SCALE-UP NATION: CHINA'S SPECIALIZATION IN INNOVATIVE MANUFACTURING

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ABSTRACT

On the basis of more than one hundred interviews conducted in 42 firms in China's wind turbine and solar PV sectors between 2010 and 2013, this article seeks to specify the nature and extent of China-based technology innovation. We argue that Chinese firms have developed unique capabilities surrounding technology commercialization and manufacturing-related innovation. We provide a taxonomy for understanding such capabilities, showing the ways in which they are related to multidirectional, cross-border learning among firms. Our analysis points the way toward new frameworks for understanding national competitiveness and industrial upgrading.

Keywords: manufacturing innovation, industrial upgrading, national competitiveness, renewable energy industries, Asia, China.

1. INTRODUCTION: THE PHENOMENON OF CHINESE INNOVATIVE MANUFACTURING

China's extraordinarily rapid emergence as a global manufacturing powerhouse is a well-known fact. Less well understood are the drivers of this emergence. Some observers have pointed to the role of state subsidies (Bergsten 2010). Others have emphasized more general issues of factor cost advantages (Lin 2012; Lin et al. 1996). A growing recent literature, however, has pointed to the existence in China of distinct forms of industrial innovation. These forms pertain not to upstream research and development (R&D) or new-to-the-world invention, but instead to downstream efforts involving both the redefinition of existing technologies and the commercialization of new ones (Breznitz and Murphee 2011; Ernst and Naughton 2008; Ernst and Naughton 2012; Ge and Fujimoto 2004; McKinsey Quarterly 2012; Thun and Brandt 2010).

This article seeks to build on that nascent literature by going further in specifying the exact nature and extent of the firm-level capabilities driving China-based innovation. We do this on the basis of qualitative, interview-based data collected from 42 firms spread across two sectors within the renewable energy technology domain, wind turbine manufacturing and solar photovoltaic (PV) panel production.

Our study has three main aims. First, we seek to develop a typology for classifying and identifying the full range of capabilities and activities surrounding what has come to be known as Chinese innovation. Previous literature has pointed to the existence of this phenomenon, identified select aspects, and described elements of it in sectorally-specific contexts. We seek to extend the effort by providing a perspective that is at once more comprehensive in terms of the phenomenon as a whole, and more specific in terms of its constituent elements. We believe that this initial effort to better pinpoint the phenomenon represents an important step ultimately toward understanding causal drivers. While our data do not permit conclusive causal statements about what drives Chinese innovation, the study is structured methodologically to suggest certain future directions for deeper causal analysis.

Second, we seek to contribute to a growing global discourse on the competitiveness implications of China's industrial rise. Given current challenges surrounding climate change and resource scarcity, governments and commercial actors worldwide have identified renewable energy technology production as an important area for long-term investment and growth. As indicated by recent solar PV-related trade disputes between China and the United States and China and the European Union, leading economies across the world now treat renewable energy technology production as a key benchmark of national industrial competitiveness (Bullis 2012; U.S. International Trade Commission 2012). By illuminating how innovation operates in China's renewable energy sector, and how it relates to what happens in comparable sectors in other economies, we seek to draw broader conclusions about national competitiveness in increasingly interdependent, globalized technology production systems.

Third, by choosing methodologically to focus on two particular sectors – solar PV production and wind turbine manufacturing – we aim to demonstrate the extent of Chinese innovation across a full spectrum of manufacturing-related activities. Some observers might be inclined to dismiss solar PV and wind turbine production as mere niche areas within an already narrowly circumscribed portion of the energy technology sector. We argue, however, that these two areas, if considered in terms of their whole supply chains, encompass the entire spectrum of technological, regulatory, and production characteristics associated with virtually all of modern industry. The technology production systems surrounding wind and solar certainly include a number of very traditional, well-established industrial activities (i.e., the fabrication of standard steel towers for wind turbines, the use of basic chemical processes invented in the 1950s to fab solar cells, etc.). But so too do they include activities residing at the technological frontier (i.e., the application of advanced aerospace designs to turbine blades, the development and incorporation of advanced nanomaterial coatings for solar cells, etc.). Just within China, let alone globally, these industries in process terms span the range from the electromechanical to the electrochemical; in skill terms span the range from basic manual fabrication to advanced engineering design and complex systems management; and in disciplinary terms draw upon everything from mechanical and electrical engineering to materials sciences, chemical engineering, and systems dynamics. Portions of each of these industries are labor intensive, while others are extremely capital and technology intensive. And at the institutional level, again even just within China, some portions of these industries are highly protected by the state, while others are left exposed to unbridled, and often quite cutthroat, free market competition. Our typology suggests that Chinese innovation can be found across all these spectra.

The various forms of China-based innovation found in our typology all share four basic attributes. First, the know-how involved at the firm level is concentrated primarily in engineering design teams that operate at the intersection between upstream R&D and actual physical fabrication. Second, Chinese innovation involves more than mere emulation or mimicry of what outsiders are already doing, but instead amounts to learning and the development of proprietary know-how. Third, learning and know-how accumulates through the innovator's participation in multi-firm networks, many of which extend across national boundaries. And fourth, the learning, as opposed to traditional technology transfer, is multidirectional, moving back and forth across firms engaged with and embedded in global production networks.

Our typology, then, demonstrates how these attributes get manifested across three modalities. The modalities differ primarily in terms of the newness of the technologies involved. At one end of the spectrum, we witness innovation surrounding existing products. Further along the spectrum, we witness innovation surrounding the introduction of new products. And then on the far end of the spectrum, we witness the integration of multiple new technologies, materials, and components into an entire technology system.

