669] Holmes 2011, 6.
[670] Pisano and Shih 2012, 8-13; Whitford 2005; Whitford 2012.

semiconductor industry, a decline of 37 percent among facilities with more than 500 employees and loss of 41 percent of medium-sized plants with 100-500 staff.[671] In the machine tool sector, foreign penetration of the U.S. market rose from 30 percent in 1983 to 72 percent in 2008, with sub-sectors, such as metal forming, reaching import rates of 91 percent. Domestic shipments for metal forming machines dropped by more than 50 percent between 1990 and 2009. Over the same period, the U.S. aerospace industry lost 10 percent of mid-sized firms (100-499 employees) and 28 percent of large firms (500-999 employees).[672]

A multitude of factors contributed to these changes in the American manufacturing sector—not least China's accession to the World Trade Association in 2001, which rapidly increased import competition in subsequent year.[673] Over the course of the 1970s, financial markets in the United States had increasingly rewarded large firms for outsourcing non-core production activities and falling tariffs and trade barriers now permitted U.S. multinationals to look to low-cost economies to find suppliers.[674] Yet the declining number of suppliers in the U.S. economy was at least partially grounded in the difficulties of small and medium-sized firms to adapt to the reorganization of production in the global economy. Josh Whitford, in a study of metalworking manufacturers in the American midwest, finds that after decades during which suppliers essentially served as production buffers for larger firms, many were ill-equipped to meet new requirements in design and customization imposed by their customers in the 1990s. Although small and medium-sized

[671] Yudken 2010, 7.
[672] Pisano and Shih 2012, 11-12; Yudken 2010, 6-12.
[673] For a discussion of the impact of changing U.S.-China trade relations on American manufacturing sectors, see Autor et al. 2012; Berger 2013, 41-44; Pierce and Schott 2014.
[674] Davis 2009, 87-96, 195-200.

firms were in principle capable of making investments in new technological capabilities and design skills, they were wary of doing so in the face of economic uncertainty, an absence of guaranteed markets, and little public institutional support for technological upgrading in manufacturing.[675]

The accounting standards required to claim R&D tax credits, for instance, long favored technological innovation developed in traditional R&D departments over the type of incremental manufacturing innovation involved in retooling a production facility for application in new sectors. For all the R&D funding available for early stage R&D, little public funding existed for the upgrading of existing technological capabilities, particularly in small and medium-sized firms.[676] Few banks were willing to fund manufacturing investments in the absence of order guarantees, compelling suppliers willing to enter new sectors to rely on retained earnings for financing.[677] Many struggled to do so. In addition to funding problems, firms willing to invest in emerging renewable energy industries often struggled to find qualified staff trained to handle increasingly complex machinery. In a survey on skills and training in manufacturing establishments, Paul Osterman and Andrew Weaver find that smaller firms with high-skill demands reported significantly more difficulty in filling vacancies, suggesting that those firms willing to move into new emerging high-tech sectors were not served well by existing skills and training institutions and local community colleges.[678]

---

[675] Whitford 2005, 95-120; Whitford 2012, 259.

[676] Author interviews: CEO of metal-forming manufacturer, October 24, 2012; CEO of aerospace supplier, April 27, 2012.

[677] Berger 2013, 115-16; Cetorelli and Strahan 2006, 459.

[678] Osterman and Weaver 2013, 33-35.

In Germany, suppliers from legacy industries entered wind and solar sectors by applying core capabilities to new applications in renewable energy—in the production of components, materials, and manufacturing equipment required to bring new technologies to scale. In the United States, by contrast, the declining number of manufacturing establishments had left far fewer firms that could potentially do so, particularly in sectors such as machine tools, where firms with diverse industrial capabilities could more easily apply themselves to wind and solar sectors. Many of those who remained were struggling to survive in existing markets, where slim margins prevented large investments in new skills. The weak institutional support for repurposing and reinvention of existing industrial capabilities—including the absence of local banks, training institutions, and collaborative research funds that had enabled suppliers in Germany to enter renewable energy industries—further prevented firms from entering new economic sectors.

Support for U.S. Wind and Solar Markets: Policy Intermittency and Investment Uncertainty

The challenges of U.S. manufacturing industries and the weakness of the domestic supplier base in adjacent industrial sectors were compounded by an uncertain investment climate in wind and solar manufacturing. Although federal government policies consistently supported early-stage R&D for wind and solar technologies, reliable government support was not extended to the creation of domestic renewable energy markets, which continued to rely on government subsidies to compete with fossil fuels. State policies to create regional markets for wind and solar installations only worked in conjunction with subsidies at the federal level, where partisan conflict and entrenched political interests prevented long-term support.

In 1978, the federal government passed the Public Utilities Regulatory Policy Act (PURPA), which required utilities to purchase power from third party generators at the level of avoided cost, i.e. the rate it would have cost for the utility to generate the same amount of electricity in-house. Although the implementation of PURPA and the definition of 'avoided cost' differed from state to state, PURPA removed a major obstacle to the widespread deployment of renewable energy technologies by requiring utilities to buy electricity from alternative sources. PURPA in principle enabled the transition from centralized power generation within utilities to a decentralized energy system structured around multiple energy sources and providers. In practice, however, it was unable to make renewable energy cost competitive and the wide variation in state implementation meant that in some states it had no effect at all.[679] In California, the generous interpretation of the production tax credit led to lucrative long-term contracts for wind power generation, creating the first large-scale market for wind turbines as more than 15000 turbines were installed between 1980 and 1986. Yet here, too, the elimination of a host of additional tax incentives in 1986 left PURPA as the only remaining support mechanism, and new installations came to a halt.[680] Ultimately, PURPA was unable to permanently close the gap in prices between emerging renewable energy technologies and electricity generated from conventional sources on its own, and a number of small turbine manufacturers filed for bankruptcy as a result.[681]

In 1992, threats to U.S. energy supplies again put the spotlight on alternative energy sources as a matter of national security. Following the Iraqi invasion of Kuwait, the first

[679] Martinot et al. 2005, 3-4; Redlinger et al. 1988, 182-5.
[680] Harborne and Hendry 2009, 3583.
[681] Heymann 1998, 642.

Gulf War from 1990 to 1991 created the possibility of a new round of global oil shocks as energy prices rose sharply. The Bush administration raised research and development budgets—albeit not to the same extent as during previous oil shocks—and enacted tax credits to make alternative energy more cost competitive. The 1992 Energy Policy Act included a Production Tax Credit (PTC) for wind energy of 1.5 cents per kWh of installed wind power capacity. An investment-based tax credit was introduced for solar PV.[682]

The tax credits provided the first federal attempt to fund the price gap between renewable energy and conventional sources of electricity through a subsidy program. However, the political tug-of-war over renewables that had begun during the Reagan era continued into the 1990s and early 2000s, as political conservatives remained strongly opposed to federal handouts for renewable energy deployment.[683] Budgets for renewable energy research experienced volatility as a result of this political conflict—presidential budget requests for renewable energy R&D were generally approved when Democrats controlled the house and cut when Republicans held a majority in Congress—yet R&D funds were never completely eliminated and fluctuated at a high level, at least when compared to those of other nations. Tax credits for deployment, by contrast, were regularly on the brink of complete elimination. Between 1992 and 2006, the Production Tax Credit for wind energy was renewed in five separate instances, often only for one or two years. On three separate occasions, the PTC expired before it was renewed, leading to periods of up to nine months during which no federal support was available at all.[684] Where government funding for renewable energy R&D was palatable to at least some fraction of the

---

[682] Laird and Stefes 2009, 2625; Martinot et al. 2005, 3-4; Wiser et al. 2007a, 78.
[683] Laird and Stefes 2009, 2625.
[684] Wiser et al. 2007a, 79.

Republican party, the use of federal tax funds to support installation and deployment remained highly contested. In contrast to research funds, which could be used for shorter-term research projects and were generally not withdrawn once allocated to universities and research institutes, tax credits were intended to encourage long-term investment in capital-intensive wind and solar installations. The persistent threat of tax credit expiration thus made for a highly uncertain investment climate for renewable energy technologies, a problem that persists to this day.[685]

The volatile federal policies for commercialization and deployment of wind and solar technologies were at least partially complemented by a range of market-supporting measures at the state level. Although state governments were able to create large and growing markets for wind turbines and, eventually, solar modules in the United States, regional policies were only able to provide sufficient support for renewable energy installations in conjunction with federal subsidies, effectively extending policy intermittency and investment uncertainty to regional markets. A number of state governments required electricity retailers to source a percentage of electricity from renewable sources by enacting so-called Renewable Portfolio Standards (RPS). Although it did not take effect until 2002, the first of such standards was passed by the Massachusetts legislature in 1997. Connecticut, Wisconsin, and Maine followed in 1998 and 1999, and by 2012, the number of states with Renewable Portfolio Standards had grown to 30.[686] The prescribed shares of renewable energy included in Renewable Portfolio Standards differed widely. Some states included caps and designated tiers for certain technologies, while others permitted large hydropower plants to be counted towards meeting the renewable

---

685 Righter 2011, 80-81.
686 Shrimali et al. 2012, 33.

energy goals. Maine's RPS of 30 percent, for instance, was lower than its existing share of hydropower resources, precluding any effect on renewable energy markets. Other states, such as California, set ambitious goals of 20 percent or more, and required utilities to include different renewable energy technologies in their portfolio.[687]

The effects of Renewable Portfolio Standards were concentrated in a few states with exacting policies, and even here, markets were created mostly for wind turbines, as they were the most cost-effective technology to meet government goals. Out of 4,300 MW of wind power installed in the United States by 2003, 2,335 MW had been put in place to meet Renewable Portfolio Standards. Wind turbine installations accounted for 2,183 MW, with the majority of wind turbines located in Texas (1,186 MW), Minnesota (501 MW), and Iowa (260 MW).[688] In other states, legislatures had passed Renewable Portfolio Standards with lax requirements (Arizona, Massachusetts, Wisconsin), exempted large utilities if existing contracts for electricity from conventional sources already met electricity demand (New Mexico), allowed such standards to be met with existing renewable energy capacity from neighboring states (Nevada), or applied such standards to only a small share of the electricity market (Connecticut, Pennsylvania).[689] Even as states slowly increased their RPS requirements and additional states passed similar legislation, the tide of state-level support for some form of demand-inducing incentives for wind and solar technologies was not sufficient to create a renewable energy mandate at the federal level. The standards allowed for growing markets for wind energy, yet state-by-state differences in RPS

---

[687] Martinot et al. 2005, 6-8.
[688] Petersik 2004, 8.
[689] For a discussion of implementation of Renewable Portfolio Standards across states, see Martinot et al. 2005; Petersik 2004; Wiser et al. 2007b.

legislation and requirement to use locally generated electricity prevented a common national market.[690]

A second policy measure to encourage renewable energy demand—often used in conjunction with Renewable Portfolio Standard—was the use of so-called Public Benefit Funds (PBF). These funds were most frequently financed through a small surcharge on end-user electric rates on the scale of one to three percent of retail sales. By 2005, 23 states had passed legislation to establish Public Benefit Funds for renewable energy, nine of which did so in conjunction with Renewable Portfolio Standards.[691] Again, the size of PBFs and the program focus differed widely across states. With USD 135 Million annual funding, California established the largest Public Benefit Fund by far; other states, such as Illinois, Pennsylvania, and Wisconsin provided between USD 1 and 15 Million for renewable energy projects.[692] The most common use of such funds was the provision of production incentives and grants for renewable energy installations (California). Others used Public Benefits Funds to provide low-interest loans and equity investments (Connecticut, Massachusetts). A third group of states, meanwhile, employed Public Benefit Funds to establish test centers, fund R&D grants, and subsidize demonstration projects and technical support

[690] International Energy Agency 2008, 102-03.
[691] Martinot et al. 2005, 10.
[692] Bolinger et al. 2001, 83.

(Wisconsin).[693] All in all, states spent some USD 300 Million annually to support renewable energy through Public Benefit Funds.[694]

The patchwork of state-level renewable energy legislation encouraged the creation of sizable wind energy markets in the United States. In the solar sector, too, installations increased over time, although Germany—the world's largest solar market—continued to outpace United States. By 2009, Germany had installed nearly 10 GW of solar panels as a result of generous federal subsidies, nearly six times as many panels as the United States.[695] Despite strong efforts of some state governments to create local markets for renewable energy, however, installations of wind turbines and solar panels continued to rely on the undependable federal Production Tax Credit for commercial success. The tide of state-level legislation did not translate into a more stable support framework in Washington. Even though the Obama administration renewed the Production Tax Credit for three years in 2009, it was not made permanent and its renewal was as contested in 2012 as in previous years. It was renewed for one year the day after it expired, yet wind turbine installations slowed dramatically in 2013.[696] A number of turbine manufacturers, including startup firm Clipper, closed facilities and laid of staff as a result.[697] In the solar sector, a 30 percent

---

693 Bolinger et al. 2001, 84-85.

694 Martinot et al. 2005, 10. In addition, a number of states also passed so-called net-metering laws, which permitted commercial and individual owners of renewable energy installations to deduct any electricity supplied to the grid from their electric bills. Such legislation allowed renewable energy generators to use store electricity in the grid at times when electricity production surpassed on-site consumption. Net-metering laws were particularly attractive for residential owners of solar panels, for instance, who were able to feed excess electricity into the grid during the day and could consume that electricity at night at no charge. By 2005, 38 states had passed such net-metering laws. See Menz 2005, 2404.

695 Data from European Photovoltaic Industry Association, compiled by Earth Policy Institute, 2011.

696 Barradale 2010, 7699; Schwabe et al. 2009, 8. Christopher Martin, 2013. "U.S. Wind Power Slumps in 2014 After Tax Credit Drives 2012 Boom." *Bloomberg*, October 31.

697 Diane Cardwell, 2012. "Tax Credit in Doubt, Wind Power Industry is Withering." *New York Times*, September 30.

investment tax credit had been extended for eight years in 2008 after several one-year-renewals, yet the political haggling over the PTC extension in the wind industry cast doubt on future extensions of solar support.[698]

The lack of a comprehensive industrial policy for the development of domestic wind and solar industries was not for lack of effort, as federal and state-level governments enacted a broad range of policies for the commercialization and deployment of wind and solar technologies in the decades since the 1970s oil crises. In the face of political opposition, industry lobbying, and divergent policy preferences across states, however, this patchwork of industrial policies never added up to a comprehensive strategy for how domestic industries could take advantage of the new technologies that continued to flow out of universities and government research institutes. Even where states enacted stable market-inducing policies, the instability of production tax credits provided by the federal government undermined local efforts.[699]

Who Enters Wind and Solar Supply Chains?

Faced with costly retooling of existing plants, the need to acquire new technological skills to customize products for renewable energy industries, supplier qualification processes lasting 12 months ore more, investments in renewable energy sectors were too risky for many small and medium sized firms in an uncertain market environment.[700] In a study of the effects of policy volatility in wind power support, Ryan Wiser of the Lawrence Berkeley Laboratory finds that uncertainty "in the future scale of the U.S. wind power

---

[698] Solar Energy Industries Association 2014.

[699] For a discussion of the impact of policy uncertainty on the development of renewable energy industries, see Barradale 2010; Wiser et al. 2007a.

[700] Rogowsky and Laney-Cummings 2009, 13-14.

market has limited the interest of both U.S. and foreign firms in investing in wind turbine and component manufacturing infrastructure in the U.S." Short term extensions to policy support "may lower the willingness of private industry to engage and invest in long-term wind technology R&D that is unlikely to pay off within a one-to-two year [cycle]."[701] Barradale confirms these findings in a survey of investor confidence among attendees of renewable energy conferences.[702] Similarly, Fabrizio finds that renewable energy firms are generally reluctant to invest in states that have previously shown policy volatility in energy market regulation, a problem exacerbated by uncertainty over federal policy support.[703] Wind turbine manufacturers, which sought to localize component production to reduce transportation costs and currency risks, conceded that they were unable to guarantee long-term order volumes necessary to attract local suppliers.[704]

The problems posed by investment uncertainty were compounded by the lack of policy support for small manufacturers that could potentially enter markets for wind and solar components. Among those that had survived the long decline in the number of manufacturing establishments in semiconductor, machine tool, and automotive supply industries, few were able to make the investments required to enter new industries in the absence of bank loans and federal R&D funding. For example, a steel manufacturer seeking to diversify into the wind industry stated that a contract to supply parts for a local offshore wind park would necessitate a USD 20 million investment in a new manufacturing facility, a risky investment in the absence of any guarantees that a contract would ultimately be awarded to the firm. Even with such guarantees, bank loans would be difficult to obtain and

---

[701] Wiser et al. 2007a, 81.
[702] Barradale 2010, 7699-701.
[703] Fabrizio 2012.
[704] Baker 2010; Spada 2010.

the manufacturer's only hope of finding external financing were federal loan guarantees. At the time of the interview, legal challenges and debates over subsidies had left the offshore project in limbo, yet the small manufacturer with 50 employees had already spent USD 1 million of retained earnings to prepare a bid. By comparison, a German manufacturer of similar components, whom the steel firm had relied on for technical advice, had received a USD 45 million grant for a USD 90 million facility from the German government and was able to secure three years of guaranteed orders from German turbine manufacturers prior to making the investment. Asked if any competitors were also trying to enter the wind industry, the steel manufacturer recounted how all of his 12 local competitors had gone bankrupt over the past 20 years, as their core markets eroded and they failed to diversify into growing industries.[705]

In face of the difficulties faced by small manufacturing firms, many firms that successfully entered U.S. wind and solar supply chains were multinational corporations, less reliant on any particular market and able to invest in new facilities without the need for external financing. In Germany, a large number of small firms repurposed a wide range of existing industrial capabilities for application in wind and solar sectors. In the United States, by contrast, multinational corporations frequently entered through acquisitions of startup firms with promising technologies for a few core wind and solar components and equipment. Applied Materials, a multinational firm with 40 years of experience in producing manufacturing equipment and software for the semiconductor industry, decided to enter the solar PV industry in 2006. Applied Materials had already modified some of its semiconductor equipment for manufacturers of conventional silicone-based solar cells.

[705] Author interview, CEO of steel manufacturing firm, October 24, 2012.

Anticipating growing markets for thin-film solar technologies, it embarked on a series of acquisitions to establish a solar PV division that could serve both traditional silicon and thin-film solar manufacturers. In 2006, it invested USD 464 million to purchase Applied Films Corp, a producer of thin-film deposition equipment.[706] In 2007, it acquired the Italian manufacturer of solar PV production equipment Baccini and the Swiss wafer manufacturers HTC Shaping Systems.[707] In 2009, the U.S. startup Advent Solar joined the Applied Materials portfolio.[708] In addition to these acquisitions, Applied Materials' in-house venture capital fund, Applied Ventures, invested smaller sums in startup companies whose technologies were not yet mature.[709]

Other suppliers followed Applied Materials' diversification into renewable energy sectors. Dupont Chemical, for instance, in 2011 bought the silicon valley startup Innovalight to expand its materials portfolio for the solar industry. Innovalight had previously received funding from NREL and DOE to develop a silicon ink and first commercialized the technology through a joint development agreement with the Chinese firm JA Solar. Dupont's acquisition thus occurred after the technology was fully commercialized, allowing Dupont to benefit from a decade of R&D activities without incurring technology risk.[710] Dow Chemical, which had participated in a federally-funded

---

[706] Mark LaPedus, 2006. "Applied Materials enters solar gear markets." *EE Times,* May 4. http://www.eetimes.com/document.asp?doc_id=1161175 (Accessed April 14, 2014).
[707] Katie Fehrenbacher, 2007. "Applied Materials to Buy Italian Solar Equipment Maker for $330M." *Gigaom,* November 19. http://gigaom.com/2007/11/19/applied-materials-to-buy-italian-solar-equipment-maker-for-330m/ (Accessed April 14, 2014).
[708] Josie Garthwate, 2009. "Applied Materials Buying Advent Solar Assets, Cheap." *Gigaom,* November 6. http://gigaom.com/2009/11/06/applied-materials-buying-advent-solar-assets-cheap/ (Accessed April 14, 2014).
[709] Applied Ventures Brochure, 2014. See http://www.appliedmaterials.com/sites/default/files/AV_Handout_0812.pdf (Accessed March 27, 2014).
[710] Nahm and Steinfeld 2014, 297. See also Kevin Bullis, 2011. "DuPont Inks a Deal to Improve Solar Cells." *MIT Technology Review,* August 1.

research consortia to develop building-integrated solar PV technologies and received USD 20 million from the Department of Energy for research on new types of solar arrays, struggled with delays in the commercialization of its technologies. In 2013, Dow Chemical acquired NuvoSun, a California startup producing solar shingles for rooftop applications. NuvoSun's technology was ripe for commercialization but the firm was struggling to fund the expansion of its manufacturing facilities to achieve scale economies.[711]

In the wind industry, growing domestic markets encouraged foreign wind and solar manufacturers set up production facilities in the United States, some of which persuaded their European suppliers to join them. The Spanish wind turbine producers Acciona and Gamesa were among the first foreign wind firms to open manufacturing plants in the United States.[712] Siemens, which had opened a manufacturing site for turbine blades in Iowa in 2007, established a full assembly plant in Kansas in 2010, a year after the American Recovery and Reinvestment Act extended federal support for wind turbine deployment. Nordex of Germany started local production in the same year.[713] A number of European suppliers of turbine components established U.S. manufacturing plants in the following years. These multinational suppliers included the blade producer LM, the gearbox manufacturers Winergy, Hansen, and Moventas, and the Portugese tower firm Martifer. Local manufacturers that diversified from other industries—such as the machine tool firm

---

711 Department of Energy, 2008. "DOE Selects 13 Solar Energy Projects for up to $168 Million in Funding." http://energy.gov/articles/doe-selects-13-solar-energy-projects-168-million-funding (Accessed March 27, 2014.) Ucilia Wang, 2013. "Dow Chemical buys NuvoSun for making solar shingles." *Forbes*, March 7. Emma Hughes, 2009. "New Product: Dow Chemical introduces solar shingle BIPV." *PV-Tech*, October 09. www.pv-tech.org/product_reviews/new_product_dow_chemical_introduces_solar_shingle_bipv (Accessed March 27, 2014).
712 Rogowsky and Laney-Cummings 2009, 4.
713 Platzer 2012b, 32.

