The Unsustainable Rise of the Chinese Wind Turbine Manufacturing Industry

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Working Paper

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Abstract: China has emerged as the world's largest carbon emitter by an increasingly large margin, and the worryingly high levels of pollution in its major cities have drawn global attention. On the other hand, a growing stream of research, which has received favorable attention in the mainstream media, stresses that China is also an increasingly important source of innovation in clean energy technology. The comforting message stressed by this countervailing research stream is that China-generated innovation can cure China-generated environmental externalities, and proponents cite the growing global dominance of Chinese firms in wind and solar power hardware as proof of their assertions.

We investigate these claims made on behalf of China's wind turbine manufacturing industry, and find that they do not stand up to scientific scrutiny. Although various studies in the received literature attest to the growing innovative capability of the Chinese wind turbine manufacturing industry (Ru et al., 2012), a careful examination of market data and patent data from the PATSTAT undermine these claims. We map out the growth of the Chinese wind turbine industry and point to the government policy initiatives that have been important in promoting that growth. Then we undertake a citation function analysis of global patenting in technologies related to wind turbine manufacturing, showing that, even at the global level, invention in this domain has become increasingly incremental in nature. Nevertheless, Chinese firms have received almost no international patents protecting their "inventions." Interview evidence and field work confirm that there are essentially no major Chinese inventions worth patenting in the West.

Chinese firms have managed to push the costs of existing technology to low levels -- a factor that undergirds their modest but growing exports to the rest of the world. However, even this achievement may not be fully sustainable. A wave of bankruptcies and industry consolidation in China suggests that the final steps of its producers down the "learning curve" required widespread pricing below marginal cost. An analysis of the recent financial statements of major surviving firms suggests that, even with a modest recent increase in hardware prices, leading producers are not deriving enough income from their core manufacturing business to cover their interest costs. We do not believe the current period of consolidation will end in the death of the Chinese industry -- to the contrary, we believe that leading China-based indigenous producers are likely to remain important global players for the foreseeable future. Nevertheless, further progress in terms of cost reductions is like to slow substantially relative to the recent past, as is the growth rate of the indigenous industry, even as the industry slowly regains financial health. The slowdown in the rate of cost reduction, in turn, has global implications.

1. Introduction: The Rapid Rise and Uncertain Future of China's Wind Energy Industry

China's geography provides it with significant wind resources. These are especially concentrated in the country's northern and northeastern regions (*Figs. 1a* and *1b*). Given the scale of China's wind resources and the environmental cost associated with conventional (mostly coal-fired) electric power generation, a significantly greater reliance on wind energy can be easily defended on environmental grounds. Recent advances in wind power engineering, pioneered by Western firms, also hold out that promise that such a shift could be accomplished at a reasonable economic cost.[1]

China has embraced a much greater role for wind energy with impressive speed. From a country with virtually no wind power capacity, China has pushed itself to the global forefront in less than a decade. China's cumulative installed capacity in 2001 measured only a little over 400MW; by 2010, it had surged to 44.7GW, allowing China to surpass the U.S. as the country with most installed wind capacity (GWEC, 2012). Through 2008, China experienced an annual installation growth rate of at least 60%. In 2009-2010,the growth rate slowed down to a still impressive 37% (See *Fig. 2a*).

Over the same period, we have also observed tremendous growth in China's indigenous wind turbine manufacturing industry. Within China, Sino-foreign joint ventures and indigenous domestic enterprises commanded only 17% of the national market as recently as 2004. By 2010, these Chinese firms dominated the local market, claiming a cumulative 90% market share (*Figs. 2b*). Today, four of the top ten global turbine manufacturers (Goldwind, Sinovel, United Power and Mingyang) are based in

[1] This would be especially true if China imposed a price on carbon emissions. Senior policymakers have embraced this as a long-run goal, but it has not yet been enacted in China.

China (BTM Consult, 2013).[2] As our paper will show, the expansion of total capacity and the rise of the domestic producers are not just temporally coincident in time -- by engaging in the world's largest program of wind farm construction and by effectively limiting those farms to domestically produced products, the Chinese authorities effectively incubated a globally significant set of domestic producers.