2. ENGAGING THE LITERATURE ON CHINESE INNOVATION

Our work builds upon, but differs somewhat, from those who have preceded us in the study of China-based innovation (Ernst and Naughton 2008; Ernst and Naughton 2012; Ge and Fujimoto 2004; Thun and Brandt 2010). In many respects, we all bear the influence of the seminal theoretical work of Henderson and Clark (1990) and Clark and Baldwin (2000). Those latter scholars, in their efforts to conceptualize the often unexpected ways in which firms create value in advanced industrial economies, moved beyond the traditional focus on product innovation, and beyond the traditional distinction between radical and incremental innovation. Instead, they focused on "product architecture," the design information that determines how a product's subcomponents connect and interact to determine the product's ultimate functionality. Firm-induced shifts in this design information – essentially, "architectural innovation" – may not change the product's physical appearance or even functionality (at least in the near term), but may radically affect other aspects of the product, including its cost, its interoperability with other products, and even in some cases its functionality over the longer run. The key example identified by Clark and Baldwin is the IBM System/360, a computer design that by standardizing and codifying the linkages between the processor and its various peripherals, transformed the computer from an "integral" to a "modular" product architecture. This shift, embodied today by objects like the standard USB connection, enabled the computer's various subsystems to embark on independent trajectories of innovation, trajectories that have given birth to industry giants such as Intel, Microsoft, and Apple.

A number of scholars in recent years have identified important instances of such architectural innovation in the Chinese business ecosystem. Ge and Fujimoto (2004) describe how Chinese motorcycle assemblers, through reverse engineering, effectively modularized the firm-specific, integral designs of Japanese lead firms. What the Chinese were doing was more than mere copying, for the newly engineered designs, though perhaps sacrificing some product functionality and quality, substantially lowered production costs, and created new options for interoperability with after-market parts. Ernst and Naughton (2008) identify a similar pattern in their discussion of the information technology (IT) equipment industry and the rise of Chinese newcomers like Huawei.

Recent scholarship has also identified cases in which Chinese firms, even if they do not themselves initiate changes in product architecture, move quickly to exploit modularization pioneered by others. Hence, as Ernst and Naughton (2012) point out in the case of semiconductor design, Chinese fabless design houses like Spreadtrum – by purchasing key integrated circuit design tools and intellectual property from abroad, while also partnering with industry-leading foundry operators like Taiwan Semiconductor – have become key suppliers to China's booming "Shanzhai" ("no brand") smart phone market.

As some scholars have reasonably argued, these instances of architectural innovation at least in some cases lead to actual product innovation. In their study of the Chinese automobile, construction equipment, and machine tool sectors, Brandt and Thun (2010) suggest that Chinese indigenous firms, by reengineering the focal models of global incumbents, have essentially created new "middle market" products, ones whose functionality and cost are particularly suited to what in many countries, including China, is the fastest-growing market segment. That Brandt and Thun's "new product innovation" may be indistinguishable from the architectural innovation, reverse engineering, and creative mimicry observed by Ge and Fujimoto (2004) or Ernst and Naughton (2008) hardly undercuts the point. After all, as Henderson and Clark (1990) emphasized in their original article, architectural innovation and product innovation frequently go hand in hand.

Our notion of Chinese innovative manufacturing has much in common with these previous perspectives, particularly our collective emphasis on reengineering, product architecture transformation, and cost reduction. However, our view of Chinese innovation differs from the existing literature in three key ways.

First, we observe not just the mimicry of overseas designs, but close inter-firm – and, in most cases, cross-border – collaboration on the development of new knowledge and new designs. Second, we observe not just one-way learning (from advanced industrial incumbents to Chinese latecomers), but multidirectional learning, particularly as outsiders with upstream design knowledge learn to adjust in the face of the manufacturing and scaling knowledge they encounter in China (and vice versa). And third, across virtually every manifestation of Chinese innovation, we observe an emphasis on tempo. Chinese innovation has undoubtedly changed how products are made, at what cost they are made, and what types of functionality they embody. But perhaps to a greater degree than anything else, Chinese innovation has changed how quickly products can be developed and brought to market. In a manner somewhat akin to Charles Fine's notion of clockspeed, our work emphasizes tempo as a crucial aspect of industrial innovation (Fine 1998).

In many ways, all three of these aspects relate to what we believe has been in recent years the complete upending and reconfiguration of the traditional global product cycle (Vernon 1966). Much of the existing literature on Chinese innovation accepts the notion that in most industries, the newest, most sophisticated products get developed by global incumbents from advanced industrial economies, and it is in the home markets of those global incumbents that the products first get rolled out. Over time, once the wealthiest markets become saturated and production gets standardized, the products – and the technologies necessary for producing them – migrate to developing locales, including

China. As underscored by the existing literature, only at that point do further types of innovation take place, including modularization, cost reduction, and even incremental modifications to the products themselves.

Thus, in the works of Ge and Fujimoto (2004), Brandt and Thun (2010), and Ernst and Naughton (2008; 2012), newcomer Chinese firms are accurately portrayed as innovative, but, the kind of things they produce – whether we term them copies, knock-offs, or simply lower cost variants – inevitably, and perhaps appropriately, come to be seen as derivative in nature. Even when new product innovation is said to take place in China, the illustrative examples pertain to the local adaptation and “down marketing” of existing global products, ones that are essentially simplified and made less expensive to meet the needs of a poorer, less sophisticated customer. The scholars observing these phenomena rightly emphasize the significant challenges involved in mastering such forms of innovation. But given that their examples, all drawn from mature industries, take place within the traditional product cycle, these scholars end up reinforcing a kind of conventional wisdom surrounding innovation that we believe is misleading. That is, they reinforce the idea that “real” innovation – the creation of truly new products and truly new technologies – takes place in advanced industrial economies (or at least is undertaken by advanced industrial firms), and it is only the follow-on duplications, simplifications, and modifications that take place in developing locales like China under the aegis of indigenous latecomer entrants.