K&M, the transmission firm Brad Foote, and the blade manufacturer TPI Composites—remained the exception.[714]

As declining manufacturing sectors reduced the number of supply firms with industrial capabilities applicable to wind and solar sectors and the volatility of public support for domestic renewable energy markets deterred existing firms from industry entry, U.S. wind and solar supply chains remained considerably less diverse than those in Germany and China. U.S. strength in early-stage research and development manifested in large numbers of high-technology startups, yet the failure of small- and medium-sized manufacturing firms to mobilize and enter renewable energy supply chains left large gaps in the types of industrial capabilities that could be accessed domestically. Although multinational suppliers manufactured key components for wind turbines and solar panels, U.S. wind and solar supply chains lacked the diversity and density of German and Chinese renewable energy sectors, where different sizes and types of firms were offering a broad range of industrial capabilities and were willing to repurpose such capabilities for multiple applications. Ultimately, the top-down technological innovation that trickled from universities and research institutes into startup firms was not matched by an equally forceful mobilization of existing industrial capabilities.

714 Platzer 2012b, 32; Rogowsky and Laney-Cummings 2009, 9-10.

4. Global Partners for U.S. Wind and Solar Firms

Despite a feeble federal commitment to the support of domestic renewable energy markets, large numbers of high-technology startups continued to develop new wind and solar technologies, seeking to lower the cost and increase the competitiveness of clean energy through disruptive technological change. These innovative U.S. wind and solar firms were not accompanied by equally large supply chains of firms that were able to provide matching technological capabilities, components, and production experience to commercialize new technologies. Where clusters of renewable firms emerged in the United States, they were frequently made up of startups pursuing similar strategies, not groups of functionally diverse firms with complementary skills. In Northern California, for instance, the density of venture capital funds and research universities created advantageous conditions for startups, but the area did not attract a network of vertically differentiated suppliers.[715] As a consequence, wind and solar producers in the United States were forced to work with partners in global supply chains on technology commercialization. In the best case, the results of America's research and development infrastructure came to market through collaborative relationships, benefitting not just U.S. firms and institutions, but a range of global actors who each contributed skills and bore associated risks. In the worst case, however, startup firms were unable to find complementary capabilities in global supply chains, abruptly ending the trajectory from lab to market for promising technologies.

As innovators in wind and solar industries looked outside the United States to find the full range of capabilities required to scale-up and mass produce the results of early-

[715] Böttcher 2009, 16-24; Colatat et al. 2009b, 5-7.

stage R&D, multinational firms—many of which had acquired startups to enter renewable energy sectors—were in an advantageous position. GE, for instance, entered the wind energy sector through the purchase of Enron's wind turbine division in the course of Enron's bankruptcy in 2003. The acquisition gave GE immediate access to the turbine technologies under Enron's portfolio, including those of of Zond, U.S. Windpower, and the German manufacturer Tacke. In addition to taking on 1,600 employees and production facilities in Germany and Spain, where large wind energy markets already existed, GE's purchase of Enron's wind energy division included turbine technologies that had been developed over decades of federal R&D support.[716]

Zond's variable speed wind turbines, which had originally been developed at the University of Massachusetts, Lowell, and matured through collaboration with DOE and the national wind-power program at NREL, provided the foundation for GE's turbine business. Enron's foreign assets, including the German manufacturer Tacke, further contributed patents, technologies, and supplier networks.[717] GE was thus able to build on three decades of federally-funded wind turbine R&D without incurring any of the initial technological risks itself.[718] Despite having ceased the in-house development of utility-scale wind turbines when federal research support dried up during the 1980s, the purchase of Enron's wind assets allowed GE to quickly become one of the largest wind turbine manufacturers in the world. By 2005, GE held 61 percent of the U.S. market for wind turbines.[719] To further improve its wind turbine technology, GE conducted both in-house R&D and acquired

---

716 Mazzucato 2013, 148. See also Christopher Mumma, 2002. "GE Seeks Refund from Enron Wind." *Los Angeles Times,* November 15.
717 Lewis 2013, 95; Windpower Monthly 1997.
718 Mazzucato 2013, 148-49.
719 Gleitz 2006, 1.

startups with specialized technologies. In 2011, for instance, GE purchased the tower manufacturer Wind Tower Systems LLC, to access its proprietary technology for the construction of low-cost wind turbine towers of more than 300 feet.[720]

Unable to find suppliers in the United States—and presumably unwilling to provide order guarantees that would have attracted suppliers into local markets—GE retained the relationships with German gearbox suppliers such as Eickhoff, Winergy, and Bosch Rexroth, which had previously supplied Tacke. GE continued to source generators from VEM Sachsenwerke and maintained an R&D facility in Munich, Germany, to coordinate the development of new components with its European suppliers.[721] Its membership in the German Engineering Federation's (VDMA) wind chapter allowed GE to participate in collaborative research activities conducted among German suppliers.[722] At the same time, GE began expanding its global supplier network, sourcing blades from Brazil and metal castings and gearboxes from China, where it also maintained an R&D facility.[723] Strong institutional and financial capabilities allowed company not only to systematically identify potential suppliers and collaborators, but also made possible the assignment of engineering staff to the production facilities of its partners. A Chinese manufacturer that developed gearboxes in collaboration with GE reported a permanent presence of GE design and

---

720 Ehren Goossens, 2011. "GE Acquires Wind Tower Systems to Build Taller Wind Turbine Towers." *Bloomberg,* February 11.

721 GE Power & Water 2012; Windpower Monthly 2002; Windpower Monthly 2005a; Windpower Monthly 2005b; Windpower Monthly 2006.

722 VDMA website. http://wind.vdma.org/en/article/-/articleview/599526 (Accessed March 15, 2013). Author interview, German Engineering Federation, May 25, 2012.

723 Author interview, Head Engineer of Chinese gearbox manufacturer, August 26, 2011. "Tecsis signs US$1bn wind turbine blade deal with GE." *Business News Americas,* December 4, 2006. http://www.bnamericas.com/news/electricpower/Tecsis_signs_US*1bn_wind_turbine_blade_deal_with_GE (Accessed April 14, 2014).

manufacturing engineers on site to improve product designs and supervise manufacturing processes.[724]

The capabilities in managing a global supply chain allowed GE to focus on assembly and research in the United States while sourcing the majority of components internationally. Local content rates for GE turbines assembled in the United States remained lower than those of its foreign competitors, many of which had established local component production.[725] As a consequence, approaches to reduce gearbox wear through novel lubricants, which GE's predecessor, Zond, had developed in together with NREL, were introduced and carried out in Chinese gearbox manufacturing plants.[726] GE continued to participate in federally funded research—collaborating, for instance, with NREL and Virginia Tech on developing new blade designs through a project funded by ARPA-E —yet it was less dependent than other manufacturers on finding local partners for implementation of the results.[727]

Large suppliers, such as Applied Materials, maintained similarly global relationships to commercialize their products. Applied Materials in 2009 opened a solar technology R&D center in China, not primarily to source components, but to improve solar PV production technologies in collaboration with China's growing number of solar manufacturers.[728] With U.S. startups working on disruptive technologies not yet in mass production, Applied Materials looked to China's 120 solar manufacturers to partner on the incremental

---

[724] Author interview, Head Engineer of Chinese gearbox manufacturer, August 26, 2011.
[725] Rogowsky and Laney-Cummings 2009, 9, 20.
[726] NREL, 2010. "Wind Turbine Design Innovations Drive Industry Transformation." http://www.nrel.gov/docs/fy10osti/47565.pdf (Accessed March 27, 2014).
[727] NREL, 2013. "Fabric-Covered Blades Could Make Wind Turbines Cheaper and More Efficient." http://www.nrel.gov/wind/news/2013/2066.html (Accessed March 27, 2014).
[728] Katherine Bourzac, 2009. "Applied Materials Moves Solar Expertise to China." *MIT Technology Review,* December 22.

improvement of silicone and thin film solar PV technologies. In 2011, for instance, Applied Materials announced a new selective emitter production that had been developed in its R&D facility in China. The underlying production technology was contributed by the Italian firm Baccini, which Applied Material had acquired in 2007, yet the technology was subsequently tested and fine-tuned in the manufacturing plants of Chinese PV producers, using components and materials developed by Honeywell in the United States.[729]

Applied Materials was less successful in developing manufacturing technologies for thin film lines. A plan to build turnkey production lines for thin film cells—based on the core technologies of several U.S. startup firms it had acquired—failed when falling silicon prices bolstered the competitiveness of conventional silicon cells.[730] The firm's 2010 exit from the thin film business effectively ended research and development on a technology that had received USD 300 million in research funding from the U.S. federal government.[731] However, its thin film division, too, was based on global relationships, and the consequences of Applied Material's were felt far beyond the United States, even if that is where the technology originated in federal research laboratories. With few prospects for further technology improvements, early adopters of Applied Materials' thin film production lines, such as the Chinese firm Suntech, closed their thin film divisions.[732]

Smaller wind and solar startups also relied on global supply chains to find complementary capabilities, even if their limited institutional and financial resources

---

729 "Advisory: Applied Materials Reports Innovations in Solar Cell Manufacturing at SCNEC." *Reuters,* February 21, 2011.
730 Jennifer Kho, 2010. "Applied Materials and the $1.5 billion sunfab flameout." *Fast Company Magazine,* December.
731 Gallaher et al. 2012, 31-34.
732 Michael Kanellos, 2010. "Suntech Abandons Thin Film, Wafer Experiments." *Greentech Media,* August 6. http://www.greentechmedia.com/articles/read/suntech-abandons-thin-film-experiments.-revenue-up-for-2q (Accessed April 14, 2014).

precluded the type of global supply chain management common to multinational corporations. Since venture capital funds were rarely willing to fund investments in capital-intensive manufacturing facilities and startup firms frequently lacked production experience, it was knowledge in scale-up and mass production, not access to technology, that many startups were seeking from global partners. For instance, Innovalight, a Silicon Valley startup that had developed a silicon ink technology capable of drastically improving the conversion efficiency of solar cells, had received funding from the Department of Energy and had collaborated with the National Renewable Energy Lab to apply its technology to the solar sector. Neither the federal research infrastructure nor American solar industry were able to supply the type of production skills required to apply the silicon ink to large-scale manufacturing. Before SolarWorld constructed a manufacturing plant for silicon-based solar PV technologies in 2008, almost all U.S. solar plants were producing thin film solar PV technologies which were incompatible with Innovalight's product. A plan to build its own production facility faltered when venture capital funds were unwilling to invest the sums required for a manufacturing plants.

Ultimately, Innovalight, like many of its peers, looked to China for a partner to commercialize its technology.[733] It joined forced with the Shanghai-based cell manufacturer JA Solar, which had a production line designated to manufacturing research and the production capabilities necessary to integrate Innovalight's silicon ink. With few engineers and depleted finances, it is unlikely that Innovalight was able to conduct a systematic search for potential partners. Rather, it were JA Solar's close connections to Silicon Valley that facilitated the match. JA Solar's CEO at the time, Peng Fang, had completed his PhD at

---

[733] Nahm and Steinfeld 2014, 297.

the University of Minnesota, conducted research as a post-doctoral student at the University of California, Berkeley, and had worked for Applied Materials and the semiconductor firm AMD in Silicon Valley before returning to China.[734] Innovalight's CEO, Conrad Burke, was also a Silicon Valley veteran, suggesting that the two firms were able to broker a collaboration through the networks of Northern California's startup clusters.[735] The partnership between the two firms resulted in the successful commercialization of Innovalight's silicon ink technology, eventually leading to Innovalight's acquisition by Dupont.

Other startups followed a similar strategy of building personal ties to China in search of complementary skills, albeit in search of componentry. FloDesign, the Massachusetts wind turbine company that had developed a turbine technology based on jet engine design principles, in 20010 hired Lars Anderson, who had previously managed the China business of Denmark's multinational turbine manufacturer Vestas.[736] Unable to find customized components for the novel turbine design in the U.S. wind power supply chain, the new CEO's familiarity with the Chinese supply chain was intended to help identify suitable suppliers in China.[737] FloDesign, which has since changed its name to Ogin, subsequently opened an R&D and component sourcing facility in Beijing to facilitate collaboration with Chinese partners.[738]

---

[734] "Peng Fang: Executive Profile." *Bloomberg Businessweek*, 2014. http://investing.businessweek.com/research/stocks/people/person.asp?personId=27714739&ticker=JASO (Accessed April 24, 2014).
[735] "Conrad Burke: Executive Profile." *Bloomberg Businessweek*, 2014. http://investing.businessweek.com/research/stocks/people/person.asp?personId=27714739&ticker=JASO (Accessed April 24, 2014).
[736] Jon Gertner, 2013. "FloDesign's Jet-Engine turbine Will Change the Way You Think about Wind Power." *Fast Company Magazine*, September.
[737] Author interview, FloDesign engineer, November 30, 2010.
[738] U.S.-China Energy Cooperation Program, 2014. "Ogin Wind Turbine." http://www.uschinaecp.org/en/Members/FloDesign.aspx (Accessed April 24, 2014).

The CEO of a Silicon Valley solar startup that had opened a production facility with in China with a local partners explained that Northern California gave the firm access to trained engineers, test facilities, and the technological expertise of universities and research laboratories. In China, however, the firm was able to find manufacturing engineers with experience in rapid scaling of new technologies. The density of solar manufacturers in China had also created a local market for used manufacturing equipment, which the firm could buy cheaply and subsequently repurpose to test and produce its thin film technology. An abundance of local suppliers permitted its production engineers to easily try new materials and work with partners to improve the manufacturing process. Although the CEO insisted that basic research should stay in Silicon Valley for the time being, he expected more and more research staff to move to the Chinese facilities, as cost reductions through improvements to the manufacturing process were becoming more important over time.[739]

Although startups were able to find partners in global supply chains, the management of research and development activities through such relationships was considerably more difficult for smaller firms. Evergreen, the MIT spinoff which in the early 1990s began the development of string-ribbon manufacturing technologies for solar wafer, was unable to find U.S. partners that were willing to adjust their production practices to Evergreen's non-standard wafer size. Evergreen's string-ribbon technology was not sufficiently mature to produce wafers in the standard formats expected by cell manufacturers, preventing Evergreen from becoming a regular wafer supplier on global component markets. In 2005, it partnered with the Norwegian silicon producer REC and

[739] Author interview, CEO of Silicon Valley solar startup, August 24, 2011.

the German cell manufacturer Q-Cells to set up a manufacturing facility in Germany, where large solar markets existed at the time.[740] For the R&D engineers at the small Massachusetts-based startup company, however, such collaboration required countless trips to the Germany, as incremental improvements to the technology had to be tested and implemented in its manufacturing facility. Any changes to wafer production and size necessitated subsequent adjustments of the entire production line, including cell and module manufacturing. R&D engineers involved in the commercialization of the string ribbon technology maintained that the geographical distance between the partners proved challenging for a small firm like Evergreen, slowing technological progress and preventing rapid incremental improvements.[741]

Despite more than USD 43 million in grants from the state of Massachusetts, Evergreen's attempts to localize production in the United States a few years later failed due the continued high cost of Evergreen's technology. The firm gradually moved its facilities to China in 2009, where it conducted R&D and production in close proximity to a local partner, a manufacturer of cells and modules. Local suppliers of production equipment were able to contribute to cost reductions for Evergreen's proprietary production lines; a greater number of local firms offered opportunities for more rapid incremental improvements for its technology. Ultimately, though, Evergreen was unable to stay in business despite such a wide range of partners. In 2011, a Chinese investor bought

[740] QCells, 2005. "REC is new strategic partner in EverQ." http://www.pvqse.de/uploads/media/pm_rec_everq_english_28_11.pdf (Accessed April 14, 2014).
[741] Author interviews: former Evergreen engineers, May 16 and October 13, 2011.

Evergreen for USD 6 million in cash and 7.6 million in stock, a fraction of the state R&D funds and production subsidies that the firm had received in the United States.[742]

Although many startup firms depended on global partners to commercialize their technologies, global relationships were not the only reason U.S.-funded technologies were commercialized abroad. In wind and solar industries, in which the capabilities required to bring new technologies from lab to market were often spread across multiple firms in far-flung locations, attempts to single-handedly manage the commercialization process could also result in failure. MiaSole, a Silicon Valley manufacturer of high-efficiency thin-film solar modules, long struggled to scale the manufacturing of its technology. The startup had received more than USD 500 million in venture financing since its founding in 2004, but was unable to move increase its production from 50MW to 150MW annually. In 2011, it hired manufacturing experts from INTEL to improve its manufacturing operations. Falling silicon prices, overcapacity in global markets, and difficulties in raising further funds to expand its facilities compounded its production problems. In 2012, the Chinese industrial manufacturer Hanergy bought MiaSole for USD 30 million, a fraction of original VC investment. Although its facilities in California have remained in place for the time being, Hanergy has since begun to scale MiaSole's technology in larger manufacturing plants in China.[743]

---

742 Keith Bradsher, 2011. "Solar Panel Maker Moves Work to China." *New York Times*, January 14. Ucilia Wang, 2011. "Evergreen Solar finds Chinese buyer for its technology." *Renewable Energy World*, November 28. http://www.renewableenergyworld.com/rea/news/article/2011/11/evergreen-solar-finds-chinese-buyer-for-its-technology

743 "Miasole, Intel strike manufacturing consulting deal." *Reuters*, April 6, 2011. Nichola Groom, 2012. "China's Hanergy to buy U.S. solar startup Miasole." *Reuters*, October 1. Julia Chan, 2013. "MiaSolé to undergo R&D expansion following acquisition by Hanergy." *PVTech*, January 09. Diane Cardwell and Keith Bradsher, 2013. "Chinese firms buys U.S. Solar Start-Up." *New York Times*, January 09.