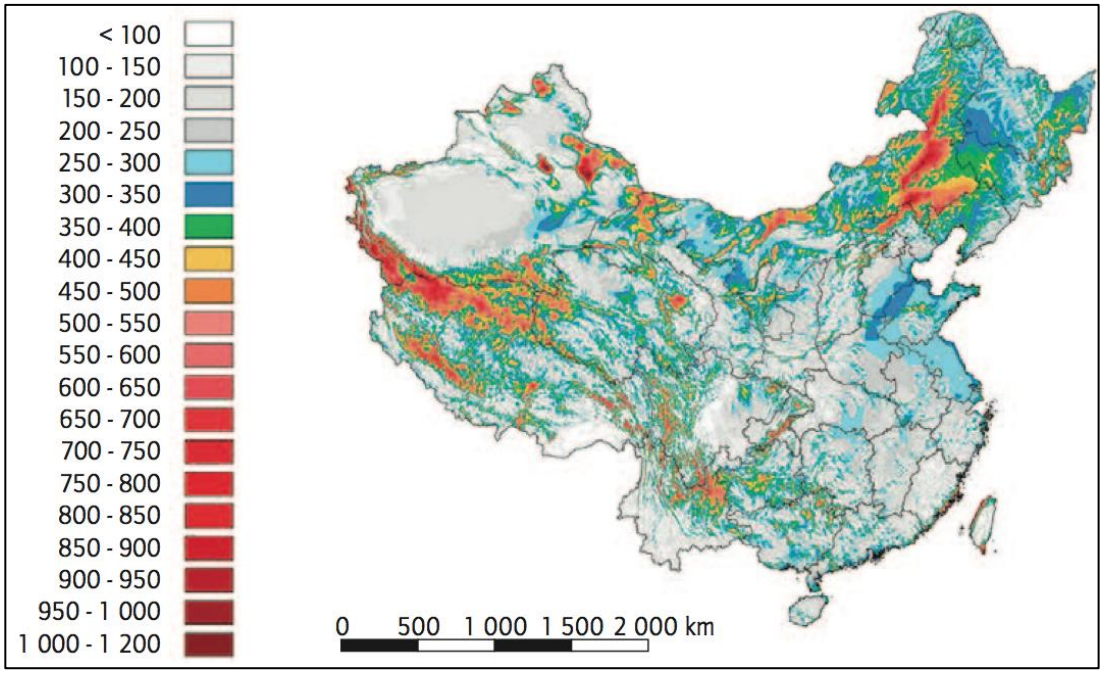


Figure 1a: Distribution of China's wind resource potential. The country's northern and northeastern regions are among the windiest. Wind power density is expressed in W/m^2, measured at 70m height. *Source*: Figure from *IEA,2011* .

[2] Goldwind, in particular, has been the subject of some favorable international press. In a widely read 2009 article, *The New Yorker*'s Evan Osnos portrayed Goldwind as an innovative, hard-charging enterprise with a Silicon Valley-like culture.

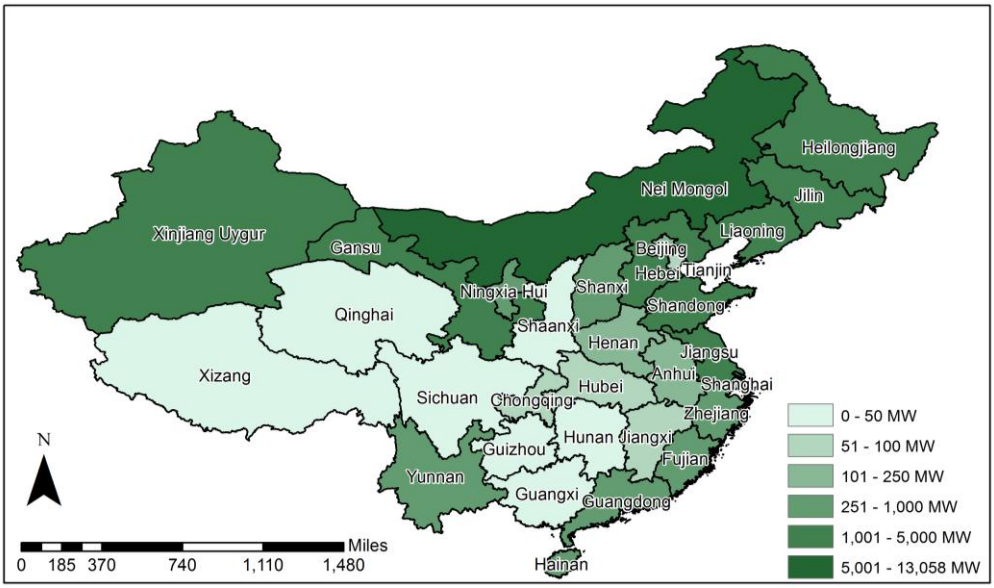


Figure 1b: China's wind power installation by provinces. *Data Source*: Figure from CWEA (2012).