Because our concept of Chinese innovative manufacturing is drawn from data on emerging industries, ones for which the technologies globally are still rapidly evolving and the markets have yet to be fully defined, we are in a position to take issue with two latent assumptions in the view described above. First, we challenge the idea that different forms of innovation should be judged hierarchically in either commercial or normative terms. That is, we disagree with the notion that new product innovation should be deemed superior, whether commercially or otherwise, to other forms of innovation, including the kind of reverse- or reengineering associated with architectural innovation. And second, we challenge the assumption that different forms of innovation can be neatly disaggregated and understood to unfold in sequential fashion over time. These assumptions, it must be said, are powerfully embedded in the popular discourse on innovation. They are as ubiquitous in places like MIT that regularly equate "innovation" with the generation of nascent technologies in university labs, as they are in China, where the government, ruing the absence of such nascent technology generation in its own country, has initiated a massive "indigenous innovation" drive in response (Liu and Cheng 2011).

Our findings push in a very different direction. At the most fundamental level, they force us to return to a more basic understanding of what innovation, at least in a commercial sense, is all about. Innovation does not simply imply newness, whether that newness involves products, processes, or design architecture. Newness is "invention." Innovation, however, is the combination of invention and commercialization. In other words, for the new product idea, production process, or design architecture to qualify as innovation, it has to be able to command value in a commercial context. What often becomes apparent with new technologies – or even more established ones like silicon solar cell (c-Si PV) fabrication that suddenly need to be scaled up to meet new, globally-sized markets – is that the biggest challenges lie not in dreaming up the new product idea, but rather in translating the idea into a commercially-viable product (Lester and Hart 2011). The engineering-related hurdles are often monumental. How can a new product idea be translated into something that can actually be manufactured? What combination of materials should be used? How should designs balance between maximizing product attributes (i.e., quality, reliability, performance, etc.) and maximizing ease of scalability on a manufacturing basis? And how can all of this be done quickly enough to accommodate markets that may be massive, but that open and close in narrow time windows, a condition quite common in the energy technology domain? Answers to those questions reside at the intersection between upstream R&D and manufacturing, the critical juncture that we identify as the core of contemporary Chinese innovation.

Such innovation cannot be seen as a derivative of – or an afterthought to – product development. Rather, it is the critical, engineering-intensive enabler of such development. As our typology will suggest, the various modalities of China-based innovation frequently involve the simultaneous management of architectural innovation, process innovation, and, in some cases, basic product definition itself.

The nature of Chinese industrial competiveness has unquestionably evolved over the past thirty years. What began as comparative advantage based on low factor costs – namely low wages – had by the end of the 20th century evolved into more knowledge-intensive forms of competitiveness. Those generally pertained to the types of follow-on reverse engineering, product repurposing, and local adaptation accurately described by the existing literature. Our notion of innovative manufacturing, however, suggests that at least parts of Chinese industry have reached a new stage of competitiveness, one situated at the frontier of global technology development, and deep within global innovation networks. Chinese innovators are no longer just finding ways to squeeze value from existing products. Instead, they have become critical players in a global, cross-border quest to commercialize new-to-the-world technologies, precisely the kinds of technologies that will be at least part of the solution to pressing global concerns surrounding climate change, resource scarcity, and urbanization.

3. INNOVATIVE MANUFACTURING IN WIND AND SOLAR INDUSTRIES

(a) Wind versus solar: diverse technological, regulatory, and industrial contexts

We conduct our analysis of innovative manufacturing in two sectors of the Chinese economy, wind turbines and solar photovoltaics (PV). Chinese firms have established large-scale manufacturing capacity in wind and solar sectors with remarkable rapidity, making them archetypal examples of the broader phenomenon of manufacturing development in China. Between 2000 and 2010, as China nearly quadrupled its share of world manufactured output, the domestic production of solar modules increased from 3 megawatt (MW) to 10,852 MW, while wind turbine manufacturing grew from roughly 80 MW to almost 19,000 MW (Earth Policy Institute 2013; Marsh 2011; UNIDO 2011).[1]

Despite their common growth trajectory, however, the wind turbine and solar PV industries differ across a number of technological, regulatory, and production characteristics. These differences provide a window on China's rapid manufacturing development in diverse industrial contexts.

At the most basic level, wind turbines and solar photovoltaic modules are fundamentally dissimilar technologies with widely divergent production requirements, supply chain structures, and requisite firm capabilities. Wind turbines contain components assembled from more than 8000 individual parts produced by more than 1000 different suppliers. For standard wind turbine technologies, the most important components (by value) are the tower, the rotor blades, the gearbox, the power converter and transformer, the generator, the main frame that holds all the components, and the pitch system to control the position of the rotor blades (Dedrick and Kraemer 2011). Some of these components require the use of advanced materials and complex manufacturing processes, while others, such the turbine towers, are produced by firms in traditional manufacturing sectors such as heavy industry and steel fabrication.

The production of solar panels, by contrast, comprises far fewer actors, and, subsequently, a much shorter supply chain. Manufacturing of crystalline photovoltaic modules, the dominant technology in the solar industry, occurs in five major steps, sequentially arranged from the production of poly or mono-crystalline silicon, through the manufacturing of ingots and cutting of wafers, to the production of cells, and, finally, the assembly of modules. The manufacturing of solar panels based on second-generation thin film technologies is concentrated even further in a single production line. Major suppliers to solar manufacturers include producers of manufacturing equipment, as well as producers of the chemicals and materials used in the module fabrication process (Shah and Greenblatt 2010). Unlike wind turbine manufacturing – which bears much resemblance to the assembly of mechanical products such as automobiles – solar panel production is much closer to chemical manufacturing processes such as the fabrication of semiconductors.