As is the case with most disruptive technologies, not all innovations were destined for success, whether firms were able to find global partners or not. Ultimately, changes in the global market environment, technology failure, lack of sufficient financing at critical development junctures, and high production cost prevented many innovations from U.S. research institutions to reach consumer markets. Startup firms incurred risks both in developing new technologies and in bringing them to large-scale production and deployment; many struggled to manufacture their products at a competitive price, even with the help of global suppliers. At the same time, prices for conventional wind and solar technologies were falling rapidly, as multinational firms with large manufacturing facilities entered the U.S. market.[744] The global financial crisis led many European governments to cut renewable energy subsidies, resulting in declining renewable energy markets in other parts of the world. The discovery of large natural gas reserves in the United States lowered the price of fossil fuels in the United States, increasing the price gap between renewable energy and conventional sources of electricity and offsetting cost reductions in of renewable energy technologies achieved over previous decades.[745] As a result, a wave of bankruptcies shut U.S. high-technology solar firms and wind turbine producers struggled to stay afloat. Evergreen Solar ceased operations.[746] Solyndra, which had benefited not only from R&D subsidies but also from a sizable loan guarantee to build a large manufacturing facility, declared bankruptcy after the decline in global silicone prices eroded the

[744] Katherine Bourzac, 2009. "U.S. Solar Startups Struggling to Compete with Chinese Firms." *Technology Review,* November 4.

[745] Wendy Koch, 2014. "U.S. wind industry slammed by tax uncertainty, fracking." *USA Today,* April 10. http://www.usatoday.com/story/news/nation/2014/04/10/wind-solar-grow-but-investments-fall/7511733/ (Accessed April 10, 2014).

[746] Greg Turner, 2011. "Evergreen Solar files for bankruptcy, plans asset sale." *Boston Herald,* August 15.

competitiveness of its products and its venture capital investors withdrew their support.[747] SunPower and First Solar closed manufacturing facilities in the United States and abroad.[748] Out of the 200 solar startups that had received venture capital funding by 2008, less than half were still operating as independent businesses by 2013.[749]

Where technologies did succeed in traveling the full trajectory from lab to market, however, they relied on federal support for R&D as much as the contributions of firms in global supply chains, as gaps in domestic supply chains forced innovators to look outside of the United States for capabilities in scale-up and mass production.

[747] Mazzucato 2013, 129-32. See also Anne C. Mulkern, 2011. "Solyndra Bankruptcy Reveals Dark Clouds in the Solar Power Industry." *New York Times,* September 6.

[748] Steve Leone, 2012. "Major Closures for First Solar, SunPower." *www.renewableenergyworld.com.* (Accessed March 27).

[749] Eric Wesoff, 2013. "Rest in Peace: The List of Deceased Solar Companies." *Greentech Media*, April 6. http://www.greentechmedia.com/articles/read/Rest-in-Peace-The-List-of-Deceased-Solar-Companies (Accessed March 27).

5. Conclusion

The United States' lead in renewable energy technology development has been remarkably consistent. Just as early wind and solar technologies were developed and tested in U.S. laboratories in the postwar decades, American universities, research institutes, and private sector enterprises have continued to advance the technological frontier in wind and solar industries. Such strengths in early-stage R&D have not been complemented by industrial capabilities in commercialization and scale-up, activities which have rarely located domestically. As a result, U.S. innovators have worked with global partners on bringing their technologies from lab to market.

As I have discussed in this chapter, large federal investments in renewable energy research supported promising lines of technology development. Successive presidential administrations and shifting political support in Washington, while adjusting annual research budgets, never completely eliminated such federal R&D funds. The federal infrastructure for energy research, first established in the wake of the 1970s oil crisis, was left in place after concerns about energy security faded over the course of the 1980s. Just as wind and solar sectors in Germany and China reproduced industrial capabilities of the broader economy by building on existing institutions and resources, U.S. R&D capabilities have also benefitted from policy support beyond the domain of renewable energy policy. In addition to R&D funding, U.S. renewable energy firms utilized broad institutional support for high-technology research, including a legal framework that made possible spinoffs and licensing of the results of federally funded research and a large venture capital community willing to invest in high-risk technology projects. These institutional resources allowed for large numbers of high-technology startups, the majority of which were focused on the development disruptive renewable energy technologies that originated in federally funded R&D.

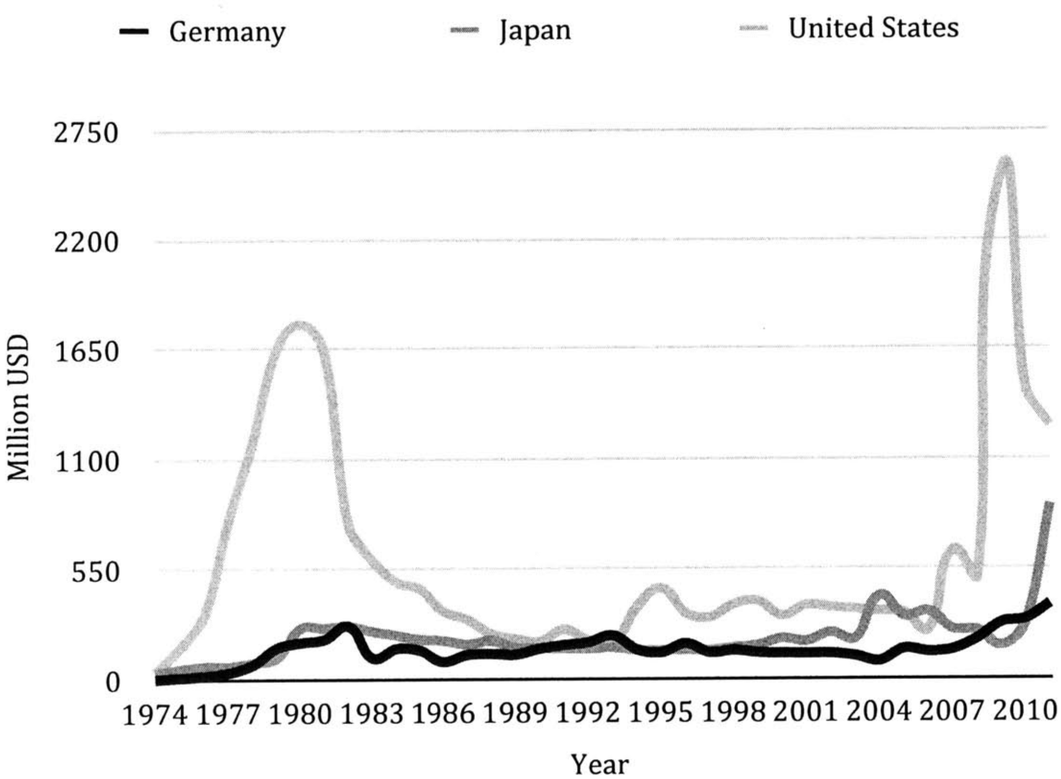
Although federal and state-level policies jointly created large markets for wind turbines and growing domestic markets for solar PV technologies, U.S. startup firms were not accompanied by large domestic supply chains focused on scale-up and manufacturing of wind and solar products. In contrast to Germany and China, where firms from adjacent industries brought production capabilities to bear on renewable energy sectors through firm-driven industrial change, the only firms involved in domestic manufacturing activities in the United States were multinational corporations. Declining domestic manufacturing sectors and a weak supplier base in adjacent industries drastically reduced the number of firms with capabilities in scale-up and mass production that could enter wind and solar supply chains. Losses were particularly strong in sectors such as aerospace, semiconductors, and machine tools—precisely the type of industries from which suppliers entered wind and solar sectors in Germany. These structural problems in the U.S. supplier base were exacerbated by uncertainty over government support for domestic wind and solar markets, as tax credits and other subsidies were perpetually on the brink of elimination. Small- and medium-sized suppliers with capabilities applicable to wind and solar sectors were deterred from industry entry.

The findings presented in this chapter suggest that U.S. strengths in innovation without capabilities in scale-up and mass production do not result from foreign competitive pressures and the disadvantages of high wage environment, but stem from industrial policy choices and changes in the existing industrial legacy of the United States. Strong support for research and development activities did not by itself result in broader industrial outcomes, as federal policies were not complemented by policy support for the type of bottom-up industrial change that brought production capabilities to China's and Germany's renewable energy supply chains. Absent a vibrant industrial base of firms with capabilities applicable to the commercialization of wind and solar technologies and lacking the types of institutional support—including skills and training institutions, financing, and collaborative research opportunities—that could help smaller firms apply their capabilities to new industrial sectors, the United States reproduced historical strength in research and development, even in new sectors such as wind and solar.

The absence of local firms with a diverse range of industrial capabilities in scale-up and commercialization required innovators to look for partners with complementary skills outside of the United States. As I have discussed in Chapters 3 and 4, firms in Germany and China possessed precisely the types of skills required to bring new energy technologies to market, and many American firms relied on global partners for the commercialization of their technologies. In practice, however, such global linkages were easier to maintain for large, multinational corporations, than for the high-tech startups that spun of universities and research institutes. Firms like GE and Applied Materials, which could quickly enter new industrial sectors through the acquisition of startup firms, were able to systematically match their own capabilities with complementary skills in global supply chains. For smaller startup firms, however, finding such partners required considerably more effort. With limited financial and human resources, such global collaborations were equally hard to maintain.

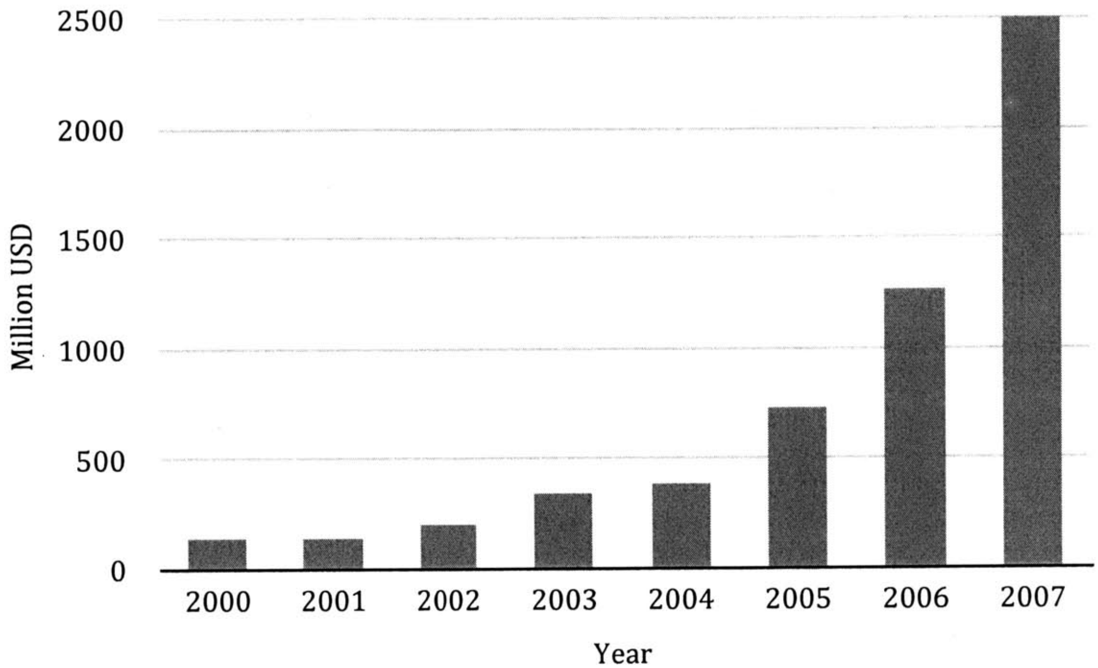
The constraints of the singular focus on early-stage R&D in U.S. wind and solar industries may be particularly hard on high-technology startups, precisely the type of firms most supported by the federal infrastructure for R&D. Multinational firms, which continue to scale down their own investments in energy R&D, may stand to benefit the most. Able to acquire startup firms with promising technologies, multinational corporations can access new technologies without incurring the risk of basic research and early-stage R&D, and manage the linkages to global partners for scale-up and mass production.

Figure 1: Public R&D Funding for Wind and Solar Energy Research, Selected Countries



Source: IEA (2013), "RD&D Budget", IEA Energy Technology RD&D Statistics (database). doi: 10.1787/data-00488-en (Accessed on 07 May 2014)

Figure 2: Global Venture Capital Investments in Clean Energy Technologies



Source: Jennings, Charles E., Robert M. Margolis, and John E. Bartlett. 2008. A Historical Analysis of Investments in Solar Energy Technologies (2000-2007). Golden, CO: National Renewable Energy Laboratory. Page 9.

Chapter 6: Conclusion

1. Review of the Findings

Literatures on innovation and industrial development have generally taken for granted a division of labor between firms in industrialized economies that invent and commercialize new technologies and those in developing economies that absorb technologies from abroad and focus on manufacture.[750] Globalization may offer new possibilities to geographically separate innovation and production, but, according to literatures on global supply chains, new options for the organization of production have reinforced, not weakened, this global division of labor.[751] Moreover, literatures on innovation and industrial development presume that at least innovation itself still largely takes place within the four walls of one firm, even as the emergence of global production networks has been accompanied by a decline of the vertically integrated enterprise. In other words, processes of technology development are assumed to be vertically integrated in the firm, whether the development process is incremental or radical in nature, and whether manufacturing occurs in house or outsourced to low-cost production locations.[752]

In contrast, this study has examined processes of industrial upgrading under conditions of fragmented production, in which few firms possess all the skills required to bring new products to market and in which industrial capabilities—from strength in early-stage R&D through commercialization and large-scale production—are dispersed across global supply chains. The two sectors at the core of this study, wind and solar PV industries,

---

750 For literatures on technological innovation that see innovation as primarily occurring in advanced economies, see, among others, Hall and Soskice 2001; Nelson 1993; Vernon 1966.
751 Steinfeld 2004; Sturgeon 2002a.
752 Gereffi et al. 2005; Hall and Soskice 2001; Sturgeon 2002a.

between them span virtually the entire range of technological and production characteristics of modern industries—from traditional metal bending to advanced materials and chemical processes. Yet both sectors developed after the decline of the types of vertically integrated firms that could have housed such a range of capabilities within the four walls of the firm, precluding the existence of global technological leaders whose industrial capabilities offer a single template for emulation.

Instead, as I show in Chapter 2, in wind and solar industries technological leaders exist across the entire range of industrial capabilities required to bring new products to market. Rather than copy the capabilities of firms in advanced economies, Chinese renewable energy firms have participated in product innovation for wind turbines and solar modules through engineering capabilities in manufacturing that have allowed global innovators to bring new technologies to market quickly, at greater scale, and lower cost. In the late 1990s, when Chinese manufacturers first entered wind and solar industries, firms in advanced economies were borrowing components and manufacturing equipment from adjacent industries and repurposing them for application in renewable energy sectors in a makeshift fashion. It were the engineering capabilities of Chinese firms that allowed wind and solar sectors to mature from niche manufacturing to mature industrial sectors, as Chinese manufacturers changed existing product designs to allow for rapid scaling of production at lower cost, and debuted new manufacturing processes and equipment in collaboration with global partners.

Consequently, industrial development in wind and solar industries did not occur at the hands of a few vertically integrated conglomerates, but relied on the contributions of large numbers of specialized firms in global supply chains. In what I have referred to as *networked innovation*, firms each contributed distinct sets of industrial capabilities to global processes of product development. High-tech startups spinning off from American research institutes and universities and German suppliers of components and manufacturing equipment equally worked with Chinese manufacturing partners to commercialize new wind and solar technologies. As a consequence, firms in China, Germany, and the United States were able to participate in product development with narrow sets of industrial capabilities, collaborating with partners to access complementary skills required to bring new products to market. Chinese wind and solar producers participated in product innovation through niche specializations in innovative manufacturing; they, too, engaged in industrial upgrading through learning at the technological frontier rather than emulation and reverse engineering. Learning, experimentation, and technological innovation occurred along the entire trajectory from lab to market, spanning geographical and organizational boundaries in the process.

Chapters 3, 4, and 5 subsequently explore how wind and solar firms in Germany, China, and the United States established distinct sets of industrial capabilities under conditions of fragmented global production. In understanding the role of the state in enabling domestic firms to enter emerging wind and solar sectors, the chapters examine industrial upgrading through the lens of the firm, documenting which public resources and industrial policies renewable energy firms utilized and how. By placing the firm at the center of the inquiry, I find that firms relied on a far broader range of state-provided resources than are commonly associated with industrial policies for renewable energy sectors. The state, through traditional tools of industrial policy—including subsidies, R&D funding, and regulatory policy—was able to mobilize interests behind emerging industries and encourage firms to enter new sectors. However, in an environment of multiple paths for industrial upgrading, each requiring distinct sets of industrial capabilities, such sectoral intervention did not fully determine what types of technological specialization firms embarked on. Nor, for that matter, did sectoral industrial policies provide sufficient support to allow them do so. Rather, the findings presented in the empirical Chapters suggest that firms matched existing skills and capabilities with opportunities in global renewable energy sectors, in the process repurposing existing institutions and public resources for application in new industries. Industrial legacies beyond the domain of renewable energy policy determined what types of firms were able to enter and what institutions and resources they were able to draw on in doing so.

In Germany (Chapter 3), where federal policies created large domestic markets for wind turbines beginning in the early 1990s and for solar PV modules in the early 2000s, small-and medium-sized suppliers from machine tools, automotive, and equipment manufacturing sectors entered renewable energy industries in large numbers. The stability of government support for renewable energy markets provided incentives for entry, yet it were skills, training, and labor market institutions, local banks, and an infrastructure for collaborative industrial research that allowed German suppliers to apply themselves to wind and solar sectors. These institutions were not deliberately established to encourage small- and medium-sized firms to enter renewable energy industries, but they nevertheless enabled such firms from Germany's legacy industries to respond to new opportunities created by federal energy policies.

Central government policies in China (Chapter 4) encouraged the emulation of advanced R&D capabilities of foreign companies through research and development funding and by fostering technology transfers from foreign-invested firms. Although domestic wind and solar producers participated in central government science and technology programs, they utilized government support to establish engineering capabilities in manufacturing. Firms were aided in their endeavors by China's infrastructure for mass manufacturing provided largely by subnational governments, often in disregard of central government preferences for advanced R&D. The ability to access componentry and technologies in global supply chains permitted China's firms to repurpose domestic support for R&D and local policies for manufacturing to build engineering capabilities focused on scale-up and commercialization, neither of which nascent wind and solar firms had mastered in other parts of the world.

While wind and solar firms in Germany and China established innovative capabilities very closely linked to production activities, renewable energy firms in the United States focused on early-stage R&D, often without locating scale-up and commercialization domestically (Chapter 5). Although some regulatory and tax policies supported the creation of domestic markets, much of federal government industrial policy for renewable energy industries took the form of R&D funding for universities and national laboratories for energy research. In the United States, too, existing institutions were critical to the entry of domestic firms into wind and solar firms. A series of legislative reforms dating back to the 1980s made possible licensing and commercial spin-offs for technologies resulting from federally-funded research. U.S. venture capital funds were willing and used to investing in early-stage R&D in startup enterprises. What startup firms were unable to access domestically, by contrast, where small and medium-sized suppliers with production capabilities in scale-up and mass manufacturing, requiring many domestic firms to find global partners to bring their technologies to market.

Ultimately, in each of the three economies examined in this study, sectoral industrial policy was able to achieve upgrading outcomes only by incrementally building on existing industrial capabilities, policies, and resources provided by the state to support broad economic activities beyond renewable energy industries themselves. Even as firms from each location participated in technological innovation in new industrial sectors such as wind and solar, they did so by repurposing existing industrial capabilities and accessing complementary skills through collaboration with others.

2. Limits to Convergence in the Global Economy

Arguments about national diversity in the global economy are not new to scholars of political economy. Globalization—the increasing interdependence and integration of national economies in global markets—has led many to ask whether competitive pressures, emulation, and the diffusion of best practices in the global economy will ultimately lead to a convergence of national production structures, regulatory institutions, and economic policies. In the 1980s, the weakness of the American economy and the strong performance of firms from Japan and Germany—economies organized around very different relationships between the state, society, and business—raised questions about whether such national differences were here to stay, or whether distinct national practices would ultimately give way to global convergence.[753]

[753] For an overview of the debates about national diversity in the global economy, see Berger 1996.

Scholars have since pointed to a range of factors that may shield national economies from pressures toward convergence. Wade, for instance, has suggested that the importance of domestic markets provides significant room for continued differences in the organization of production.[754] Hall and Soskice, among others studying the *Varieties of Capitalism*, have argued that mutually reinforcing institutional arrangements lead to divergent but stable national political economies, each suitable to different types of production activities.[755] Building on these arguments, Breznitz, in a study of IT industries in Ireland, Israel, and Taiwan, finds that differences in domestic politics and institutions continue to allow even small, developing economies to craft divergent paths for the establishment of domestic high-tech firms in global economic sectors.[756]

Such scholarship on the diversity of national capitalisms has been concerned with options for the state to protect domestic industrial practices from the pressures of the global economy. This study, by examining trajectories of upgrading through the lens of the firm, highlights the possibility that industrial capabilities of firms remain distinct even in new sectors such as wind energy and solar PV. The importance of industrial legacies and public resources provided for existing sectors in shaping upgrading trajectories for firms in emerging industries suggest that national capabilities may continue to diverge. In the case of wind and solar industries, this remained true even as governments sought to locate new activities domestically, effectively encouraging some degree of convergence in domestic industrial activity. This is most obvious in China, where central government policy very deliberately sought to encourage the development of R&D capabilities similar to those of

[754] Wade 1996.
[755] Hall and Soskice 2001.
[756] Breznitz 2007.

firms in the West. China's wind and solar firms, meanwhile, chose to improve capabilities in scale-up and mass production instead. Even in Germany and the United States, governments hoped that demand-side subsidies, R&D support, and tax credits for manufacturing in renewable energy industries would lead to the development of industrial capabilities along the full trajectory from early-stage R&D to mass production. Yet, small- and medium-sized suppliers of components and manufacturing equipment in Germany have been far more successful in applying their strengths in customization and small-batch production to wind and solar industries than large manufacturers of solar panels, which have competed with China's innovative manufacturing skills head-on. Beset with a weak supplier base, U.S. federal R&D support has allowed for the renewal of historical strength in early-stage R&D, but has not led to a broad revival for domestic manufacturing. Distinct national strengths in different types of industrial activities remained, even in new economic sectors in which the absence of global incumbents offered firms myriad options for specialization.

Although firms have engaged in industrial upgrading in renewable energy sectors—in the sense that they developed skills and capabilities to participate in global processes of technology development—they have done so through the incremental improvement of existing strengths and by repurposing existing resources and institutions for new applications. Perhaps counterintuitively, the findings of this study suggest that it were new possibilities for collaboration in the global economy that allowed firms to craft such distinct paths for participation in wind and solar industries. Opportunities to access complementary skills in global partners relieved firms of having to master all the activities required to develop and commercialize new technologies. This opened the way for firms to renew and augment existing industrial practices, narrow they may be, instead of abandoning them in favor of global best practices and business models of foreign competitors. Consequently, national diversity in the structures of production and firms' industrial capabilities may not just result from the ability of the state to protect the domestic economy from the economic pressures of globalization or sticky institutional legacies. Rather, my research suggests that national diversity can also proceed from aggregate firm choices to compete through the augmentation of existing industrial strengths, actively renewing and repurposing existing institutions and resources in the process.

The flip side of the embeddedness of industrial capabilities in existing industrial legacies, institutions, and practices, however, may be that different economies are not equally suitable to all types of industrial activities. If specializations of firms have roots in past practices and sectoral intervention can only incrementally change how firms take advantage of opportunities in new industries, governments cannot easily encourage firms to match the skills of foreign competitors. Even if governments were to do so, the influence of existing industrial ecosystems on future paths for industrial upgrading makes such endeavors unlikely to succeed. In Germany and the United States, manufacturers of solar panels, among others, have recently called for trade barriers to prevent import competition from Chinese competitors.[757] The framework offered in this study suggests that such measures are unlikely to lead to the establishment of innovative manufacturing capabilities in the West, if such practices indeed grow out of China's unique combination of local

[757] Bullis, Kevin. 2012. The Chinese Solar Machine. In MIT Technology Review Jan/Feb.U.S. International Trade Commission. 2012. Crystalline Silicon Photovoltaic Cells and Modules From China. Washington, DC.

ecosystems for mass production and central government science and technology policy. Trade barriers may effectively ban Chinese solar panels and wind turbines from entering Germany and the United States. They may even encourage the location of more manufacturing activities domestically. Yet absent similar industrial ecosystems, renewable energy producers in the West may not be able to replicate the engineering specializations of their Chinese competitors in the short-term.

Possibly worse may be the effects of such barriers on the collaborative processes of technology development that span geographical and organizational boundaries. If opportunities for global collaboration indeed enable firms to focus on existing strengths while relying on partners for complementary capabilities, trade barriers may undermine the very basis on which firms have been able to participate in wind and solar sectors. The protests of Germany's component suppliers and manufacturers of production equipment, which vehemently opposed European Union plans to enact anti-dumping measures against China's solar producers, may stem from the recognition that their contributions to solar technology development rely on collaboration with Chinese partners.[758] Although U.S. news outlets in 2013 gleefully reported the bankruptcy of one of China's largest solar manufacturers, Suntech, the troubles besetting the Chinese solar industry have consequences also for technology development in the United States.[759] Applied Materials, a U.S. based manufacturer of production equipment that had invested large sums in solar PV

---

[758] Florian Wessendorf, 2013. "VMDA Photovoltaik Produktionsmittel: VDMA begrüßt Einigung im Solarhandelsstreit." VDMA, July 29. http://www.vdma.org/article/-/articleview/1989046 (Accessed May 11, 2014.)

[759] Brad Plumer, 2013. "China may soon stop flooding the world with cheap solar panels." *Washington Post,* March 23. " Keith Bradsher, 2013. "Chinese Solar Panel Giant Is Tainted by Bankruptcy." *New York Times,* March 20.

research, all but shut its solar PV division after its Chinese partners ran into trouble, ending lines of research originally funded by U.S. government grants.[760]

Tensions between those who successfully find a niche in global industries and those who suffer from competition in global markets are unlikely to fade. The challenge may not be to preserve distinct national structures of production and industrial activity, but to ensure that sufficient numbers of firms can apply existing resources and industrial capabilities to opportunities in global industries. Governments may be best advised to craft policies that allow for the type of repurposing and firm experimentation I have described in the empirical chapters, without shutting access to global partners in the hope that new activities will locate domestically.

3. Industrial Legacies and Economic Development

In developing economies with local rich ecosystems for manufacturing, the framework presented in this study bodes well for industrial upgrading. Chinese wind and solar producers have been able to use existing skills in mass manufacturing to develop advanced engineering capabilities in commercialization and mass production. These capabilities have attracted foreign innovators to China, they have afforded Chinese firms cost advantages grounded in knowledge, not factor prices, and, ultimately, have allowed Chinese wind and solar producers to contribute core skills to global processes of technology development. At a time when nascent wind and solar firms in advanced industrialized economies were struggling with scale-up and commercialization of new

[760] Shara Tibken, 2012. "Applied Materials Trims Solar Business." *Wall Street Journal*, May 10. Michael Kanellos, 2010. "Applied Materials Kills its SunFab Solar Business." *Greentech Media*, July 21. http://www.greentechmedia.com/articles/read/applied-materials-kills-its-sunfab-solar-business (Accessed May 11, 2014).

technologies, manufacturing capabilities offered Chinese firms an entry into two high-technology sectors with growing global markets. Chinese producers were able to do so without having to emulate the capabilities of firms in advanced economies, nor did they have to compete head-on with incumbents firms that offered similar strengths.

Although this study has restricted its focus to wind and solar industries, a growing body of research suggests that Chinese firms have been able to acquire knowledge-intensive manufacturing capabilities in other industries. Brandt and Thun find that in automobile and machine tool sectors, Chinese firms' engineering capabilities have allowed them to create products particularly suited for China's "middle market" in terms of cost and functionality.[761] Although these firms are not yet able to outcompete global incumbents for high end products, the changes to product designs to reduce cost and optimize functionality are not entirely different from the findings presented here, even if improvements in design and manufacturing process target mid-tier markets. Brandt and Thun argue that the ability of Chinese machine tool and automotive suppliers to build such capabilities is an unintended consequence of the sequencing of China's economic reforms, which first focused on nurturing domestic manufacturing capabilities before allowing foreign direct investment and trade liberalization.[762]

Breznitz and Murphree, in a study of electronics and semiconductor firms in China, also find engineering capabilities in manufacturing that allow local firms to improve and reengineer existing products.[763] Similar to the dynamic I have described in wind and solar industries, electronics and semiconductor manufacturers were able to build such

[761] Brandt and Thun 2010.
[762] Brandt and Thun 2010, 1571.
[763] Breznitz and Murphree 2011.

capabilities with the help of local governments, which, due to limited resources, favored investments in the improvement of existing technologies over high-risk technology ventures. That Chinese firms in these sectors conduct what Breznitz and Murphree call "secondary innovation" may have to do with the existence of global incumbents in electronics and semiconductor industries, which existed long before Chinese entrants. If the theory presented in this study holds, however, such innovation may also be grounded in the continued support of local governments for mass production and the ability to access technology in global supply chains, which permitted Chinese firms to upgrade by building on existing manufacturing skills. It is not at all certain, then, that such innovation is indeed secondary to early-stage R&D; it may well turn out to be an integral component on the trajectory from lab to market.

By comparing China to two advanced industrialized economies, this study has offered an explanation for China's role in global processes of technology development in wind and solar industries. Comparing the contributions of German and American firms has allowed me to identify the role of China's renewable energy firms in collaborative processes of networked innovation. By design, my research cannot offer a systematic comparison of how Chinese capabilities in innovative manufacturing stack up to against those of other developing economies. It is possible that China—with its large domestic market, its extensive support for manufacturing, and its ability to bring partners for collaboration within arm's reach of local firms through the attraction of foreign direct investment—may be uniquely equipped to establish engineering capabilities in manufacturing. But can such upgrading through the repurposing of industrial legacies be replicated in other contexts?

One possibility might be that variations in the existing manufacturing activities of domestic firms affect the specialization of producers throughout the process of upgrading. Chapter 3 has described how wind and solar suppliers have carried Germany's industrial legacy of customization and small-batch production into new economic sectors. Differences in local industrial capabilities, public resources, and institutional support should affect upgrading trajectories in developing economies as well.

In Malaysia, the combination of flexible labor policy and state investments in training institutions have attracted multinational and domestic semiconductor firms that have specialized on production in highly-volatile markets requiring rapid changes in production volumes. Samel, in a study of semiconductor firms in Penang, finds that those firms that did take advantage of opportunities in global supply chains by upgrading to knowledge-intensive activities did so by building on existing strengths in managing volatility among local producers.[764] Producers of technology-intensive test equipment required to optimize flexible production processes built on local expertise in rapid scale-up and scale-down of production. Although manufacturers specialized on managing volatility were early collaborators and customers of such equipment, these products ultimately allowed producers to sell into more stable global industrial markets.[765] The local government hoped to encourage local firms to develop skills in chip design and early-stage R&D, yet Samel's findings suggest that firms built on existing strengths to respond to niche markets instead.

Another scenario, and one that possibly applies to a far larger number of developing economies, may be that few industrial capabilities exist locally, or that such capabilities are

[764] Samel 2013.
[765] Samel 2013, 71.

concentrated in a few sectors shielded from the broader economy. My research suggests that in such cases the establishment of knowledge-intensive capabilities within manufacturing should be significantly more difficult, as industrial policy, at its best, can only mobilize firms to incrementally improve on existing skills. However, the framework presented in this study implies that firms no longer need to pass through mass production to participate in innovative activities in global sectors, as manufacturing capabilities can be accessed through external collaborators in global supply chains.

In Vietnam, for instance, the state has spent much of its resources on the state-owned sector, which has focussed largely on extractive industries, has provided little revenue or skill upgrading, and has been shielded from the broader economy. In spite of these preferences on part of the state, Chirot et al. identify a growing number of private sector firms in software and services such as e-commerce, which have been able to participate in global supply chains through higher-value activities without capabilities in physical manufacturing.[766] These firms, small in numbers they may be, have utilized resources and policies aimed at the state-owned sector—including infrastructure investments and broader market-oriented reforms—relied on investment from overseas Vietnamese, and have worked with global partners to move into new industries.

India's strength in software and services without accompanying capabilities in mass production may represent another case of upgrading without production. With half of the population employed in agriculture and a small manufacturing sector that has historically struggled to compete despite low labor cost, Indian firms have built on strengths in elite education to enter global supply chains. Sixty percent of India's GDP stem from firms in

[766] Chirot et al. 2012.

services and software today.[767] Possibly as a consequence of weak domestic manufacturing capabilities, Suzlon, a global wind turbine manufacturer headquartered in Pune, entered the wind industry not through capabilities in production, but through aggressive foreign acquisitions funded by its founder, a local textile magnate. Established in 1995, Suzlon had purchased R&D subsidiaries in Germany and the Netherlands as well as European gearbox, generator, and blade manufacturers by 2007.[768] Although the absence of domestic legacies in mass production likely precludes upgrading trajectories akin to China's, the fragmentation of production in global supply chains has opened opportunities to participate in innovation through collaboration and learning also for firms unable to draw on local manufacturing strengths.

With its focus on wind and solar sectors in China, Germany, and the United States, this study can only be one contribution to a broader research effort to understand the possibilities for industrial upgrading under conditions of fragmented production. The findings presented here suggest that options for collaboration in global supply chains have opened new opportunities for industrial upgrading through niche capabilities: in contributing to global processes of technology development, firm no longer emulate technological leaders in advanced economies, but draw on strengths in local industrial ecosystems and repurpose resources and institutions provided for the broader economy. In this context, sectoral intervention can mobilize firms to enter new sectors, but it does not fully determine which firms respond to opportunities in global supply chains and how. Understanding how variation in industrial capabilities affects upgrading outcomes across

[767] Iyer and Vietor 2014, 8-13.
[768] Lewis 2007.

developing economies is an important next step to determining whether new opportunities for industrial upgrading are uniquely suitable to China, or whether changes in the global system of production have opened broader avenues for development and industrialization.

Appendix: Qualitative Data

The data used in this study come from 224 interviews conducted between May 2008 and June 2013, as well as from official and statistical sources, company press releases, and industry reports. Chinese local government yearbooks and other archival records provided an important source on government resources for manufacturing, and served to cross-check interview data. Interviews were conducted with CEOs and CTOs of wind turbine and solar PV manufacturers operating in China, Germany, and the United States, as well as their suppliers. In addition, I interviewed representatives from wind and solar industry associations, both at the national and subnational level, in each of these locations.

In China, I met with civil servants at national and provincial-level developmental agencies (NDRC and DRC), executives at local developmental zones with a sizable presence of renewable energy firms, chambers of commerce representing foreign wind and solar firms operating in China, and academics at government research institutes working on renewable energy technologies and wind and solar industry development. A final group of interviews was conducted with state-owned banks, venture capital funds, and private investment firms with stakes in China's renewable energy industries. In Germany, I interviewed government representatives in federal and *Länder* ministries, officials working in funding agencies dispensing federal research funds for collaborative research projects, and government officials in charge of regional economic development initiatives. A second group of interview subjects included representatives of lending institutions, including local credit unions and state-owned economic development banks. Community colleges and other training institutions are included under this category. In the United States, I complemented industry research with interviews at public utility commissions, regional development organizations, national laboratories, and non-governmental organizations in support of renewable energy development in the United States. Through my participation in the MIT study on Production in the Innovation Economy, I had access to an additional database of 264 small U.S. manufacturers across various industrial sectors.

For both wind and solar sectors, I compiled a list of companies from industry publications and official records. In each locations, I sent interview requests to the 15 largest wind and solar manufacturers, as well as to suppliers of key components and production equipment. With some exceptions, company executives agreed to be interviewed on the condition of confidentiality. In some cases, I was able to conduct multiple interviews within the same firm, meeting with CEOs and heads of technical departments. When companies had close ties with suppliers and other firms in the process of bringing new products to market, I supplemented my list and scheduled additional interviews with their partners to better understand each firm's individual contributions to product development and innovation. For a number of companies operating globally, I conducted separate interviews in each of these locations. While these subsequent interview subjects were picked according to their relationship to companies I had already visited, initial interview requests for manufacturers and suppliers were made at random based on lists compiled from industry publications.

To keep company interviews consistent while also allowing respondents to address unique characteristics of their firm's manufacturing and product development process, I employed a semi-structured interview technique. The core of each interview consisted of a series of questions about the product development process for two products the firm had commercialized within the past five years. After asking interviewees to walk us through the process by which the firms had brought each idea from the R&D stage to large-scale manufacturing, I followed up with specific questions about workforce skills and technical capabilities, partnerships with suppliers and other firms, sources of capital and financing, and, finally, reasons for choosing particular production locations. Interviews were transcribed and indexed, although the complex and qualitative nature of the responses did not allow us to go beyond grouping firm experiences in broad themes. All interview subjects were promised complete confidentiality, so identifying characteristics have been removed in the footnotes. Where such information does not reveal the identify or company of the interview subject, job title and the broad nature of the firm are indicated.

In total, I conducted 224 interviews, including 118 interviews in 90 wind and solar manufacturers and their suppliers. 107 interviews were conducted in China. For complete interview counts, see Tables 1 and 2 below.

Table 1: Interview Counts, China, Germany, and the United States

	# of Interviews	# of firms interviewed
Wind turbine manufacturers	29	22
Wind turbine component suppliers	22	20
Solar PV manufacturers	35	29
Solar PV component suppliers	32	19
Industry associations	20	n/a
Government interviews	49	n/a
Banks, VCs, investment firms	37	n/a
Total	224	90

Table 1: Interview Counts, China Only

	# of Interviews	# of firms interviewed
Wind turbine manufacturers	19	12
Wind turbine component suppliers	12	11
Solar PV manufacturers	14	12
Solar PV component suppliers	19	7
Industry associations	6	n/a
Government interviews	23	n/a
Banks, VCs, investment firms	14	n/a
Total	107	42

References

Abernathy, William J, and Kim B. Clark. 1985. Innovation: Mapping the winds of creative destruction. In *Research Policy* 14 (1): 3-22.

Abernathy, William J, and James M Utterback. 1978. Patterns of Industrial Innovation. In *Technology Review* 80.

Ackermann, Thomas, and Lennart Söder. 2002. An overview of wind energy-status 2002. In *Renewable and Sustainable Energy Reviews* 6 (1–2): 67-127.

Advocate General Jacobs. 2000. Opionion of Advocate General Jacobs. In *PreussenElektra v Schleswag AG* European Court of Justice (Case C-379-98).

Ahrens, Nathaniel. 2013. China's Competitiveness: Myth, Reality, and Lessons for the United States and Japan. Case Study: Suntech. Washington DC: Center for Strategic and International Studies.

Akamatsu, Kaname. 1962. A historical pattern of economic growth in developing countries. In *The Developing Economies* 1: 3-25.

Akkermans, Dirk, Carolina Castaldi, and Bart Los. 2009. Do 'liberal market economies' really innovate more radically than 'coordinated market economies'?: Hall and Soskice reconsidered. In *Research Policy* 38 (1): 181-91.

American Energy & Manufacturing Partnership. 2013. Driving Regional Transformation. Washington, DC: Council on Competitiveness.

Amsden, Alice H. 1989. *Asia's Next Giant: South Korea and Late Industrialization*. Oxford: Oxford University Press.

———. 2001. *The rise of "the rest": challenges to the west from late-industrializing countries*. Oxford: Oxford University Press.

Antràs, Pol. 2003. Incomplete contracts and the product cycle. In *National Bureau of Economic Research* Working Paper 9945.

Arbeitsgemeinschaft Windenergie-Zulieferindustrie. 2012. Komponenten, Systeme und Fertigungtechnik für die Windindustrie. Frankfurt: VDMA.

Archibugi, Daniele, Jeremy Howells, and Jonathan Michie. 1999. Innovation systems in a global economy. In *Technology Analysis & Strategic Management* 11 (4): 527-39.

Autor, David H., David Dorn, and Gordon H. Hanson. 2012. The China Syndrome: Local Labor Market Effects of Import Competition in the United States. In *National Bureau of Economic Research Working Paper Series* No. 18054.

AWEA Manufacturing Working Group. 2011. Demand-Side Policies Will Fuel Growth in Wind Power Manufacturing Sector. Washington DC: AWEA.

Bailey, Sheila G., Ryne Raffaelle, and Keith Emery. 2002. Space and terrestrial photovoltaics: synergy and diversity. In *Progress in Photovoltaics: Research and Applications* 10 (6): 399-406.

Baker, Joseph. 2010. Spurring Development & Building a U.S. Wind Power Supply Chain Industry. Paper presented at the Wind Power Manufacturing & Supply Chain Summit, Chicago, IL.