In addition to such technological differences, wind and solar sectors also vary across a set of regulatory and industrial attributes that are frequently used to explain China's developmental trajectory. First, Western observers have often pointed to China's low-cost labor supply as an explanation for China's rapid expansion of manufacturing capacity. Indeed, labor costs in China are a fraction of those in the United States or Europe. The Bureau of Labor Statistics estimates that in 2008, hourly manufacturing wages averaged USD 1.36 in China, compared to USD 32.26 in the United States (Bureau of Labor Statistics 2010; 2011). However, wind and solar sectors, though both have experienced growth in China, exhibit vastly different levels of labor intensity. In contrast to what takes place in the wind sector, the production of solar wafers, cells, and modules is extremely automated, even in low-wage economies such as China. A survey of studies on employment in renewable energy industries finds an average of 24 manufacturing jobs per megawatt of wind turbines, compared to 7 manufacturing jobs per megawatt of solar panels (Wei et al. 2010: 922). Moreover, neither wind nor solar firms have chased labor cost to cheaper manufacturing locations in interior provinces although wage differentials in China are large and growing. 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 percent, up from 28 percent two decades earlier (Li et al. 2012: 62).

Second, China's large domestic market has been frequently mentioned as a reason behind China's manufacturing success. Here, too, we observe large differences between wind and solar industries. Because the Chinese central government only in 2011 established modest demand-side subsidies to encourage a solar market, China-based solar PV producers have expanded without the help of domestic demand. Instead, Chinese solar firms have exported virtually their entire output to European markets (Grau et al. 2011).

In the wind sector, the opposite occurred. In the mid-2000s, Beijing started enacting a series of demand-side interventions which turned China into the world's largest market for wind turbines (Schuman and Lin 2012). Domestic demand, coupled with policy-induced localization requirements on the production side, benefitted local wind turbine manufacturers, not least by attracting international wind firms to China. These firms in many cases transferred technologies and trained local suppliers (Ru et al. 2012). However, the success of solar firms in the absence of local demand suggests that domestic markets cannot be the sole explanation for the development of China's renewable energy industries.

Third, critics of have argued that ownership structures of Chinese firms, in particular the legacy of the state-owned sector, have encouraged central and local governments to shield firms from market forces. Supported by and integrated in the government bureaucracy, firms in many pillar industries have been protected from bankruptcy, allowing them to take investment risks, access credit, and pursue aggressive pricing strategies. Here, too, we observe large variation across the wind and solar sectors. While many Chinese wind turbine manufacturers have maintained close ties to the government – either being state-owned or spun-off from a state-owned firm – virtually all of China's solar firms are privately-owned, and many are listed on American stock exchanges (Liu and Goldstein 2013).

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Fourth, proponents of anti-dumping tariffs to protect U.S. and European firms from Chinese competition have argued that blunt government subsidies are at the root of China's manufacturing development. It is clear that the rapid expansion of Chinese wind and solar manufacturing has been accompanied by unprecedented price reductions for solar modules and wind turbines. As indicated by figures 1 and 2, prices for wind turbines plummeted with increased Chinese localization, from nearly RMB 7000/kilowatt in 2007 to RMB 3500/kilowatt in 2010. Price reductions were even more extreme in the solar sector. With China-based producers multiplying production capacity to accommodate rapidly growing markets, solar module prices fell from USD 2.75/watt in 2009 to USD 1.10/watt in 2012 (see figures 3, 4). It is just as clear that Chinese firms have most benefitted from government support, most notably in the form of loans from state-owned banks. Recent journalistic reports have suggested that the China Development Bank extended USD 29 billion in credit to fifteen solar and wind companies, including almost USD 1 billion to Jinko Solar alone (Bakewell 2011; Sustainable Business News 2012). Although there is little reliable information on what interest rates firms are actually charged, it is safe to assume, based on what has transpired in other countries, including the United States, that at least some loans are provided at below-market rates (Deutch and Steinfeld 2013).

It is not equally certain, however, that government support for Chinese renewable energy firms is the sole source of rapid price reductions in wind and solar sectors. Government subsidies in China have not necessarily been greater than what renewable energy firms have enjoyed in other parts of the world. In the United States, for instance, recent subsidies included a USD 13 billion loan guarantee program for renewable energy firms, and, according to *The New York Times,* USD 25.5 billion annually in local government land grants and tax credits for manufacturing firms (Platzer 2012; Story 2012). More importantly, Chinese government support has come in different forms and from different levels of government in wind and solar industries. For more than a decade, the Chinese wind sector has benefitted from extensive policy support, for example in the form of tech-transfer and localization requirements for foreign firms. The solar sector, by contrast, has developed largely without targeted help from the central government. A recent study by the Climate Policy Initiative calculates that Chinese central government support for the PV industry amounted to only 25 million Euro from 2006 to 2010 (Grau et al. 2011). China's solar firms have instead relied on non-sector specific support offered to all manufacturing firms (including wind turbine manufacturers) by subnational governments, most often in the form of tax breaks and discounted land rates. While we do not deny that wind and solar sectors have received extensive government help, the differences in the way government has intervened in both industries suggest that subsidies alone are insufficient to explain the success of China's renewable energy firms.

In short, wind turbine and solar PV industries – more than just two cases of emerging renewable energy sectors unified by the rapid expansion of production capacity

– offer an opportunity to analyze China's manufacturing development in diverse technological, regulatory, and production environments.

(b) Empirical strategy

Our analysis of manufacturing in China's wind turbine and solar PV industries employs a qualitative, interview-based empirical strategy. The data used in this article come from 107 interviews conducted between May 2010 and June 2013, as well as from official and statistical sources, company press releases, and industry reports. The interviews were conducted with CEOs and CTOs of domestic and foreign wind turbine and solar PV manufacturers operating in China, as well as their suppliers. In addition, we interviewed representatives from wind and solar industry associations, both at the national and subnational level. We also met with civil servants at national and provincial-level developmental agencies (NDRC and DRC), executives at local developmental zones with a sizeable 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 (for interview counts, see Table 1).