Baldwin, Carliss, and Kim Clark. 2000. *Design Rules. The Power of Modularity.* Cambridge, MA: MIT Press.

Baoding Year Book [保定年检]. 1999. Beijing: People's Press [人民出版社].

Baoding Year Book [保定年检]. 2004/2005. Beijing: Gazetteer Press [方志出版社].

Barradale, Merrill Jones. 2010. Impact of public policy uncertainty on renewable energy investment: Wind power and the production tax credit. In *Energy Policy* 38 (12): 7698-709.

Bartlett, John E, Robert M Margolis, and Charles E Jennings. 2009. The Effects of the Financial Crisis on Photovoltaics: An Analysis of Changes in Market Forecasts from 2008 to 2009. Golden CO: National Renewable Energy Laboratory.

Bechberger, Mischa. 2000. Das Erneuerbare-Energien-Gesetz (EEG): Eine Analyse des Politikformulierungsprozesses. In *FFU-report 00-06.* Berlin: Forschungsstelle für Umweltpolitik, Freie Universität Berlin.

———. 2006. Das Erneuerbare-Energien-Gesetz (EEG): Eine Analyse des Politikformulierungsprozesses. In *FFU-report 00-06.* Berlin: Forschungsstelle für Umweltpolitik, Freie Universität Berlin.

Bechberger, Mischa, and Danyel Reiche. 2004. Renewable energy policy in Germany: pioneering and exemplary regulations. In *Energy for Sustainable Development* 8 (1): 47-57.

Becker, Ralf M, and Thomas F Hellmann. 2003. The Genesis of Venture Capital - Lessons from the German Experience. In *CESifo Working Paper Series* (883).

Belitz, Heike, Alexander Eickelpasch, and Anna Lejpras. 2012. Volkswirtschaftliche Bedeutung der Technologie- und Innovationsförderung im Mittelstand. Berlin: Deutsches Institut für Wirtschaftsforschung.

Bereny, Justin A. 1977. *Survey of the emerging solar energy industry.* San Mateo CA: Solar Energy Information Services.

Bergek, Anna, and Staffan Jacobsson. 2003. The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries. In *Change, Transformation and Development,* edited by JohnStan Metcalfe and Uwe Cantner, 197-227. Heidelberg: Physica-Verlag HD.

Berger, Suzanne. 1996. Introduction. In *National Diversity and Global Capitalism,* edited by Suzanne Berger and Ronald Dore. Ithaca, NY: Cornell University Press.

———. 2005. *How We Compete: What Companies Around the World Are Doing to Make it in Today's Global Economy.* New York, NY: Currency Doubleday.

———. 2013. *Making in America.* Cambridge MA: MIT Press.

Bergsten, C. Fred. 2010. Correcting the Chinese Exchange Rate. In *Hearing on China's Exchange Rate Policy, Committee on Ways and Means*. Washington DC: US House of Representatives.

Bettencourt, Luis M. A., Jessika E. Trancik, and Jasleen Kaur. 2013. Determinants of the Pace of Global Innovation in Energy Technologies. In *Plos ONE* 8 (10).

Bierenbaum, Dan, Mary Margaret Frank, Michael Lenox, and Rachna Maheshwari. 2012. Winning the Green Innovation Economy: An Analysis of Worldwide Patenting. Charlottesville VA: Batten Institute at the University of Virginia.

Bird, Lori, Mark Bolinger, Troy Gagliano, Ryan Wiser, Matthew Brown, and Brian Parsons. 2005. Policies and market factors driving wind power development in the United States. In *Energy Policy* 33 (11): 1397-407.

Bolinger, Mark. 2013. Understanding Wind Turbine Price Trends in the U.S. Over the Past Decade. Berkeley, CA: Lawrence Berkeley National Laboratory.

Bolinger, Mark, Ryan Wiser, Lew Milford, Michael Stoddard, and Kevin Porter. 2001. States Emerge as Clean Energy Investors: A Review of State Support for Renewable Energy. In *The Electricity Journal* 14 (9): 82-95.

Bosch, Gerhard. 2011. The German labour market after the financial crisis: Miracle or just a good policy mix? In *Work Inequalities in the Crisis: Evidence from Europe*, edited by Daniel Vaughan-Whitehead. Cheltenham: Edward Elgar Publishing.

Boskin, Michael J., and Lawrence J. Lau. 1992. Capital, Technology, and Economic Growth. In *Technology and the Wealth of Nations*, edited by Nathan Rosenberg, Ralph Landau and David C. Mowery. Stanford, CA: Stanford University Press.

Böttcher, Matthias. 2009. Global and local networks in the Solar Energy Industry – The case of the San Francisco Bay Area. Irvine, CA: University of California, Irvine.

Bouncken, Ricarda B. 2004. Kooperationen von KMU in jungen Branchen: Empirische Ergebnisse im Bereich regenerativer Energien. In *Kooperationen von kleinen und mittleren Unternehmen in Europa*, edited by Jörn-Axel Meyer. Lohmar: EUL Verlag.

Brandhorst, Henry W. Jr. 1984. Photovoltaics - The Endless Spring. NASA Technical Memorandum 83684. Paper presented at the Seventeenth Photovoltaic Specialist Conference, May 1-4, Kissimmee, Florida.

Brandt, Loren, and Eric Thun. 2010. The Fight for the Middle: Upgrading, Competition, and Industrial Development in China. In *World Development* 38 (11): 1555-74.

Braun, Boris. 2001. Regionale Innovationsnetzwekre in der mittelständischen Maschinenbauindustrie Japans und Deutschlands. In *Regionale Innovationsnetzwerke im internationalen Vergleich*, edited by Reinhold Grotz and Ludwig Schätzl. Münster: LIT Verlag.

Breznitz, Dan. 2007. *Innovation and the state: Political choice and strategies for growth in Israel, Taiwan, and Ireland*: Yale Univ Pr.

Breznitz, Dan, and Michael Murphree. 2011. *Run of the Red Queen: Government, Innovation, Globalization and Economic Growth in China*. New Haven CT: Yale University Press.

Brown, Phillip. 2011. Solar Projects: DOE Section 1705 Loan Guarantees. Washington DC: Congressional Research Service.

Bruns, Elke, Dörte Ohlhorst, Bernd Wenzel, and Johann Köppel. 2011. *Renewable Energies in Germany's Electricity Market: A Biography of the Innovation Process*. Heidelberg: Springer.

Bullis, Kevin. 2012. The Chinese Solar Machine. In *MIT Technology Review* Jan/Feb.

Bundeminister für Forschung und Technologie der Bundesrepublik Deutschland. 1977. *Programm Energieforschung und Energietechnologien 1977-1980*. Bonn: Bundesministerium für Forschung und Technologie, Referat Presse und Öffentlichkeitsarbeit.

Bundesministerium für Wirtschaft und Arbeit. 2005. Innovation und neue Energietechnologien - Das 5. Energieforschungsprogramm der Bundesregierung. Berlin.

Bundesverband Windenergie. 2012. Bundesverband Windenergie: Eine starke Stimme für den Wind.

Butler, Lucy, and Karsten Neuhoff. 2008. Comparison of feed-in tariff, quota and auction mechanisms to support wind power development. In *Renewable Energy* 33 (8): 1854-67.

Campbell, Richard J. 2011. China and the United States - A Comparison of Green Energy Programs and Policies. Washington DC: Congressional Research Service.

Campoccia, A., L. Dusonchet, E. Telaretti, and G. Zizzo. 2009. Comparative analysis of different supporting measures for the production of electrical energy by solar PV and Wind systems: Four representative European cases. In *Solar Energy* 83 (3): 287-97.

Camuffo, Arnaldo. 2004. 'Turning Out a World Car': Globalization, Outsourcing, and Modularity in the Auto Industry. In *Korean Journal of Political Economy* 2: 183-224.

Cao, Cong. 2004. Zhongguancun and China's High-Tech Parks in Transition: "Growing Pains" or "Premature Senility"? In *Asian Survey* 44 (5): 647-68.

Cao, Cong, Richard P Suttmeier, and Denis Fred Simon. 2006. China's 15-year science and technology plan. In *Physics Today* 59 (12): 38-43.

Cao, Jing, and Felix Groba. 2013. Chinese Renewable Energy Technology Exports: The Role of Policy, Innovation and Markets. Berlin: Deutsches Institut für Wirtschaftsforschung.

Carfield, Monte Jr. 1977. The Federal Wind Energy Program. Report to Robert W. Fri, Acting Administrator, Energy Research and Development Administration. Washington DC: Government Accountability Office.

Carlsson, Bo, Staffan Jacobsson, Magnus Holmén, and Annika Rickne. 2002. Innovation systems: analytical and methodological issues. In *Research policy* 31 (2): 233-45.

Carlsson, Bo, and Rikard Stankiewicz. 1991. On the nature, function and composition of technological systems. In *Journal of evolutionary economics* 1 (2): 93-118.

Casper, Steven, Mark Lehrer, and David Soskice. 2009. Can High-technology Industries Prosper in Germany? Institutional Frameworks and the Evolution of the German Software and Biotechnology Industries. In *Debating Varieties of Capitalism*, edited by Bob Hancké. Oxford: Oxford University Press.

Cetorelli, Nicola, and Philip E. Strahan. 2006. Finance as a Barrier to Entry: Bank Competition and Industry Structure in Local U.S. Markets. In *The Journal of Finance* 61 (1): 437-61.

Chandler, Alfred D. 1977. *The Visible Hand: The Managerial Revolution in American Business*. Cambridge, MA: Harvard Belknap.

Chandler, Alfred D, and Takashi Hikino. 1997. The Large Industrial Enterprise and the Dynamics of Modern Growth. In *Big Business and the Wealth of Nations*, edited by Alfred D Chandler, Franco Amatori and Takashi Hikino. Cambrige Cambridge University Press.

Changzhou Yearbook [常州年检]. 1998. Changzhou: Changzhou Gazetteer Editorial Committee [常州市地方志编纂委员会].

Changzhou Yearbook [常州年检]. 2004. Changzhou: Changzhou Gazetteer Editorial Committee [常州市地方志编纂委员会].

Changzhou Yearbook [常州年检]. 2005. Changzhou: Changzhou Gazetteer Editorial Committee [常州市地方志编纂委员会].

Cheng, Fangfang, Frank van Oort, Stan Geertman, and Pieter Hooimeijer. 2013. Science Parks and the Co-location of High-tech Small- and Medium-sized Firms in China's Shenzhen. In *Urban Studies*.

Cheng, Tun-jen. 1990. Political Regimes and Development Strategies: South Korea and Taiwan. In *Maufacturing Miracles*, edited by Gary Gereffi and Donald L Wyman. Princeton, NJ: Princeton University Press.

———. 1993. Guarding the Commanding Heights: The State as Banker in Taiwan. In *The Politics of Finance in Developing Countries*, edited by Stephen Haggard, Chung H Lee and Sylvia Maxfield. Ithaca, NY: Cornell University Press.

China Ming Yang Wind Power Group Limited. 2011. Annual Report 2010, Form 20-F.

China Statistical Yearbook. 2007. Beijing: China Statistics Press.

Chirot, Laura, Vu Thanh Tu Anh, and Edward S. Steinfeld. 2012. Private Sector Development: An Alternative Target for Industrial Policy in Vietnam. Cambridge, MA: Massachusetts Institute of Technology.

Chung, Chi-Nien, and Ishtiaq P Mahmood. 2010. Business Groups in Taiwan. In *THe Oxford Handbook of Business Groups*, edited by Asli M Coplan, Takashi Hikino and James R Lincoln. Oxford: Oxford University Press.

Colatat, Phech, Georgeta Vidica, and Richard K Lester. 2009a. Innovation Systems in the Solar Photovoltaic Industry: The Role of Public Research Institutions. In *IPC Working Paper Series*. Cambridge MA: MIT Industrial Performance Center.

Colatat, Phech, Georgeta Vidican, and Richard K Lester. 2009b. Innovation Systems in the Solar Photovoltaic Industry: The Role of Public Research Institutions. In *IPC Working Paper Series*. Cambridge MA: MIT Industrial Performance Center.

Couture, Toby, and Yves Gagnon. 2010. An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. In *Energy Policy* 38 (2): 955-65.

Crane, R.A., P.J. Verlinden, and R.M. Swanson. 1996. Building a Cost-Effective, Fabrication Facility for Silicon Solar Cell R&D and Production. In *25th PVSC*. Washington DC.

CRESP. 2005. National Action Plan for China's Wind Power Industry Development [中国风电产业化发展国家行动方案]. Beijing: China Renewable Energy Scale-Up Programme.

Culpepper, Pepper D. 1999. Still a Model for the Industrialized Countries? In *The German Skills Machine: Sustaining Comparative Advantage in a Global Economy*, edited by Pepper D Culpepper and David Finegold. New York: Berghahn.

Culpepper, Pepper D. . 2001. Employers, Public Policy, and the Politics of Decentralizd Cooperation in Germany and France. In *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, edited by Peter A. Hall and David Soskice. Oxford: Oxford University Press.

Cumings, Bruce. 1984. The origins and development of the Northeast Asian political economy: industrial sectors, product cycles, and political consequences. In *International Organization* 38 (01): 1-40.

Dagger, Steffen B. . 2009. *Energiepolitik & Lobbying: Die Novelle des Erneuerbare-Energien Gesetzes*. Stuttgart: ibidem-Verlag.

Dalian Yearbook [大连年检]. 2007. Dalian: Dalian Yearbook Publishing Office [大连年鉴编辅部].

David, Andrew S. 2009. Wind Turbines: Industry & Trade Summary. Washington DC: United States International Trade Commission.

Davis, Gerald F. 2009. *Managed by the Markets: How Finance Reshaped America*. Oxford: Oxford University Press.

de la Tour, Arnaud, Matthieu Glachant, and Yann Ménière. 2011. Innovation and international technology transfer: The case of the Chinese photovoltaic industry. In *Energy Policy* 39 (2): 761-70.

De Soto, Hernando. 2000. *The Mystery of Capital: Why Capitalism Triumphs in the West and Fails Everywhere Else*. New York, NY: Basic Books.

de Vries, Eize. 2011. Bard turbine know-how boosts project potential In *Windpower Monthly* (July).

———. 2013. Close up - own foundries give strategic edge. In *Windpower Monthly* March.

de Vries, Sybe Alexander. 2006. *Tensions Within the Internal Market: The Functioning of the Internal Market And the Development of Horizontal And Flanking Policies.* Groningen: Europa Law Publishing.

del Río, Pablo, and Pere Mir-Artigues. 2012. Support for solar PV deployment in Spain: Some policy lessons. In *Renewable and Sustainable Energy Reviews* 16 (8): 5557-66.

Deudney, Daniel, and Christopher Flavin. 1983. *Renewable Energy: The Power to Choose.* New York NY: W.W. Norton & Company.

Deutch, John, and Edward S Steinfeld. 2013. A Duel in the Sun: The Solar Photovoltaic Technology Conflict between China and the United States. In *Report for the MIT Future of Solar Energy Study.* Cambridge MA: MIT.

Deutscher Bundestag. 1990a. Entwurf eines Gesetzes über die Einspeisung von Strom aus erneuerbaren Energien in das öffentliche Netz. 11. Wahlperiode (Drucksache 11/7971, September 25).

———. 1990b. Gesetz über die Einspeisung von Strom aus erneuerbaren Energien in das öffentliche Netz (Stromeinspeisungsgesetz). In *754-9,* 2622-34: Bundesgesetzblatt I.

———. 1994. Gesetz zur Sicherung des Einsatzes von Steinkohle in der Verstromung und zur Änderung des Atomgesetzes und des Stromeinspeisungsgesetzes. In *754-9,* 1618: Bundesgesetzblatt I.

———. 1998. Gesetz zur Neuregelung des Energiewirtschaftsrechts. In *Bundesgesetzblatt I.*: 730-37.

———. 1999. Entwurf eines Gesetzes zur Förderung der Stromerzeugung aus erneuerbaren Energien (Erneuerbare-Energien-Gesetz – EEG) sowie zur Änderung des Mineralölsteuergesetzes. 11. Wahlperiode (Drucksache 14/2341, December 13).

———. 2000a. Gesetz zum Vorrang Erneuerbarer Energien - Erneuerbare-Energien-Gesetz. In *Bundesgesetzblatt I.*: 305-09.

———. 2000b. Gesetz zum Vorrang Erneuerbarer Energien (Erneuerbares-Energien-Gesetz). 205: Bundesgesetzblatt I.

———. 2000c. Plenarprotokoll. 14. Wahlperiode, 91. Sitzung (Februar 25).

Deutscher Industrie- und Handelskammertag. 2012. Ausbildung 2012: Ergebnisse einer DIHK-Online-Unternehmensbefragung. Berlin.

Dumas, Larry N., and Alex Shumka. 1982. Photovoltaic Module Reliability Improvement through Application Testing and Failure Analysis. In *IEEE Transactions on Reliability* R-31 (3): 228-34.

Durstewitz, Michael, Martin Hoppe-Kilpper, and Catarina von Schwerin. 2003. Nutzung von Windkraft durch die Landwirtschaft - Schlussbericht Forschungsprojekt 01HS053 im Auftrag der Bundesanstalt für Landwirtschaft und Ernährung. Kassel: Institut für Solare Energieversorgungstechnik e.V. (ISET).

Ebner, Christian, Lukas Graf, and Rita Nikolai. 2013. New Institutional Linkages Between Dual Vocational Training and Higher Education: A Comparative Analysis of Germany, Austria and Switzerland. In *Integration and Inequality in Educational Institutions*, edited by Michael Windzio, 281-98: Springer Netherlands.

Eckl, Verena, and Dirk Engel. 2009. Benefiting from publicly funded pre-competitive research: differences between insiders and outsiders. In *Ruhr economic papers*. Essen: Rheinisch-Westfälisches Institut für Wirtschaftsforschung.

Edin, Maria. 2003. State Capacity and Local Agent Control in China: CCP Cadre Management from a Township Perspective. In *The China Quarterly* 173: 35-52.

Edinger, Raphael. 1999. *Distributed Electricity Generation with Renewable Resources: Assessing the Economics of Photovoltaic Technologies in Vertically Integrated and in Restructured Energy Markets*. Marburg: Tectum.

Edquist, Charles. 1997. Introduction. In *Systems of innovation: technologies, institutions, and organizations*, edited by Charles Edquist. London: Routledge.

———. 2005. Systems of Innovation: Perspectives and Challenges. In *The Oxford Handbook of Innovation*, edited by Jan Fagerberg, David C. Mowery and Richard R. Nelson. Oxford: Oxford University Press.

Eichhorst, Werner, and Paul Marx. 2009. Kurzarbeit — Sinnvoller Konjunkturpuffer oder verlängertes Arbeitslosengeld? In *Wirtschaftsdienst* 89 (5): 322-28.

Ernst, Dieter. 2011a. China's Innovation Policy is a Wake-Up Call for America. In *Asia Pacific Issues* 100: 1-12.

———. 2011b. *Indigenous Innovation and Globalization: The Challenge for China Standardization Strategy*. Honolulu HI: East-West Center.

Ernst, Dieter, and Linsu Kim. 2002. Global production networks, knowledge diffusion, and local capability formation. In *Research Policy* 31 (8–9): 1417-29.

Ernst, Dieter, and Barry Naughton. 2012. Global technology sourcing and Chian's integrated circuit design industry: A conceptual framework and preliminary research findings. In *East-West Center Working Papers, Economics Series*. Honolulu, HI: East-West Center.

Ernst, Dieter, and Barry Naughton. 2008a. China's emergin industrial eocnomy: insights from the IT industry. In *China's Emergent Political Economy*, edited by Christopher A McNally. New York, NY: Routledge.

———. 2008b. China's emerging industrial economy: insights from the IT industry. In *China's Emergent Political Economy*, edited by Christopher A McNally. New York, NY: Routledge.

Estevez-Abe, Margarita, Torben Iversen, and David Soskice. 2001. Social Protection and the Formation of Skills: A Reinterpretation of the Welfare State. In *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, edited by Peter A. Hall and David Soskice. Oxford: Oxford University Press.

European Court of Justice. 2001. Judgment of the Court. In *PreussenElektra AG v Schleswag AG* Case C-379/98 (March 13).

European Photovoltaic Industry Association. 2012. Global Market Outlook for Photovoltaics until 2016. Brussels.

Evans, Peter. 1995. *Embedded Autonomy - States and Industrial Transformation.* Princeton NJ: Princeton University Press.

Ezell, Stephen J. , and Robert D. Atkinson. 2011. The Case for a National Manufacturing Strategy. Washington, DC: The Information Technology & Innovation Foundation (ITIF).

Fabrizio, Kira R. 2012. The Effect of Regulatory Uncertainty on Investment: Evidence from Renewable Energy Generation. In *Journal of Law, Economics, and Organization.*

Fagerberg, Jan, and Martin Srholec. 2008. National innovation systems, capabilities and economic development. In *Research policy* 37 (9): 1417-35.

Fischedick, Manfred, and Mischa Bechberger. 2009. Die ökologische Industriepolitik Deutschlands am Beispiel der Solar- und Windindustrie. Musterschüler oder Problemkind? In *Moderne Industriepolitik.* Berlin: Friedrich-Ebert-Stiftung.

Forschungszentrum Jülich. 1993. Programm Energieforschung und Energietechnologien - Statusreport 1993 Photovoltaik. Bonn: Bundesministerium für Forschung und Technologie.

Freeman, Christopher. 1987. *Technology policy and economic performance: lessons from Japan.* London: Pinter Publishers.

———. 1995. The 'National System of Innovation' in historical perspective. In *Cambridge Journal of Economics* 19 (1): 5-24.

Frondel, Manuel, Nolan Ritter, Nils Moore, and Christoph Schmidt. 2011. Die Kosten des Klimaschutzes am Beispiel der Strompreise für private Haushalte. In *Zeitschrift für Energiewirtschaft* 35 (3): 195-207.

Fuller, Douglas, Akintunde Akinwande, and Charles Sodini. 2003. Leading, Following or Cooked Goose? Innovation Successes and Failures in Taiwan's Electronics Industry. In *Industry and Innovation* 10 (2): 179-96.

Gabriele, Alberto. 2002. S&T policies and technical progress in China's industry. In *Review of International Political Economy* 9 (2): 333-73.

Gallagher, Kelly Sims. 2006. *China shifts gears: automakers, oil, pollution, and development.* Cambridge MA: MIT Press.

Gallagher, Kelly Sims, Arnulf Grübler, Laura Kuhl, Gregory Nemet, and Charlie Wilson. 2012. The Energy Technology Innovation System. In *Annual Review of Environment and Resources* 37 (1): 137-62.

Gallaher, Michael P, Albert N Link, and Alan O'Connor. 2012. *Public Investments in Energy Technology.* Cheltenham: Edward Elgar Publishing.

Gawel, Erik, and Christian Klassert. 2013. Wie weiter mit der Besonderen Ausgleichregelung im EEG? In *UFZ Discussion Papers* (9).

Ge, Dongsheng, and Takahiro Fujimoto. 2004. Quasi-open Product Architecture and Technological Lock-in: An Exploratory Study on the Chinese Motorcycle Industry. In *Annals of Business Administrative Science* 3 (2): 15-24.

GE Power & Water. 2012. Windenergie - Mehrwert für den Kunden durch evolutionäre Produktentwicklung. General Electric Company.

Gereffi, Gary. 2009. Development Models and Industrial Upgrading in China and Mexico. In *European Sociological Review* 25 (1): 37-51.

Gereffi, Gary, John Humphrey, and Timothy Sturgeon. 2005. The Governance of Global Value Chains. In *Review of International Political Economy* 12 (1): 78-104.

Germany Trade & Invest. 2009a. Photovoltaic Equipment in Germany. Berlin.

———. 2009b. Photovoltaic R&D in Germany. Berlin.

———. 2011a. Leading PV Manufacturers Produce in Germany. Berlin.

———. 2011b. PV Balance of System. Berlin.

———. 2012. Investment Opportunities in the Photovoltaic Industry in Germany. Berlin

Gerschenkron, Alexander. 1962. *Economic Backwardness in Historical Perspective.* Cambridge, MA: Harvard University Press.

Giesecke, Susanne. 2000. The contrasting roles of government in the development of biotechnology industry in the US and Germany. In *Research Policy* 29 (2): 205-23.

Gipe, Paul. 1995. *Wind Energy Comes of Age.* New York NY: John Wiley & Sons

Gleitz, Robert. 2006. The Case for Wind: GE Energy's Perspective. GE Energy.

Goodrich, Alan C., Douglas M. Powell, Ted L. James, Michael Woodhouse, and Tonio Buonassisi. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. In *Energy & Environmental Science* 6 (10): 2811-21.

Gordon, Kate, and Julian L Wong. 2010. Out of the Running? How Germany, Spain, and China Are Seizing the Energy Opportunity and Why the United States Risks Getting Left Behind. Washington DC: Center for American Progress.

Goudarzi, N., and W. D. Zhu. 2013. A review on the development of wind turbine generators across the world. In *International Journal of Dynamics and Control* 1 (2): 192-202.

Gourevitch, Peter, Roger Bohn, and David McKendrick. 2000. Globalization of Production: Insights from the Hard Drive Disk Industry. In *World Development* 28 (301-317).

Graf, Lukas. 2013. Duale Studiengänge als 'unerwartete' Form der institutionellen Durchlässigkeit zwischen Berufs- und Hochschulbildung in Deutschland. In *Vergleiche innerhalb von Gruppen und institutionelle Gelingensbedingungen. Vielversprechende Perspektiven für die Ungleichheitsforschung*, edited by Heike Solga, Christian Brzinsky-Fay, Lukas Graf, Cornelia Gresch and Paula Protsch. Berlin: WZB.

Grant, Robert M., and Renato Cibin. 1996. Strategy, structure and market turbulence: The international oil majors, 1970–1991. In *Scandinavian Journal of Management* 12 (2): 165-88.

Grau, Thilo, Molin Huo, and Karsten Neuhoff. 2011. Survey of Photovoltaic Industry and Policy in Germany and China. Berlin: Climate Policy Initiative.

———. 2012. Survey of photovoltaic industry and policy in Germany and China. In *Energy Policy* 51 (0): 20-37.

Green, Martin A. 2001. Crystalline Silicon Solar Cells. In *Clean Electricity from Photovoltaics*, edited by M.D. Archer and R. Hill. London: Imperial College Press.

Green, Martin A. 2005. Silicon photovoltaic modules: a brief history of the first 50 years. In *Progress in Photovoltaics: Research and Applications* 13 (5): 447-55.

Grewe, Hartmut. 2009. Die Branche der erneuerbaren Energien und ihre Lobby. In *Konrad Adenauer Stiftung - Analysen & Argumente* (December).

Grossman, Gene M, and Elhanan Helpman. 1991. Endogenous Product Cycles. In *The Economic Journal* 101.

Grune, Susann, and Sebastian Heilmann. 2012. Deutsch-chinesische Technologiekooperation. In *China Analysis* 99 (December).

Grünhagen, Marc, and Holger Berg. 2011. Modelling the antecedents of innovation-based growth intentions in entrepreneurial ventures: the role of perceived regulatory conditions in the German renweable energies and disease management industries. In *International Journal of Technology, Policy and Management* 11 (3/4): 220-49.

GTM Research. 2011. U.S. Solar Energy Trade Assessment 2011. Washington, DC: Solar Energy Industries Association.

Guan, Dabo, Glen P. Peters, Christopher L. Weber, and Klaus Hubacek. 2009. Journey to world top emitter: An analysis of the driving forces of China's recent CO2 emissions surge. In *Geophysical Research Letters* 36 (4): L04709.

Guang Dong Mingyang Wind Power Technology Co. Ltd. 2007. 1.5 MW Wind Turbine: Germany Technolgy + China Manufacturing Capacity. Zhongzhan.

Günterberg, Brigitte, and Gunter Kayser. 2004. SME's in Germany - Facts and Figures 2004. Bonn: Institut für Mittelstandsforschung.

Hager, Carol J. 1995. *Technological Democracy: Bureaucracy and Citizenry in the German Energy Debate*. Ann Arbor MI: University of Michigan Press.

Haley, Usha, and George Haley. 2013. *Subsidies to Chinese Industry: State Capitalism, Business Strategy, and Trade Policy*. Oxford: Oxford University Press.

Hall, Peter A., and David Soskice. 2001. An Introduction to Varieties of Capitalism. In *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, edited by Peter A. Hall and David Soskice. Oxford: Oxford University Press.

Harborne, Paul, and Chris Hendry. 2009. Pathways to commercial wind power in the US, Europe and Japan: The role of demonstration projects and field trials in the innovation process. In *Energy Policy* 37 (9): 3580-95.

Harwit, Eric. 1995. *China's Automobile Industry: Policies, Problems, and Prospects* New York NY: M.E. Sharpe.

Hauschildt, Jürgen, and Jörn Pulczynski. 1995. Growian: Zielbildung für bedeutende Innovationsvorhaben. In *Management von Innovationen*, edited by Klaus Brockhoff, 45-54: Gabler Verlag.

———. 1996. Rigidität oder Flexibilität der Zielbildung in Innovationsprojekten? In *Networking und Projektorientierung*, edited by Henning Balck, 199-210: Springer Berlin Heidelberg.

He, Dexin, and Pengfei Shi. 1991. Present Status and the Development of Wind Energy Utilization in China. In *The Development of New and Renewable Rouces of Energy in China [中国新能源和可再生能源]*, edited by Chinese Solar Energy Society. Beijing: China Science & Technology Press.

Heilmann, Sebastian, Lea Shih, and Andreas Hofem. 2013. National Planning and Local Technology Zones: Experimental Governance in China's Torch Programme. In *The China Quarterly* 216: 896-919.

Hellemans. 2007. Manufacturing Mayday. In *Spectrum* 44 (1): 10-13.

Henderson, Rebecca, Adam B. Jaffe, and Manuel Trajtenberg. 1998. Universities as a Source of Commercial Technology: A Detailed Analysis of University Patenting, 1965–1988. In *Review of Economics and Statistics* 80 (1): 119-27.

Henderson, Rebecca M., and Kim B. Clark. 1990. Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. In *Administrative Science Quarterly* 35 (1): 9-30.

Herrigel, Gary. 1996. *Industrial constructions: the sources of German industrial power.* Cambridge: Cambridge University Press.

Heymann, Matthias. 1995. *Die Geschichte der Windenergienutzung 1890-1990*. Frankfurt: Campus.

———. 1998. Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990. In *Technology and Culture* 39 (4): 641-70.

———. 1999. A Fight of Systems? Wind Power and Electric Power Systems In Denmark, Germany, and the USA. In *Centaurus* 41 (1-2): 112-36.

Holmes, Thomas J. 2011. The Case of the Disappearing Large-Employer Manufacturing Plants: Not Much of a Mystery After All. Minneapolis, MN: Federal Reserve Bank of Minneapolis.

Hoppe-Kilpper, Martin. "Entwicklung der Windenergietechnik in Deutschland und der Einfluss staatlicher Förderpolitik - Technikentwicklung in den 90er Jahren zwischen Markt und Forschungsförderung." Universität Kassel, 2003.

———. 2004. *Perspektiven der Windenergienutzung in Deutschland - Zukünftige Anforderungen an Forschung, Entwicklung und Markterschließung*. Bonn: Friedrich-Ebert-Stiftung.

Hu, Albert G. Z., Gary H. Jefferson, and Qian Jinchang. 2005. R&D and Technology Transfer: Firm-Level Evidence from Chinese Industry. In *Review of Economics and Statistics* 87 (4): 780-86.

Hu, Chengchun. 1991. Present Status and Policy in the Development of New and Renewable Sources of Energy in China. In *The Development of New and Renewable Rouces of Energy in China [中国新能源和可再生能源]*, edited by Chinese Solar Energy Society. Beijing: China Science & Technology Press.

Huang, Yasheng. 2002. Between two coordination failures: automotive industrial policy in China with a comparison to Korea. In *Review of International Political Economy* 9 (3): 538-73.

———. 2003. *Selling China - Foreign Direct Investment During the Reform Era*. Cambridge: Cambridge University Press.

———. 2008. *Capitalism with Chinese Characteristics: Entrepreneurship and the State*. Cambridge: Cambridge University Press.

Hustedt, Michaele. 1998. Windkraft - Made in Germany. In *Windiger Protest - Konflikte um das Zukunftspotential der Windkraft*, edited by Franz Alt, Jürgen Claus and Hermann Scheer. Bochum: Ponte Press.

Ikenberry, G. John. 1986. The irony of state strength: comparative responses to the oil shocks in the 1970s. In *International Organization* 40 (01): 105-37.

International Energy Agency. 2008. *Energy Policies of IEA Countries: The United States*. Paris: OECD.

International Renewable Energy Agency. 2012. Wind Power. In *Renewable Energy Technologies: Cost Analysis Series*. Abu Dhabi: IRENA.

Iyer, Lakshmi, and Richard H. Vietor. 2014. India 2014: The Challenges of Governance. Boston, MA: Harvard Business School.

JA Solar Holdings. 2007. 2006 Annual Report, Form 20-F.

Jacobsson, Staffan, Björn A. Andersson, and Lennart Bångens. 2002. Transforming the energy system - the evolution of the German technological system for solar cells. Gothenburg: Chalmers University of Technology

Jacobsson, Staffan, and Volkmar Lauber. 2005. Germany: From a Modest Feed-in Law to a Framework for Transition. In *Switching to Renewable Power - A Framework for the 21st Centurey*, edited by Volkmar Lauber. London: Earthscan.

———. 2006. The politics and policy of energy system transformation - explaining the German diffusion of renewable energy technology. In *Energy Policy* (34): 256-76.

Jennings, Charles E., Robert M. Margolis, and John E. Bartlett. 2008. A Historical Analysis of Investments in Solar Energy Technologies (2000-2007). Golden, CO: National Renewable Energy Laboratory.

Jin, Hehui, Yingyi Qian, and Barry Weingast. 2005. Regional decentralization and fiscal incentives: Federalism, Chinese style. In *Journal of Public Economics* 89: 1719-42.

Johnson, Chalmers A. 1982. *MITI and the Japanese miracle : the growth of industrial policy, 1925-1975.* Stanford, Calif.: Stanford University Press.

Johnson, Kristina. 2011. The U.S. Department of Energy's Perspective. In *The Future of Photovoltaics Manufacturing in the United States*, edited by Charles W. Wessner. Washington DC: The National Academies Press.

Johnstone, Nick, Ivan Haščič, and David Popp. 2010. Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. In *Environmental and Resource Economics* 45 (1): 133-55.

Kang, Junjie, Jiahai Yuan, Zhaoguang Hu, and Yan Xu. 2012. Review on wind power development and relevant policies in China during the 11th Five-Year-Plan period. In *Renewable and Sustainable Energy Reviews* 16 (4): 1907-15.

Karplus, Valerie J. 2007. Innovation in China's Energy Sector. Stanford CA: Stanford University Center for Environmental Science and Policy.

Keck, Otto. 1993. The national system for technical innovation in Germany. In *National innovation systems: A comparative analysis*, edited by Richard Nelson, 115-57. Oxford: Oxford University Press.

Kenney, Martin, and Richard L. Florida. 2004. *Locating global advantage: industry dynamics in the international economy.* Stanford, CA: Stanford University Press.

Keuper, Armin, Jens Peter Molly, and Christiane Stückemann. 1992. Windenergienutzung in der Bundesrepublik Deutschland. In *DEWI Magazin* 1: 5-25.

Kim, Linsu. 1993. National System of Innovation: Dynamics of Capability Building in Korea. In *National Innovation Systems*, edited by Richard R. Nelson. Oxford: Oxford University Press.

———. 1997. *Imitation to Innovation: The Dynamics of Korea's Technological Learning.* Boston: Harvard Business School Press.

Kim, Linsu, and Richard Nelson. 2000. Introduction. In *Technology, Learning & Innovation*, edited by Linsu Kim and Richard Nelson. Cambridge: Cambridge University Press.

Knight, Chis P. 2011. Failure to Deploy: Solar Photovoltaic Policy in the United States. In *The Staet of Innovation: The U.S. Government's Role in Technology Development*, edited by Fred Block and Matthew Keller. London: Paradigm Publishers.

Kohli, Atul. 2004. *State-directed development: political power and industrialization in the global periphery.* Cambridge: Cambridge University Press.

Kraemer, Kenneth L., Greg Linden, and Jason Dedrick. 2011. Capturing Value in Global Networks: Apple's iPad and iPhone. Irvine, CA: Personal Computing Industry Center, UC Irvine.

Kreditanstalt für Wiederaufbau. 2006. Sonderband Innovationen im Mittelstand. In *Mittelstands- und Strukturpolitik* 37 (July).

Kremzner, Mark T. 1998. Managing Urban Land in China: The Emerging Legal Framework and Its Role in Development. In *Pacific Rim Law & Policy Journal* 7 (3): 611-55.

Kroll, Henning, Marcus Conlé, and Marcus Schüller. 2008. China: Innovation System and Innovation Policy. In *New Challenges for Germany in the Innovation Competition*, edited by Fraunhofer Institute for Systems and Innovation Research, German Institute of Global and Area Studies and Georgia Tech Program in Science Technology and Innovation Policy.

Krugman, Paul. 1979. A model of innovation, technology transfer, and the world distribution of income. In *the Journal of political economy*: 253-66.

Laird, Frank, and Christoph Stefes. 2009. The diverging paths of German and United States policies for renwable energy: Sources of difference. In *Energy Policy* 37: 2619-29.

Landrum, Nancy E, and David M Boje. 2002. Kairos: Strategies Just in Time in the Asian Athletic Footwear Industry. In *Asian Post-crisis Management: Corporate and Governmental Strategies for Sustainable Competitive Advantage*, edited by Usha Haley and Frank-Jürgen Richter. London: Palgrave.

Landry, Pierre F. 2008. *Decentralized Authoritarianism in China: The Communist Party's Control of Local Elites in the Post-Mao Era* Cambridge: Cambridge University Press.

Langlois, Richard. 2002. Modularity in technology and organization. In *Journal of Economic Behavior & Organization* 49 (2002): 19-37.

Lauber, Volkmar, and Lutz Mez. 2004. Three Decades of Renewable Electricity Policies in Germany. In *Energy & Environment* 15 (4): 599-623.

———. 2006. Renewable Electricity Policy in Germany, 1974 to 2005. In *Bulletin of Science, Technology & Society* 26 (2): 105-20.

Le, Minh. 2012. U.S. Initiatives in Solar Energy Policy. In *Meeting Global Challenges: German-U.S. Innovation Policy*, edited by National Research Council. Washington DC: National Academies Press.

Lemoine, Françoise, and Deniz Ünal-Kesenci. 2004. Assembly Trade and Technology Transfer: The Case of China. In *World Development* 32 (5): 829-50.

Levinson, Marc. 2014. U.S. Manufacturing in International Perspective. Washington, DC: Congressional Research Service.

Lew, Debra J. 2000. Alternatives to coal and candles: wind power in China. In *Energy Policy* 28 (4): 271-86.

Lewis, Joanna I. 2011. Building a national wind turbine industry: experiences from China, India and South Korea. In *International Journal of Technology and Globalisation* 5 (3): 281-305.

Lewis, Joanna I., and Ryan H. Wiser. 2007. Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms. In *Energy Policy* 35 (3): 1844-57.

Lewis, Johanna I. 2007. Technology Acquisition and Innovation in the Developing World: Wind Turbine Development in China and India. In *Studies in Comparative International Development* 42 (3-4): 208-32.

———. 2012. *Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low Carbon Economy*. New York, NY: Columbia University Press.

———. 2013. *Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low Carbon Economy*. New York, NY: Columbia University Press.

Li, Hongbin, Lei Li, Binzhen Wu, and Yanyan Xiong. 2012. The End of Cheap Chinese Labor. In *The Journal of Economic Perspectives* 26 (4): 57-74.

Li, Junfeng. 2011a. China Wind Power Outlook [中国风电发展报告] . Beijing: China Environmental Science Press [中国环境科学出版社].

Li, Qingwen. 2011b. *Compilation of China Policies and Regulations on New Energy and Renewable Energy 1986-2011 [中国- 新能源和可在能源政策法规汇编]*. Beijing: Economy & Management Publishing House.

Lin, George C. S., and Fangxin Yi. 2011. Urbanization of Capital or Capitalization on Urban Land? Land Development and Local Public Finance in Urbanizing China. In *Urban Geography* 32 (1): 50-79.