For both wind and solar sectors, we compiled a list of companies from industry publications and official records. We sent interview requests to the 15 largest wind and solar manufacturers, as well as to suppliers of key components and production equipment located in Beijing, Guangdong, Hebei, Hubei, Jiangsu, Shanghai, Tianjin, and Zhejiang. With some exceptions, company executives agreed to be interviewed on the condition of confidentiality. In some cases, we were 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, we supplemented our list and scheduled additional interviews with their partners to better understand each firm's individual contributions to product development and innovation. In total, we conducted 64 interviews in 42 wind and solar firms and their suppliers, 19 of which were foreign firms operating in China. A further 43 interviews were conducted with industry associations, government agencies, and financial institutions (see Table 1).

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To keep company interviews consistent while also allowing respondents to address unique characteristics of their firm's manufacturing and product development process, we 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, we 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.

4. A TYPOLOGY OF CHINA'S SPECIALIZATION IN INNOVATIVE MANUFACTURING

Based on data collected in 107 interviews conducted in Chinese renewable energy sectors between 2010 and 2013, we find that firms in China's wind turbine and solar PV industries – despite the technological, regulatory, and production differences between these two sectors – share a specialization in a unique set of knowledge-intensive, innovative manufacturing capabilities.

China's particular brand of innovative manufacturing has four main attributes. First, the know-how involved at the firm level is concentrated primarily in engineering design teams operating at the intersection between upstream R&D and physical fabrication. These engineering teams have unique capabilities to translate upstream designs, most of which come from beyond the firm, into commercially viable products that can be produced at scale. Since many of the designs initially lack essential information for commercializing the product – information, for example, regarding materials specification or subcomponent design for ease of manufacturability – the translation of these designs into viable products often requires China-based engineering teams to engage in combinations of process innovation, architectural innovation, and product innovation. What links all of these efforts, though, is the consistent focus on ease of production scalability and reduction of unit cost.

By virtue of studying this phenomenon in renewable energy sectors, we find that innovative manufacturing is not unique to mature industries, but occurring in emerging technology sectors as well. This underscores the second attribute of innovative manufacturing, namely that the learning involved entails more than just emulation of what outsiders are already doing. A number of Chinese manufacturers today are learning at the frontiers of global technological development, commercializing products through creative reengineering, innovative changes to product architecture, creative modification of traditional production processes, and innovative applications of new materials and technologies.

Third, because this form of innovative manufacturing entails learning at the technological frontier, a great deal of it is multidirectional. Chinese firms, of course, absorb know-how from partners – many of whom are overseas – and combine that know-how with their own firm-specific knowledge. But interestingly, the solutions Chinese firms provide now frequently become important sources of learning for their overseas partners as well. This is different from unidirectional technology transfers from the advanced incumbents to latecomer aspirants so frequently described in the literature (Amsden 1989; Kim 1997; Kim and Nelson 2000). We essentially witness multidirectional, simultaneous learning – a variant of what Gary Herrigel has described as industrial "co-development" (Herrigel 2010) – as overseas and Chinese firms cooperate to overcome challenges associated with the commercialization of emergent technologies.

That leads to the fourth attribute, the deep embeddedness of Chinese innovative manufacturing in multi-firm, cross-border production networks. In such networks, upstream product designs and even key production technologies in many cases come from firms outside China.[2] The Chinese producers, then, figure out how to take those designs and use that production equipment to mass-produce a product at a commercially viable price, and within a market-determined time window. But the phenomenon is somewhat different from what has been described previously in the electronics and apparel industries. In those long-established sectors, the hand-off between upstream design and downstream fabrication is relatively straightforward and seamless (Gereffi 1999; Sturgeon 2002). However, in the emerging industries at the core of this research, both the products and production processes are new and relationships between upstream design, manufacturability, scalability, cost, and ultimate product functionality are still highly uncertain. Therefore, the network must involve more than just highly specialized firms focusing internally on their own assigned tasks, and then handing off the results to the next partner in line. Instead, there has to be the capacity for multi-directional inter-firm communication, learning, and collaborative problem solving. We argue that this capacity is central to Chinese innovative manufacturing.

Three modalities of Chinese-style innovative manufacturing

Our data from China's wind and solar sectors indicate three modalities of innovative manufacturing, each of which is described below with firm-level examples. The variants we discuss share the four basic attributes of innovative manufacturing noted above. In each modality, wind and solar firms combine new kinds of knowledge-intensive design capabilities with more traditional manufacturing activities that have long resided at the core of economic development. These firms' contributions to global wind and solar supply chains thus in some ways resemble traditional forms of reverse engineering, contract manufacturing, and export processing (Ernst and Kim 2002; Gereffi 2009; Lüthje 2002; Minagawa et al. 2007). But in other ways, the contributions extend well beyond traditional emulation and assembly, reaching deep into new product and process design.

However, just like reverse engineering, contract manufacturing, and export processing, the variants of innovative manufacturing we identify differ with regard to the basic characteristics of the products involved, in some cases commercializing new versions of existing technologies, in other cases bringing new-to-the-world technologies to the market, and in yet other instances integrating new components into products already produced at scale. And just like traditional manufacturing activities, these variants of innovative manufacturing are not mutually exclusive. Where manufacturing firms in the past were often simultaneously engaged in reverse engineering, contract manufacturing, and export processing – all with the goal to stay afloat and, if possible, upgrade to higher value-added activities – firms in Chinese renewable energy industries are now applying their capabilities in innovative manufacturing in multiple ways to survive in the highly competitive and volatile producer markets so characteristic of contemporary China.