Linscott, Bradford S, Joann T Dennett, and Larry H Gordon. 1981. *The Mod-2 Wind Turbine Development Project*. Wasington DC: U.S. Department of Energy: Conservation and Renewable Energy, Division of Wind Energy Systems.

Lipp, Judith. 2007. Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. In *Energy Policy* 35 (11): 5481-95.

Liu, Xiaohui, and Trevor Buck. 2007. Innovation performance and channels for international technology spillovers: Evidence from Chinese high-tech industries. In *Research Policy* 36 (3): 355-66.

Liu, Xielin, and Peng Cheng. 2011. Is China's Indigenous Innovation Strategy Compatible with Globalization? In *Policy Studies*. Honululu: East-West Center.

Liu, Xielin, and Steven White. 2001. Comparing innovation systems: a framework and application to China's transitional context. In *Research Policy* 30 (7): 1091-114.

Liu, Yingqi, and Ari Kokko. 2010. Wind power in China: Policy and development challenges. In *Energy Policy* 38 (10): 5520-29.

Liu, Yongzheng, and Jorge Martinez-Vazquez. 2013. Interjurisidictional Tax Competition in China. In *Journal of Regional Science*.

Lockström, Martin, Joachim Schadel, Norma Harrison, Roger Moser, and Manoj K. Malhotra. 2010. Antecedents to supplier integration in the automotive industry: A multiple-case study of foreign subsidiaries in China. In *Journal of Operations Management* 28 (3): 240-56.

Loferski, Joseph J. 1993. The first forty years: A brief history of the modern photovoltaic age. In *Progress in Photovoltaics: Research and Applications* 1 (1): 67-78.

Lubinski, Christina. 2011. Path Dependency and Governance in German Family Firms. In *Business History Review* 85 (04): 699-724.

Lundvall, Bengt-Åke. 2007. National innovation systems—analytical concept and development tool. In *Industry and innovation* 14 (1): 95-119.

———. 2009. Innovation as an interactive process : user-producer interaction to the national system of innovation. 10-34.

Lüthje, Boy. 2002. Electronics Contract Manufacturing: Global Production and the International Division of Labor in the Age of the Internet. In *Industry and Innovation* 9 (3): 227-47.

Lynette, Robert. 1988. Status of the U.S. wind power industry. In *Journal of Wind Engineering and Industrial Aerodynamics* 27 (1–3): 327-36.

Mair, Peter. 2001. The Green Challenge and Political Competition: How Typical is the German Experience? In *German Politics* 10 (2): 99-116.

Marigo, Nicoletta. 2007. The Chinese silicon photovoltaic industry and market: a critical review of trends and outlook. In *Progress in Photovoltaics: Research and Applications* 15 (2): 143-62.

Martinot, Eric, Ryan Wiser, and Jan Hamrin. 2005. Renewable Energy Markets and Policies in the United States. San Francisco: Center for Resource Solutions.

Maycock, PaulD. 1991. International Photovoltaic Markets, Developments and Trends. In *Tenth E.C. Photovoltaic Solar Energy Conference*, edited by A. Luque, G. Sala, W. Palz, G. Santos and P. Helm, 1396-400: Springer Netherlands.

Mayer, Colin, Koen Schoors, and Yishay Yafeh. 2005. Sources of funds and investment activities of venture capital funds: evidence from Germany, Israel, Japan and the United Kingdom. In *Journal of Corporate Finance* 11 (3): 586-608.

Mazzucato, Mariana. 2013. *The Entrepreneurial State - Debunking Public Vs. Private Sector Myths*. London: Anthem Press.

McKendrick, David, Richard F. Doner, and Stephen Haggard. 2000. *From Silicon Valley to Singapore: Location and Competitive Advantage in the Hard Disk Drive Industry*. Stanford, CA: Stanford University Press.

Meinhardt, Mike, Bruno Burger, and Alfred Engler. 2007. PV-Systemtechnik - Motor der Kostenreduktion für die photovoltaische Stromerzeugung. Paper presented at the Produktionstechnologien für die Solarenergie - Jahrestagung des ForschungsVerbunds Sonnenenergie in Kooperation mit dem Bundesverband Solarwirtschaft, September 26-27, Hannover.

Mendonça, Miguel. 2007. *Feed-in Tariffs: Accelerating the Deployment of Renewable Energy*. London: Earthscan.

Menz, Fredric C. 2005. Green electricity policies in the United States: case study. In *Energy Policy* 33 (18): 2398-410.

Mewes, Horst. 1998. A Brief History of the German Green Party. In *The German Greens*, edited by Margit Mayer and John Ely. Philadelphia PA: Temple University Press.

Mez, Lutz. 2003. Ökologische Modernisierung und Vorreiterrolle in der Energie- und Umweltpolitik? Eine vorläufige Bilanz. In *Das Rot-Grüne Projekt: Eine Bilanz der Regierung Schröder 1998-2002*, edited by Christoph Egle, Tobias Ostheim and Tobias Zohlnhöfer. Wiesbaden: Westdeutscher Verlag.

Minagawa, Tetsuya, Paul Trott, and Andreas Hoecht. 2007. Counterfeit, imitation, reverse engineering and learning: reflections from Chinese manufacturing firms. In *R&D Management* 37 (5): 455-67.

Ministry of Industry and Information Technology. 2012. Second Five Year Plan for Solar PV Industry Issued [太阳能光伏产业"十二五"发展规划印发]. Available from http://www.gov.cn/gzdt/2012-02/24/content_2075802.htm. (Accessed January 12, 2014).

Ministry of Science and Technology. 2007a. *China Science & Technology Statistics Data Book [中国科技统计数据]*. Beijing: Department of Development Planning, Minisry of Science and Technology.

———. 2007b. Industry Establish National Key Labs. In *China Science and Technology Newsletter* 481.

Minks, Karl-Heinz, Nicolai Netz, and Daniel Völk. 2011. Berufsbegleitende und duale Studienangebote in Deutschland: Status quo und Perspektiven. Hannover: Hochschul-Informations-System (HIS), Bundesinstitut für Berufsbildung.

Mitchell, C., D. Bauknecht, and P. M. Connor. 2006. Effectiveness through risk reduction: A comparison of the renewable obligation in England and Wales and the feed-in system in Germany. In *Energy Policy* 34 (3): 297-305.

Moore, Bill, and Rolf Wüstenhagen. 2004. Innovative and sustainable energy technologies: the role of venture capital. In *Business Strategy and the Environment* 13 (4): 235-45.

Moore, Glen J 1981. Solar Energy and the Reagan Adminstration. Washington DC: Congressional Research Service.

Morris, Craig. 2012. A German Solar Bubble? Look Again! In *German Energy Transition*, edited by Arne Jungjohann. Wasington DC: Heinrich Böll Stiftung.

Morton, Oliver. 2006. Solar energy: A new day dawning?: Silicon Valley sunrise. In *Nature* 443 (7107): 19-22.

Mowery, David C. 1992. The US national innovation system: origins and prospects for change. In *Research Policy* 21 (2): 125-44.

———. 1998. The changing structure of the US national innovation system: implications for international conflict and cooperation in R&D policy. In *Research Policy* 27 (6): 639-54.

Mowery, David C. , and Nathan Rosenberg. 1999. *Paths of innovation: Technological change in 20th-Century America*: Cambridge Univ Press.

Mowery, David C., Richard R. Nelson, Bhaven N. Sampat, and Arvids A. Ziedonis. 2001. The growth of patenting and licensing by U.S. universities: an assessment of the effects of the Bayh–Dole act of 1980. In *Research Policy* 30 (1): 99-119.

———. 2004. *Ivory Tower and Industrial Innovation: University-Industry Technology Transfer before and after the Bayh-Dole Act*. Stanford, CA: Stanford University Press.

Mowery, David C., and Joanne E. Oxley. 1995. Inward technology transfer and competitiveness: the role of national innovation systems. In *Cambridge Journal of Economics* 19 (1): 67-93.

Musgrove, Peter. 2010. *Wind power*. Cambridge: Cambridge University Press.

Nahm, Jonas, and Edward S. Steinfeld. 2012. Reinventing Mass Production: China's Specialization in Innovative Manufacturing. In *MIT Political Science Department Working Paper 2012-25*. Cambridge MA: Massachusetts Institute of Technology.

———. 2014. Scale-up Nation: China's Specialization in Innovative Manufacturing. In *World Development* 54 (0): 288-300.

National Energy Administration. 2011. 12th Five-Year Plan on Solar Power Development [国家能源局文件, 国能新能(2012)194号].

National Research Council. 2012. *Rising to the Challenge: U.S. Innovation Policy for the Global Economy*. Washington DC: National Academies Press.

Naughton, Barry. 1994. Chinese Institutional Innovation and Privatization from Below. In *The American Economic Review* 84 (2): 266-70.

———. 2007. *The Chinese Economy - Transitions and Growth*. Cambridge MA: MIT Press.

Nelson, Richard R. 1993. *National Innovation Systems*. Oxford: Oxford University Press.

Nemet, Gregory F. 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. In *Research Policy* 38 (5): 700-09.

Nemet, Gregory F., and Daniel M. Kammen. 2007. U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. In *Energy Policy* 35 (1): 746-55.

Neuhoff, Karsten. 2012. The German Solar Industry. In *Meeting Global Challenges: German-U.S. Innovation Policy*, edited by National Research Council. Washington DC: National Academies Press.

Nielsen, Kristian H., and Matthias Heymann. 2012. Winds of change: communication and wind power technology development in Denmark and Germany from 1973 to ca. 1985. In *Engineering Studies* 4 (1): 11-31.

Nitsch, Joachim, and Manfred Fischedick. 1999. Klimaschutz durch Nutzung erneuerbarer Energien. Bonn: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit.

NREL. 2002. National Renewable Energy Laboratory - 25 Years of Research Excellence 1977-2002. Golden CO: National Renewable Energy Laboratory.

Nussbaumer, Hartmut, Daniel Biro, Helge Haverkamp, and Karsten Bothe. 2007. Forschung für neue Technologien und ihre Wechselwirkung mit der Industrie – vom Mittelständler zum Global Player. Paper presented at the Produktionstechnologien für die Solarenergie - Jahrestagung des ForschungsVerbunds Sonnenenergie in Kooperation mit dem Bundesverband Solarwirtschaft, September 26-27, Hannover.

O'Connor, Alan, Ross J. Loomis, and Fern M. Braun. 2010. Retrospective Benefit- Cost Evaluation of DOE Investment in Photovoltaic Energy Systems. Washington, DC: U.S. Department of Energy.

OECD. 1994. *Vocational Training in Germany: Modernisation and Responsiveness*. Paris: OECD Publishing.

———. 2005. The Measurement of Scientific and Technological Activities: Guidelines for Collecting and Interpreting Innovation Data: Oslo Manual, Third Edition. Paris: OECD, Working Party of National Experts on Scientific and Technology Indicators.

———. 2008. *OECD Reviews of Innovation Policy: China*. Paris: OECD Publications.

———. 2012. *Economic Surveys: Germany 2012*. Paris: OECD Publishing.

Ohlhorst, Dörte. 2009. *Windenergie in Deutschland: Konstellationen, Dynamiken, und Regulierungspotenziale im Innovationsprozess*. Wiesbaden: VS Research.

Oi, Jean C. 1992. Fiscal Reform and the Economic Foundations of Local State Corporatism in China. In *World Politics* 45 (1): 99-126.

———. 1995. The Role of the Local State in China's Transitional Economy. In *China Quarterly* 144 Special Issue: China's Transitional Economy: 1132-49.

———. 1999. *Rural China Takes Off*. Berkeley, CA: University of California Press.

Oppermann, Karl. 2004. Das 100.000 Dächer-Solarstrom-Programm: Eine Schlussbilanz. In *KfW-Resarch Mittelstands- und Strukturpolitik* (31).

Osterman, Paul, and Andrew Weaver. 2013. Skills and Skill Gaps in Manufacturing. In *Production in the Innovation Economy*, edited by Rachel L. Wellhausen and Richard M. Locke. Cambridge, MA: MIT Press.

Palz, Wolfgang. 2011. The Rising Sun in a Developing World. In *Power for the World: The Emergence of Electricity from the Sun*, edited by Wolfgang Palz. Sinapore: Pan Stanford Publishing.

Papadakis, Elim. 1983. The Green Party in Contemporary West German Politics. In *The Political Quarterly* 54 (3): 302-07.

Park, Jong H. 2002. The East Asian Model of Economic Development and Developing Countries. In *Journal of Developing Societies* 18 (4): 330-53.

Perlin, John. 1999. *From Space to Earth - The Story of Solar Electricity.* Ann Arbor MI: Aatec Publications.

Peters, Theodor. 2009. Das Vensys Konzept. In *Wind Kraft Journal* 6: 18-22.

Petersik, Thomas. 2004. State Renewable Energy Requirements and Goals: Status Through 2003. Washington DC: Energy Information Administration.

Pierce, Justin R., and Peter K. Schott. 2014. The Surprisingly Swift Decline of U.S. Manufacturing Employment. Washington, DC: Federal Reserve Board.

Pinkse, Jonatan, and Daniel van den Buuse. 2012. The development and commercialization of solar PV technology in the oil industry. In *Energy Policy* 40 (0): 11-20.

Pisano, Gary P, and Willy C Shih. 2009. Restoring American Competitiveness. In *Harvard Business Review* July.

———. 2012. *Producing Prosperity: Why America Needs A Manufacturing Renaissance.* Boston, MA: Harvard Business Review Press.

Platzer, Michaela D. 2012a. U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support. Washington DC: Congressional Research Service.

———. 2012b. U.S. Wind Turbine Manufacturing: Federal Support for an Emerging Industry. Washington, DC: Congressional Research Service.

Porter, Michael E. 1986. *Competition in Global Industries.* Boston: Harvard Business School Press.

Proceedings of the United Nations Conference on New Sources of Energy: Solar Energy, Wind Power, and Geothermal Energy. Rome, 21-31 August. 1961. New York NY.

Prognos AG, Fraunhofer ISE, Institut für Energetik und Umwelt, Internationales Wirtschaftsforum Regenerative Energien, and WindGuard. 2007. Evaluierung des 4. Energieforschungsprogramms Erneuerbare Energien. Berlin.

Pulczynski, Jörn. 1991. *Interorganisationales Innovationsmanagement - Eine kritische Analayse des Forschungsprojektes GROWIAN.* Kiel: Wissenschaftsverlag Vauk.

Qi, Wu. 2013. GE and Harbin end Chinese joint-venture. In *Windpower Monthly* (July).

Qin, Haiyan. 2013. Wind Power in China: Chasing a Dream that Creates Value. In *The Rise of Modern Wind Energy: Wind Power for the World,* edited by Preben Maegaard, Anna Krenz and Wolfgang Palz. Boca Raton FL: Pan Stanford Publishing.

Rappaport, Paul, Roderick Clayton, Peter Glaser, Joseph J. Loferski, Sol Pollack, Hans Queisser, Douglas Warschauer, Martin Wolf, A.F. Yanoni, William C. Bartley, Arvin Smith, and Ernst Cohn. 1972. Solar Cells: Outlook for Improved Efficiency. Washington DC: National Academy of Sciences.

Redlinger, Robert Y, Per Dannemand Anderson, and Poul Erik Morthorst. 1988. *Wind Energy in the 21st Century: Economics, Policy, Technology, and the Changing Electricity Industry.* Edited by United Nations Environment Programme. New York NY: Palgrave.

Reiche, Danyel. 2004. *Rahmenbedingungen für erneuerbare Energien in Deutschland.* Frankfur am Main: Peter Lang Verlang.

REN21. 2010. Renewables 2010 Global Status Report. Paris: REN21 Secretariat.

———. 2012. Renewables 2012 Global Status Report. Paris: REN21 Secretariat.

Reynolds, Elisabeth B. "Institutions, Public Policy and the Product Life Cycle: The Globalization of Biomanufacturing and Implications for Massachusetts." Massachusetts Institute of Technology, 2010.

Rheinisch-Westfälisches Institut für Wirtschaftsforschung, and WSF Wirtschafts- und Sozialforschung Kerpen. 2010. *Erweiterte Erfolgskontrolle beim Programm zur Förderung der IGF im Zeitraum 2005-2009.* Essen: Rheinisch-Westfälisches Institut für Wirtschaftsforschung.

Righter, Robert W. 1996. Wind energy in America: a History. Norman OK: University of Oklahoma Press.

———. 2011. *Windfall: wind energy in America today.* Norman OK: University of Oklahoma Press.

Rithmire, Meg. 2013. Land Politics and Local State Capacities: The Political Economy of Urban Change in China. In *The China Quarterly* 216: 872-95.

Rogers, Dan. 2008. Winds of change. In *Energy Engineering* (18).

Rogowsky, Robert A., and Karen Laney-Cummings. 2009. Wind Turbines: Industry & Trade Summary. Washington, DC: United States International Trade Commission.

Röhl, Klaus-Heiner. 2010. Der deutsche Wagniskapitalmarkt - Ansätze zur Finanzierung von Gründern und Mittelstand. In *IW-Positionen*: Institut der deutschen Wirtschaft.

Romer, Paul M. 1994. The origins of endogenous growth. In *The journal of economic perspectives*: 3-22.

Roth, Silvia. 2007. Vom Wissenschaftler zum Unternehmer. Paper presented at the Produktionstechnologien für die Solarenergie - Jahrestagung des ForschungsVerbunds Sonnenenergie in Kooperation mit dem Bundesverband Solarwirtschaft, September 26-27, Hannover.

Rothgang, Michael, Matthias Peistrup, and Bernhard Lageman. 2011. Industrial Collective Research Networks in Germany: Structure, Firm Involvement and Use of Results. In *Industry and Innovation* 18 (4): 393-414.

Ru, Peng, Qiang Zhi, Fang Zhang, Xiaotian Zhong, Jianqiang Li, and Jun Su. 2012a. Behind the development of technology: The transition of innovation modes in China's wind turbine manufacturing industry. In *Energy Policy* 43 (0): 58-69.

———. 2012b. Behind the development of technology: The transition of innovation modes in China's wind turbine manufacturing industry. In *Energy Policy* 43: 58-69.

Salas, V., and E. Olias. 2009. Overview of the photovoltaic technology status and perspective in Spain. In *Renewable and Sustainable Energy Reviews* 13 (5): 1049-57.

Samel, Hiram. "Essays on Volatility and the Division of Innovative Labor." Massachusetts Institute of Technology, 2013.

Sandtner, Walter, Helmut Geipel, and Helmut Lawitzka. 1997. Forschungsschwerpunkte der Bundesregierung in den Bereichen erneuerbarer Energien und rationeller Energienutzung. In *Energiepolitik - Technische Entwicklung, politische Strategien, Handlungskonzepte zu erneuerbaren Energien und zur rationellen Energienutzung*, edited by Hans Günter Brauch. Berlin: Springer.

Saxenian, AnnaLee. 1994. *Regional advantage : culture and competition in Silicon Valley and Route 128*. Cambridge MA: Harvard University Press.

Saxenian, Annalee, and Jinn-Yuh Hsu. 2001. The Silicon Valley–Hsinchu Connection: Technical Communities and Industrial Upgrading. In *Industrial and Corporate Change* 10 (4): 893-920.

Schlegel, Stephanie. "Innovationsbiographie Windenergie." TU Berlin, 2005.

Schumpeter, Joseph A. 1934. *A Theory of Economic Development*. Cambridge MA: Harvard University Press.

Schwabe, Paul, Karlynn Cory, and James Newcomb. 2009. Renewable Energy Project Financing: Impacts of the Financial Crisis and Federal Legislation. Golden CA: National Renewable Energy Laboratory.

Schwag Serger, Sylvia, and Magnus Breidne. 2007. China's Fifteen-Year Plan for Science and Technology: An Assessment. In *Asia Policy* 4: 135-64.

Seemann, Mareike. 2012. *Innovationsnetzwerke in jungen Branchen - Formation, Morphologie und unternehmenstrategische Implikationen am Beispiel der deutschen Photovoltaikbranche*. Marburg: Metropolis-Verlag.

Segal, Adam. 2003. *Digital Dragon - High-Technology Enterprises in China*. Ithaca, NY: Cornell University Press.