(a) Backward design and the reengineering of an existing product

(i) Definition of backward design

In this first pattern of knowledge-intensive scale-up, which we call backward design, capabilities at the intersection of manufacturing and upscale R&D are deployed to re-design an existing product in order to reduce manufacturing cost. This pattern resembles traditional processes of reverse engineering. By creating versions of existing products that are simpler to manufacture at scale, Chinese entrants have been able to outcompete established incumbents by undercutting them on the basis of price, and gaining domestic or global market share at their expense. However, in contrast to conventional reverse engineering, in which mature technologies are simply copied and cost advantages stem from cheaper inputs and scale economies (Amsden 1989; 2001; Kim 1997; Kim and Nelson 2000), Chinese firms are cutting costs through changes to product designs. Product alternatives are weighed and product attributes are subjected to a particular cost curve, even if this necessitates sacrifices in quality and performance. What results from this process of backward design is a product that resembles the original archetype, but, by way of simplified componentry, cheaper materials, and better design for manufacturability, can be scaled at low cost and incredible speed. Backward design thus retains a core feature of reverse engineering in that the product development process is based on an existing product or product design. However, rather than attempting to reproduce the original template, firms create new products with distinct characteristics. Cost advantages do no primarily stem from lower factor costs, but are the result of deliberate, knowledge-intensive changes to the product design. The relationships within which such processes of backward design occur are varied, in some cases creating highly competitive environments that allow for little but the thinnest of margins, and in other cases permitting Chinese firms to command significant value.

(ii) Illustration of backward design

The wind turbine sector illustrates the range of backward design processes well. In a typical example in which backward design skills were mutually beneficial for the Chinese manufacturer and its foreign partner, the original developer of the technology, a Chinese wind turbine supplier was granted a license by a German firm to produce a key wind turbine subsystem, the generator. Due to engineering constraints, the German firm had previously been unable to incorporate the most cost-effective fan model in the generator design. In this case, it was the Chinese licensee that – in the process of scaling production of the licensed generator – was able to redesign the original model to accommodate the cheaper fan. The backward design capabilities of the Chinese firm permitted it to realize a product alternative that the German firm had considered, but 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.[3]

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 have used backward design skills to develop cheaper, mid-level products that compete directly with the product archetypes and their originator firms (Ge and Fujimoto 2004; Thun and Brandt 2010). Particularly in the Chinese domestic market, many established multinationals have been unable – and to some extent unwilling – to engage in such processes of cost-driven design, and have lost market share to cheaper alternatives as a result.

The speed at which they have been able to engage in backward design has provided Chinese turbine manufacturers with a competitive advantage even in instances where foreign firms have attempted to replicate this strategy. For example, a European turbine manufacturer tried to emulate the backward design strategy and developed a cheaper, mid-level product for the Chinese market by utilizing materials, components, and suppliers equivalent to those used by the Chinese competition. Although the firm was able to develop a product for a similar price, by the time it had completed the backward design process and established a local supply chain, the product was obsolete, as the Chinese market had moved on to larger turbine sizes.[4] In part, the European firm was slowed in its product development by lengthy negotiation and approval processes involving its European headquarters. Yet the speed advantage of its Chinese competitors also emanated from a more general willingness on the part of Chinese firms to set a target price (one that often seems unrealistically low to outsiders), and then scramble improvisationally to figure out the feasibility and design details.[5]

(iii) Backward design in a broader context

In the Chinese wind energy sector, where expanding domestic markets for wind turbines have attracted established foreign manufacturers and key suppliers to China, domestic firms have employed backward design strategies to rapidly develop competing products are much lower cost. By sourcing important components from foreign suppliers, by licensing technology, and, in some cases, by buying smaller foreign competitors, Chinese wind turbine suppliers have been able to access technology relatively easily (Lewis 2007; 2012). Yet instead of producing these designs as they are, Chinese firms have subsequently employed backward design strategies to exploit cheaper materials, ensure easier manufacturability, and, where possible, utilize simpler components from domestic suppliers. As a result, market prices for turbines have dropped from 7500 RMB/watt to 3500 RMB/watt in just three years (Chinese Wind Energy Association 2011), leaving many foreign players unable to compete despite fully localized production.[6]

The large number of mechanical components, the importance of product architecture for the manufacturing process, and the sophisticated material needs of advanced wind turbines make wind turbine technologies particularly suitable for design improvements through backward design. As a result, out of twelve 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 indicated using backward design strategies for some of their production machinery. 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 on the market.[7] A competitor expressed frustration with the lack of flexibility and speed of some of its European suppliers in adapting production lines to ever changing technology applications, instead switching to local suppliers who could more quickly – and cheaply – improve existing equipment designs for new manufacturing needs.[8] Although instances of backward design took on different appearances in the Chinese solar sector – focusing on customization, rather than manufacturing scale – they retained the core feature of improving on existing technologies through knowledge-intensive manufacturing innovation.

(b) Translating designs into new products

(i) Definition of translating designs into new products

The ability of Chinese firms to rapidly move complex products towards commercialization is also manifested in a second pattern of innovative manufacturing, which we call “making designs come true.” In this variant, capabilities at the intersection of manufacturing and upscale R&D are again marshaled in support of tempo, volume, and cost. However, rather than re-engineer an existing product, Chinese firms deploy innovative manufacturing capabilities to prepare new-to-the-world technologies for mass production. In some cases, the technology stems from a (foreign) partner, who may not have in-house manufacturing capabilities, may be unable to manufacture the product at a viable price, or may be deterred by the capital and tooling costs of commercializing a new technology. In other cases, Chinese firms commercialize their own product innovation based on nascent technologies that are available in the public domain, but have lain dormant because others deemed them too costly or risky to develop.

What these cases have in common is their reliance on the production know-how of Chinese firms to replace, redesign, and substitute parts until the product can be manufactured at a commercially viable price. Hence, 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 (Gereffi 1994; Lüthje 2002), Chinese firms “make designs come true” by changing product designs to allow for successful commercialization. Even if such commercialization occurs under legal arrangements that resemble the highly hierarchical nature of contract manufacturing, the interaction between Chinese firms and foreign partners often entails mutual gains and multidirectional learning.

(ii) Illustration of translating designs into new products

The importance of innovative manufacturing skills in the commercialization of new-to-the-world product design is illustrated by another example from the 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. Although the European firm developed the turbine design concept, which offers greater reliability and versatility through novel componentry, the redesign for manufacturability and cost reduction occurred during small batch production on the site of the Chinese 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. Additional design adjustments were then made during the process of scale-up to accommodate requirements for mass manufacturing.

The European engineering firm selected the Chinese partner 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. Yet, both sides acknowledged the benefits from this cooperation. The European firm, without any manufacturing capacity of its own, placed great emphasis on being part of small batch production and subsequent scale-up in order to maintain and improve its own design capabilities. This was especially important in the case of this particular turbine concept, because its novel componentry required all the components to be produced in-house. For the Chinese firm, meanwhile, the cooperation with the European partner brought access to an innovative turbine design, which it hoped would help expand market share in a highly competitive market environment.[9]

As noted above, not all instances of "making designs come true" rely on a foreign partner. A case involving a Chinese solar PV manufacturer exemplifies this second version of "making designs come true". 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, this particular innovation 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, which at least in theory promised higher efficiency solar panels. 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 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 solar cells, yet the high price of silicon justified the additional expense to produce a higher efficiency cell at the time. Speed was of the essence, however, 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.[10]

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.[11]

(iii) Translating designs in a broader context

The contexts within which we observed design changes to facilitate the rapid and cost-effective commercialization of innovative technologies varied widely. In some cases, as in the first example introduced above, licensing agreements between two firms gave way to 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.[12] In the solar industry, where cell technologies are more easily accessible and returnees from global universities have introduced advanced R&D

capabilities to Chinese firms, manufacturers were frequently applying innovative manufacturing capabilities to new technologies developed in-house.[13]

What these instances had in common was that a) manufacturability was a key constraint in commercializing an idea, and that b) scaling had to take place in short timeframes to take advantage of opportunities in fast-moving markets. Out of 24 wind turbine and solar PV manufacturing firms we visited in China, 19 discussed the importance of knowledge-intensive manufacturing capabilities in achieving cost and tempo in the commercialization of new-to-the-world technologies. Contract manufacturers, particularly in the electronics industry, depend on advantages in factor cost and scale economies to churn out foreign-designed technologies. By contrast, the majority of wind and solar manufacturers we visited relied on knowledge-intensive capabilities in product design to make new technologies commercially viable in fast-moving wind and solar markets.

(c) Manufacturing as a platform for technology systems integration

(i) Definition of manufacturing as a platform for technology systems integration

In a third variant of innovative manufacturing, the presence of both production scale and considerable know-how in vast Chinese manufacturing operations provide a platform for a variety of international innovators to rapidly integrate their technology into an existing product. In contrast to the previous two patterns of innovative manufacturing, which focus on the improvement of an existing product and the commercialization of a new technology, in this third case of innovative manufacturing a new technology or component is used to improve a product that is already mass-produced in China.

The external innovator, however, is more than just a high-end component vendor who sells a product at arms-length to a Chinese customer. Rather, the vendor commercializes its new technology in cooperation with a Chinese partner. The vendor contributes knowledge about a particular technology that may have applications to a product the Chinese manufacturer has already scaled up. The Chinese manufacturer, in turn, provides knowledge about production, knowledge about how the component technology might be applied at scale while utilizing existing production technology, and knowledge about how the original product will be improved as a result. In this process, the role of the Chinese manufacturer is not unlike that of a firm in traditional export-processing industries, where parts and components enter a developing economy to be assembled and then shipped abroad. However, in this knowledge-intensive version, the Chinese manufacturer, rather than simply bolting together the parts, first helps a foreign firm configure its technology so that it has application for an existing product and then manages the integration of the technology into existing production processes.

(ii) Illustration of manufacturing as a new technology integration platform

The cooperation of US-based Innovalight with the Chinese solar cell manufacturer JA Solar illustrates an interaction in which a foreign firm relies on China’s manufacturing infrastructure as a platform for product development. A Silicon Valley start-up founded in 2002, Innovalight developed a nanomaterial with a number of 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. Yet, while Innovalight and NREL could together determine how the material might improve a single solar cell, neither had experience in large-scale manufacturing. Presumably, 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 (Wang 2011).

In 2009, short of funds and nearly out of business, the company changed strategy, focusing on licensing its technology to solar manufacturers rather than building a production business itself. The same year, 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 – and, thus, market appeal – 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 (JA Solar 2010).

For JA Solar, the collaboration with Innovalight resulted in the ability to utilize foreign technologies for the production of a new line of high-efficiency solar cells. For Innovalight, JA Solar's manufacturing capabilities offered a type of expertise it could not gain from the collaboration with NREL. 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. Established as a legitimate player in the solar industry, Innovalight subsequently began licensing its technology to other solar manufacturers (Stuart 2012).

With its record of successes, Innovalight in 2011 was acquired by Dupont, and integrated into the global conglomerate's solar division. While it is unclear whether JA Solar will be able to translate its cooperation with Innovalight into a long-term competitive advantage – particularly in light of the fact that Innovalight began licensing the product to JA's competitors as well – it is evident that JA's manufacturing capabilities played a critical role in developing silicon ink technology as a viable product in the solar industry.

(iii) Manufacturing as a technology innovation platform in a broader context

This third variant of innovative manufacturing capabilities is especially common in the interaction between manufacturers and component suppliers, which rely on customers not just for demand, but also for engineering skills and product knowledge required to integrate new components and materials. Particularly for technologies with multiple applications – such as a liquid nanomaterial that may have potential uses in flat panel displays, solar panels, or LED lighting – integration into an existing mass-manufactured product transforms the technology into a component with commercial value.[14] This type of technology absorption entails contributions of knowledge from both the original innovator and the Chinese manufacturing firm, again resulting in a process of multidirectional learning. Yet in contrast to cases in which Chinese manufacturing capabilities make possible the commercialization of complex designs, in the instances of technology absorption described here, the Chinese product platform determines the fundamental features – and markets – of the new technologies being fed in by outsiders.