Segal, Adam, and Eric Thun. 2001. Thinking Globally, Acting Locally: Local Governments, Industrial Sectors, and Development in China. In *Politics and Society* 29 (4): 557-88.

Shambaugh, David. 2013. *China Goes Global: The Partial Power*. Oxford: Oxford University Press.

Shrimali, Gireesh, Steffen Jenner, Felix Groba, Gabriel Chan, and Joe Indvik. 2012. Have State Renewable Portfolio Standards Really Worked? Berlin: German Institute for Economic Research.

Siegfriedsen, Sönke. 2008. *25 Jahre aerodyn - Den Wind der Welt einfangen*: aerodyn

Simon, Denis Fred, and Cong Cao. 2009. *China's Emerging Technological Edge: Assessing the Role of High-End Talent*. Cambridge: Cambridge University Press.

Sissine, Fred. 2006. Renewable Energy: Tax Credit, Budget, and Electricity Production Issues. Washington DC: Congressional Research Service.

Smith, Beauchamp E. 1973. Smith-Putnam wind turbine experiment. Paper presented at the Wind Energy Conversion Systems, June 11-13, Washington DC.

Solar Energy Industries Association. 2014. The Case for the Solar Investment Tax Credit. Washington, DC: SEIA.

Solow, Robert M. 1956. A Contribution to the Theory of Economic Growth. In *The Quarterly Journal of Economics* 70 (1): 65-94.

Soskice, David. 1997. German technology policy, innovation, and national institutional frameworks. In *Industry and Innovation* 4 (1): 75-96.

Sozialdemokratische Partei Deutschlands, and Bündnis 90/Die Grünen. 1998. Aubruch und Erneuerung - Deutschlands Weg ins 21. Jahrhundert. Koalitionsvereinbarung zwischen der Sozialdemokratischen Partei Deutschlands und Bündnis 90/Die Grünen. Bonn.

Spada, Alfred. 2010. U.S. Metalcasting For Wind Energy. Paper presented at the Wind Power Manufacturing & Supply Chain Summit, Chicago, IL.

State Council. 1997. Notice on the adjustment of import equipment tax policy [国务院关于调整进口设备税收政策的通知]. In *December 29*. Beijing.

———. 2005. The Renewable Energy Law of the People's Republic of China [中华人民共和国可再生能源法] . Beijing.

———. 2006. Medium- and Long-term Strategic Plan for the Development of Science and Technology [国家中长期科学和技术发展规划纲要].

———. 2010. Decision of the State Council on Accelerating the Fostering and Development of Strategic Emerging Industries [国务院关于加快培育和发展战略性新兴产业的决定]. State Council Document 2010/32.

State Planning Commission, and State Science and Technology Commission. 1999. Notice on Further Promoting the Development of Renewable Energy [进一步支持可再生能源发展有关问题的通知]. Beijing.

Stefes, Christoph. 2010. Bypassing Germany's Reformstau: The Remarkable Rise of Renewable Energy. In *German Politics* 19 (2): 148-63.

Steinfeld, Edward S. 2004. China's Shallow Integration: Networked Production and the New Challenges for Late Industrialization. In *World Development* 32 (11): 1971-87.

Stokes, Leah C. 2013. The politics of renewable energy policies: The case of feed-in tariffs in Ontario, Canada. In *Energy Policy* 56 (0): 490-500.

Streeck, Wolfgang. 1989. On the Institutional Conditions of Diversified Quality Production. In *Beyond Keynesianism: The Socio-Economics of Production and Full Employment*, edited by Egon Matzner and Wolfgang Streeck. Hants: Edward Elgar.

———. 2009. *Re-Forming Capitalism*. Oxford: Oxford University Press.

Streeck, Wolfgang, and Kathleen Ann Thelen. 2005. *Beyond continuity : institutional change in advanced political economies*. Oxford ; New York: Oxford University Press.

Strobl, G. F. X., G. LaRoche, K. D. Rasch, and G. Hey. 2009. From Extraterrestrial to Terrestrial Applications. In *High-Efficient Low-Cost Photovoltaics*, edited by Vesselinka Petrova-Koch, Rudolf Hezel and Adolf Goetzberger, 7-27: Springer Berlin Heidelberg.

Strum, Harvey, and Fred Strum. 1983. Solar Energy Policy, 1952-1982. In *Environmental Review: ER* 7 (2): 135-54.

Sturgeon, Timothy. 2000. Turnkey Production Networks: The Organizational Delinking of Production from Innovation. In *New Product Development and Production Networks*, edited by Ulrich Jürgens. New York, NY: Springer.

———. 2002a. Modular Production Networks: A New American Model of Industrial Organization. In *Industrial and Corporate Change* 11 (3): 451-96.

Sturgeon, Timothy J. 2002b. Modular Production Networks: A New American Model of Industrial Organization. In *Industrial and Corporate Change* 11 (3): 451-96.

Sturgeon, Timothy, and Richard K Lester. 2004. The New Global Supply Base: New Challenges for Local Suppliers in East Asia. In *Global Production Networking and Technological Change in East Asia*, edited by Yusuf Shahid, M. Anjum Altaf and Koru Nabeshima. Oxford: Oxford University Press.

Suck, André. 2005. The politics for sustainable energy industry: renewable energy policy in the United Kingdom and Germany. In *Refining Regulatory Regimes: Utilities in Europe*, edited by David Coen and Adrienne Héritier. Cheltenham: Edward Elgar.

Sun, Sunny Li, and Xiaoming Yang. 2013. Transformative capacity and absorptive capacity - The rise of Chinese wind turbine manufacturers. In *Disruptive Innovation in Chinese and Indian Businesses - The strategic implications for local entrepreneurs and global incumbents*, edited by Peter Ping Li. New York NY: Routledge.

Sutherland, Dylan. 2005. China's Science Parks: Production Bases or a Tool for Institutional Reform? In *Asia Pacific Business Review* 11 (1): 83-104.

Suttmeier, Richard P, and Cong Cao. 1999. China Faces the New Industrial Revolution: Achievement and Uncertainty in the Search for Research and Innovation Strategies. In *Asian Perspective* 23 (3): 153-200.

Swanson, Richard M 2011. The Story of Sun Power. In *Power for the World: The Emergence of Electricity from the Sun*, edited by Wolfgang Palz. Singapore: Pan Stanford Publishing.

Tacke, Franz. 2003. *Windenergie - Die Herausforderung*. Frankfurt VDMA Verlag.

Tan, Xiaomei. *Scaling up Low-carbon Technology Deployment: Lessons from China*. Beijing, 2012.

Tan, Xiaomei, and Zhao Gang. 2009. An Emerging Revolution: Clean Technology Research, Development and Innovation in China. Washington DC: World Resources Institute.

Taylor, Margaret. 2008. Beyond technology-push and demand-pull: Lessons from California's solar policy. In *Energy Economics* 30 (6): 2829-54.

Taylor, Zachary M. 2004. Empirical evidence against varieties of capitalism's theory of technological innovation. In *International Organization* 58 (03): 601-31.

Thomas, Ronald L, and Richard M Donovan. 1978. Large Wind Turbine Generators. Paper presented at the 5th Energy Technology Conference and Exposition, Washington DC.

Thun, Eric. 2006. *Changing Lanes in China - Foreign Direct Investment, Local Governments, and Auto Sector Development.* Cambridge: Cambridge University Press.

Thun, Eric, and Loren Brandt. 2010. The Fight for the Middle: Upgrading, Competition, and Industrial Development in China. In *World Development* 38 (11): 1555-74.

Tianjin Yearbook [天津年鉴]. 2010. Tianjin: Tianjin Yearbook Publishing [天津年鉴杜编辑出版发行].

Trina Solar. 2008. Annual Report 2008 - Form 20-F.

———. 2013. Global Perspectives: Annual Report 2012.

Tushman, Michael L, and Philip Anderson. 1986. Technological Discontinuities and Organizational Environments. In *Administrative Science Quarterly* 31 (3): 439-65.

U.S. Department of Commerce. 1994. *U.S. Industrial Outlook*

U.S. International Trade Commission. 2011. China: Effects of Intellectual Property Infringement and Indigenous Innovation Policies on the U.S. Economy. In *Investigation No. 332-519, USITC Publication 4226.*

———. 2012. Crystalline Silicon Photovoltaic Cells and Modules From China. Washington, DC.

U.S. Senate. 1980. DOE's Role in the Solar Energy Industry, and Possible Anticompetitive Trends. Hearing Before the Subcommittee on Antitrust, Monopoly, and Business Rights of the Committee on the Judiciary. Washington DC: U.S. Government Printing Office.

UNIDO. 2011. World Manufacturing Production: Statistics for Quarter IV. Vienna.

Urumqi Year Book [乌鲁木齐年检]. 2000. Urumqi: Xinjiang People's Press [新疆人民出版社].

Urumqi Year Book [乌鲁木齐年检]. 2007. Urumqi: Xinjiang People's Press [新疆人民出版社].

US-China Business Council. 2013. China's Strategic Emerging Industries: Policy, Implementation, Challenges, & Recommendations. Washington DC.

van Mark, Michael, and Joachim Nick-Leptin. 2011. Renewably employed - Short and long-term impacts of the expansion of renewable energy on the German labour market. Berlin: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit.

Vasseur, Véronique, and René Kemp. 2011. The role of policy in the evolution of technological innovation systems for photovoltaic power in Germany and the

Netherlands. In *International Journal of Technology, Policy, and Management* 11 (3/4): 307-27.

VDMA Powersystems and Bundesverband Windenergie. 2009. Die Windindustrie in Deutschland: Wirtschaftsreport 2009.

Vensys. 2012. Geschichte und Gegenwart. Available from http://www.vensys.de/energy/unternehmen/historie.php. (Accessed March 15, 2012).

Vernon, Raymond. 1966. International Investment and International Trade in the Product Cycle. In *The Quarterly Journal of Economics* 80 (2): 190-207.

———. 1979. The product cycle hypothesis in a new international environment. In *Oxford bulletin of economics and statistics* 41 (4): 255-67.

Vestergaard, Jens, Lotte Brandstrup, and Robert D. III Goddard. 2004. Industry Formation and State Intervention: The Case of the Wind Turbine Industry in Denmark and the United States. Paper presented at the Academy of International Business Conference, Southeast USA Chapter, Knoxville TN.

Vitols, Sigurt. 2001. Varieties of Corporate Governance: Comparing Germany and the UK. In *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, edited by Peter A. Hall and David Soskice. Oxford: Oxford University Press.

Wade, Robert. 1990. *Governing the Market - Economic Theory and the Role of Government in East Asian Industrialization*. Princeton NJ: Princeton University Press.

———. 1996. Globalization and Its Limits: Reports of the Death of the National Economy are Greatly Exaggerated. In *National Diversity and Global Capitalism*, edited by Suzanne Berger and Ronald Dore. Ithaca, NY: Cornell University Press.

Wallace, R. L., J. I. Hanoka, A. Rohatgi, and G. Crotty. 1997. Thin silicon string ribbon. In *Solar Energy Materials and Solar Cells* 48 (1-4): 179-86.

Wang, Qiang. 2010a. Effective policies for renewable energy—the example of China's wind power—lessons for China's photovoltaic power. In *Renewable and Sustainable Energy Reviews* 14 (2): 702-12.

Wang, Zhengming. 2010b. *The Evolution and Development of China's Wind Power Industry [中国风电产业的演化与发展]*. Zhenjiang: Jiangsu University Press.

Warnke, Götz. 1998. Zur Geschichte der Photovoltaik und ihrer Anwendung. In *Sozialgeschichte der Technik*, edited by Günter Bayerl and Wolfhard Weber. Münster: Waxmann.

Wen, Fushuan, Dong Hua, Qin Wang, and S. N. Singh. 2008. Wind power generation in China: present status and future prospects. In *International Journal of Energy Technology and Policy* 6 (3): 254-76.

Wenzelmann, Felix, Gudrun Schönfeld, and Regina Dionisius. 2009. Beriebliche Berufsausbildung: Eine lohnende Investition für die Betriebe. In *BiBB Report*. Bonn: Bundesinstitut für Berufsbildung.

West, Joel. 2013. Too little, too early: California's transient advantage in the photovoltaic solar industry. In *The Journal of Technology Transfer*: 1-15.

Whitford, Josh. 2005. *The New Old Economy: Networks, Institutions, and the Organizational Transformation of American Manufacturing*. Oxford: Oxford University Press.

———. 2012. Waltzing, Relational Work, and the Construction (or Not) of Collaboration in Manufacturing Industries. In *Politics & Society* 40 (2): 249-72.

Whiting, Susan. 2011. Values in Land: Fiscal Pressures, Land Disputes and Justice Claims in Rural and Peri-urban China. In *Urban Studies* 48 (3): 569-87.

Whiting, Susan H. 2004. The Cadre Evaluation System at the Grass Roots: The Paradox of Party Rule. In *Holding China Together: Diversity and National Integration in the Post-Deng Era*, edited by Barry Naughton and Dali L. Yang. Cambridge: Cambridge University Press.

Wind Energy Conversion Systems. 1973. Washington D.C..

Windolph, Melanie. 2010. Innovationskooperationen 2010 - Mit kooperativen Projekten Ideen erfolgreich umsetzen. In *Schriftenreihe der Professur für Unternehmensrechnung und Controlling*, edited by Klaus Möller. Göttingen: Universität Göttingen.

Windpower Monthly. 1997. American giant moves into European market. November.

———. 1999. Retrofit of hundreds of Danish turbines. May.

———. 2002. GE Wind Energy celebrates 1000th, 1.5 MW turbine installation. October.

———. 2005a. A more conservative approach. November.

———. 2005b. Who supplies to whom - wind industry gearboxes and bearings. November.

———. 2006. Gearbox supply in Asia and Europe expands -- Wind power now an industry worth making investments for. October.

———. 2008a. Another production series blade retrofit -- Suzlon the latest to initiate major blade exchange program. April.

———. 2008b. China gearbox factory orders 5000 high capacity bearings. September.

———. 2008c. Special Report - Opportunity and Risk in China - Quality issues - Lots of turbines but too little electricity. November.

Wiser, Ryan, and Mark Bolinger. 2008. Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007. Washington DC: Department of Energy.

———. 2011. 2011 Wind Technologies Market Report. Washington DC: U.S. Department of Energy.

Wiser, Ryan, Mark Bolinger, and Galen Barbose. 2007a. Using the Federal Production Tax Credit to Build a Durable Market for Wind Power in the United States. In *The Electricity Journal* 20 (9): 77-88.

Wiser, Ryan, Mark Bollinger, Galen Barbose, Kathy Belyeu, Maureen Hand, Donna Heimiller, Debra Lew, Michael Milligan, Andrew Mills, Alejandro Moreno, Walt Musial, Ric

O'Connell, Kevin Porter, and Zack Subin. 2008. Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2006. Washington, DC: Department of Energy.

Wiser, Ryan H., and Steven J. Pickle. 1998. Financing investments in renewable energy : the impacts of policy design. In *Renewable and Sustainable Energy Reviews* 2 (4): 361-86.

Wiser, Ryan, and Ole Langniss. 2001. The Renewables Portfolio Standard in Texas:

An Early Assessment. Berkeley CA: Lawrence Berkeley National Laboratory.

Wiser, Ryan, Christopher Namovicz, Mark Gielecki, and Robert Smith. 2007b. The Experience with Renewable Portfolio Standards in the United States. In *The Electricity Journal* 20 (4): 8-20.

Wolman, Paul. 2007. The New Deal for Electricity in the United States, 1930-1950. In *The Challenge of Rural Electrification: Strategies for Developing Countries*, edited by Douglas F. Barnes. Washington DC: RFF Press.

Wong, Christine 1991. Central-Local Relations in an Era of Fiscal Decline: The Paradox of Fiscal Decentralization in Post-Mao China. In *China Quarterly* 128: 691-715.

Woo-Cumings, Meredith. 1999. Introduction. In *The Developmental State*, edited by Meredith Woo-Cumings. Ithaca, NY: Cornell University Press.

Wood, Stewart. 2001. Business, Government, and Patterns of Labor Market Policy in Birtain and the Federal Republic of Germany. In *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, edited by Peter A. Hall and David Soskice. Oxford: Oxford University Press.

World Bank. 1993. *The East Asian Miracle: Economic Growth and Public Policy* Washington DC: World Bank.

World Research Activities. 1958. In *Solar Energy* 2 (2): 34-41.

Wu, Kang, and Binsheng Li. 1995. Energy development in China: National policies and regional strategies. In *Energy Policy* 23 (2): 167-78.

Wu, Qi. 2011. State steps in to set standards. In *Windpower Monthly* October.

Wuxi Yearbook [无锡年检]. 2003. Shanghai: Pudong Electronic Press [浦东电子出版社].

Wuxi Yearbook [无锡年检]. 2006. Beijing: Gazetteer Press [方志出版社].

Wuxi Yearbook [无锡年检]. 2008. Beijing: Gazetteer Press [方志出版社].

Xia, Changliang, and Zhanfeng Song. 2009. Wind energy in China: Current scenario and future perspectives. In *Renewable and Sustainable Energy Reviews* 13 (8): 1966-74.

Yang, H., H. Wang, H. Yu, J. Xi, R. Cui, and G. Chen. 2003. Status of photovoltaic industry in China. In *Energy Policy* 31 (8): 703-07.

Yang, Yungkai. 2006. The Taiwanese Notebook Computer Production Network in China: Implication for Upgrading of the Chinese Electronics Industry. Personal Computing Industry Center, University of California, Irvine.

Yeh, Emily T., and Johanna I. Lewis. 2004. State Power and the Logic of Reform in China's Electricity Sector. In *Pacific Affairs* 77 (3): 437-65.

Yudken, Joel S. 2010. Manufacturing Insecurity: America's Manufacturing Crisis and the Erosion of the U.S. Defense Industrial Base. Washington, DC: Industrial Union Council, AFL-CIO.

Zademach, Hans-Martin, and Christian Baumeister. 2013. Wagniskapital und Entrepreneurship: Grundlagen, empirische Befunde, Entwicklungstrends. In *Wertschöpfungskompetenz und Unternehmertum. Rahmenbedingungen für Entrepreneurship und Innovation in Regionen*, edited by H. Pecklaner, B.C. Doepfer and S. Märk. Berlin: Gabler.

Zha, Daojiong. 2006. China's Energy Security: Domestic and International Issues. In *Survival* 48 (1): 179-90.

Zhang, Fang, and Jun Su. 2012. Wind Power Manfuacturing Technology Transfer in China and Its Challenges [中国风电制造产业国际技术 转移现状及问题分析]. In *China Forum on Science and Technology [中国科技论坛]* (7): 81-88.

Zhang, Lixiao, Zhifeng Yang, Bin Chen, and Guoqian Chen. 2009a. Rural energy in China: Pattern and policy. In *Renewable Energy* 34 (12): 2813-23.

Zhang, Xiliang, Shiyan Chang, Molin Huo, and Ruoshui Wang. 2009b. China's wind industry: policy lessons for domestic government interventions and international support. In *Climate Policy* 9 (5): 553-64.

Zhao, Pengjun. 2011. Managing urban growth in a transforming China: Evidence from Beijing. In *Land Use Policy* 28 (1): 96-109.

Zhao, Yuwen. 2004. The present situation and future challenges of China's photovoltaic industry [我国光伏产业现状与面临的挑战] . In *Solar Energy [太阳能]* 4: 3-6.

Zhao, Zhen Yu, Jian Zuo, Tian Tian Feng, and George Zillante. 2011. International cooperation on renewable energy development in China – A critical analysis. In *Renewable Energy* 36 (3): 1105-10.

Zhu, Junsheng. 2001. New And Renewable Sources of Energy in China -- Technologies and Products [中国新能源和可再生能源技术与产品. Beijing: Chinese Renewable Energies Industries Association [中国资源综合利用协会可再生能源专业务员会].

Zimmermann, Volker, and Christoph Hofmann. 2007. Schaffen innovative Gründungen mehr Arbeitsplätze? . In *Zeitschrift für KMU und Entrepreneurship* 55 (1): 48-70.

Zweibel, K., H. S. Ullal, and R. L. Mitchell. 1990. Polycrystalline thin film photovoltaics. Paper presented at the Photovoltaic Specialists Conference, 1990, Conference Record of the Twenty First IEEE, 21-25 May 1990.