As China has become a center for the commercialization for some of the most advanced renewable energy technologies, global supply firms have increasingly relied on Chinese partners to find applications for novel components, materials, and production equipment (Neuhoff 2012). Although the intensity of collaboration differed from case to case, six out of seven solar PV suppliers we interviewed reported working with Chinese solar manufacturers on the commercialization of new-to-the-world 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.[15] China, then, has become not just a hub for physical assembly, but, increasingly, a global center for the tacit knowledge required to adjust, improve, and integrate individual parts and components into complex renewable energy products.

5. CONCLUSION

In this paper, we have used data collected through qualitative interviews with 42 wind and solar firms to document China's specialization in a distinct brand of innovative manufacturing. Our primary intent has been to describe a firm-level phenomenon and the particular mechanisms underlying it. Although the nature of our data does not permit us at this point to make causal statements about the precise drivers of the phenomenon, we hope future research efforts – our own as well as those of other scholars – will extend the analysis into causation. Such efforts are imperative, we believe, because even in just more precisely documenting the phenomenon, we have raised questions and doubts about some of the more conventional explanations for the drivers of innovation in China and other developing economies. Our data certainly suggest that China's specialization in innovation through commercialization does not follow the trajectory of many of its East Asian neighbors, one of upgrading through mimicry and emulation in traditional industries (Amsden 1989; Kim 1997). Equally, China's capabilities in innovative manufacturing do not appear to simply result from state support through protection and capital accumulation (Huang 2003; Krugman 1994; Young 1995). This opens up an array of alternative avenues for future study, including the role of social networks, the capacity to learn, the origins of skill development, the role of human capital flows, and the relationship of outcomes in any of those areas to public policy.

Even in the absence of a full causal explanation, our analysis of Chinese innovation demonstrates that the phenomenon is by no means limited exclusively to Chinese firms. Nor is it limited exclusively to China. As we have shown, Chinese innovative manufacturing relies in elemental ways on outsiders as critical sources of technology and knowledge. In turn, these outsiders – regardless of whether they are physically present in China or whether they interact with Chinese counterparts from afar – rely on Chinese firms for indispensable know-how surrounding the commercialization of innovation.

It is not always clear who captures the most value in these interactions. Risk and reward are spread in complicated ways, particularly given that many of these global relationships are not clearly hierarchical. This is not simply the world of the traditional supply chain in which a foreign lead firm commanding the bulk of the revenue drives the behavior of subordinate suppliers or subcontractors (Gereffi et al. 2005; Nolan 2012). Rather, it seems that across a number of industrial sectors, firms globally will soon either have to work closely with Chinese counterparts or learn ways to mimic their know-how in order to successfully commercialize technology. Yet, although many Chinese firms have avoided the main pitfall associated with participation in modular production – the possibility of getting eternally stuck in the lowest skill, lowest value pieces of global supply chains (Steinfeld 2004) – they have also borne considerable cost and risks, not least through their enormous investments in manufacturing capacity. Chinese firms have placed large bets on sectors such as wind and solar in which demand depends ultimately on market stimulation by regulatory actors. Here, as in other industrial sectors, the rapid expansion of manufacturing has created the risk – and reality in many cases – of overcapacity, redundant investment, and the painful sectoral shakeouts that frequently follow. Simply put, Chinese innovative manufacturers are bearing substantial risks – financial, environmental, and otherwise.

We also believe that current debates about trade policy – which generally posit of a world of Western commercial interests pitting against Chinese interests – have shown insufficient awareness of the globally interconnected nature of commercial technology innovation today. In recent efforts by the United States and European Union to impose punitive tariffs against Chinese solar PV manufacturers, little reference was made to the fact that the ostensibly “made in China” technology products are the result of highly collaborative commercial innovation efforts, ones that frequently involve – and redound to the profit of – firms from the countries ostensibly being most harmed (Bullis 2012;

U.S. International Trade Commission 2012). This is not to deny that trade frictions between nations are real, and that certain trade practices in violation of international rules are worthy of censure and sanction. Rather, it is to say that better policy – the kind of policy that better serves the interests of the countries and companies involved, and better serves the broader public interest in bringing problem-solving technology to market – is more likely to be generated if it accurately reflects the commercial reality of technology development on the ground.

We have tried to demonstrate in this article that innovation in the contemporary wind turbine and solar PV industries depends on the merging of capabilities across multiple firms, including many in China. Such innovation relies on multidirectional learning between global partners. And, often, it requires risk-taking on the part of multiple actors, in China and elsewhere, to commercialize new products better, faster, and cheaper. The know-how – and the risks – surrounding technology commercialization are relevant not just to China or China's position as a potential threat, but instead to innovation-related challenges faced by all economies, whether advanced industrial or developing. In essence, upgrading through manufacturing-related innovation and technology commercialization is at once a challenge and a possibility for all economies. Chinese firms have made impressive strides in this domain. It is perhaps time to start thinking about what we can all learn from their experience.

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[1] Figures for wind turbine production are estimates based on annual turbine installations. Virtually all of China's wind turbines are assembled domestically, virtually none have been exported, making installation figures the closest estimates for domestic production.

[2] For example, the American firm Applied Materials, the world's leading producer of PV manufacturing equipment, is a supplier to virtually the entire Chinese PV manufacturing sector. Over 90 percent of Applied Material's global customers in the PV area are located in China, and Applied Materials has an exclusive position in the supply of screen printing equipment, critical technology for all manufacturers in the crystalline silicon PV sector.

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

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

[5] Head of China operations, foreign wind turbine manufacturer, interviewed August 17, 2011.

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

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[7] Senior VP global supply chains, Chinese solar manufacturer, interviewed March 13, 2011.

[8] CTO and director of R&D at Chinese solar manufacturer, both interviewed August 26, 2011.

[9] 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.

[10] 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.

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

[12] 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.

[13] 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.

[14] CEO of American nanomaterial manufacturer, interviewed October 13, 2011.

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