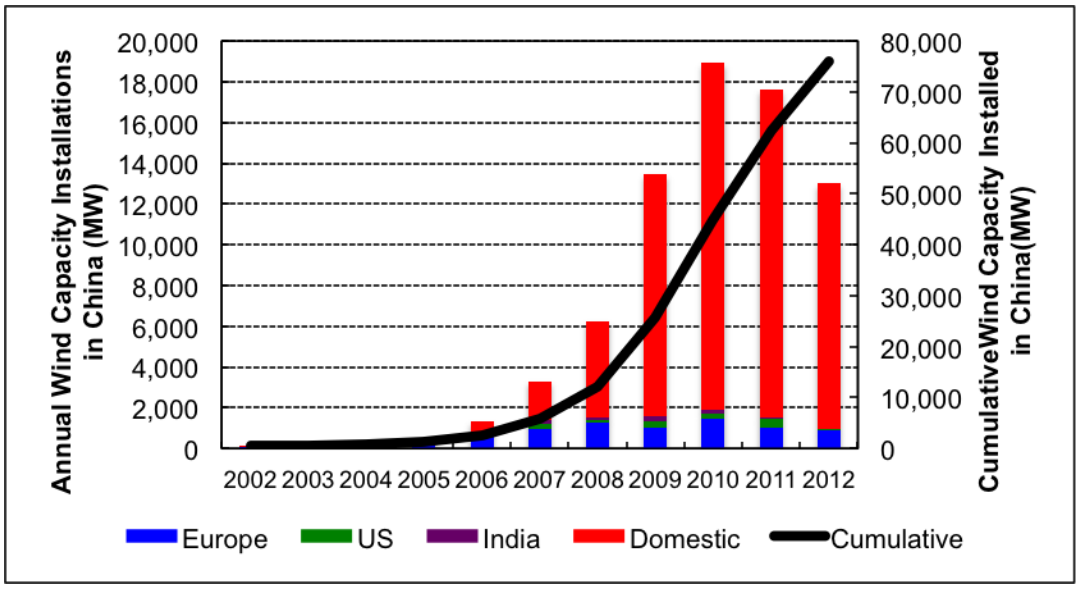


Figure 2a: Annual and cumulative wind nameplate capacity installations in China by year. China surpassed the U.S. in 2010 to become the country with the most wind power in nameplate capacity. Plot constructed by the authors using data from*:* CWEA (2007-2012), Shi (2003-2006), and Alternative eTrack (2012).

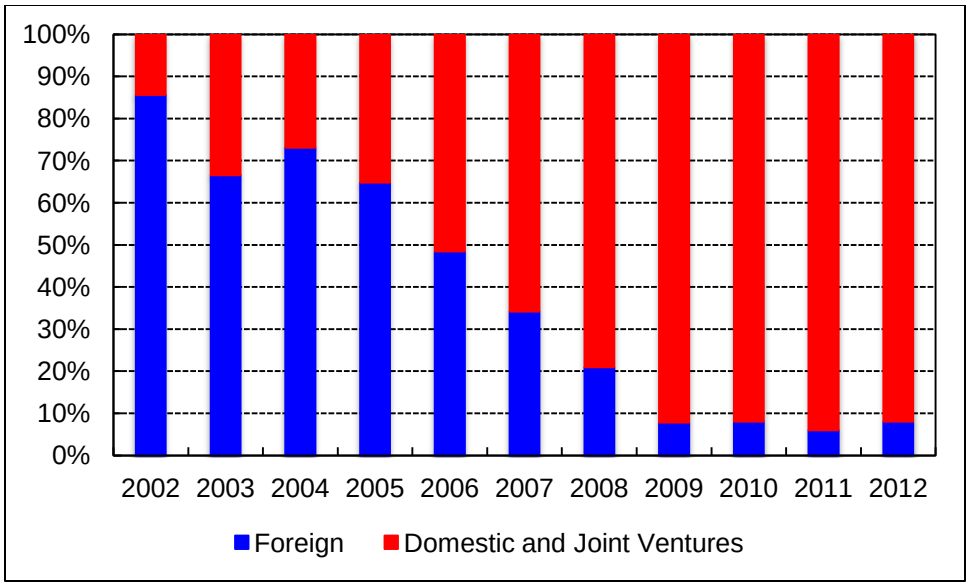


Figure 2b: Market share of China's wind turbine installed capacity. Domestic and joint ventures dominate Chinese wind turbine market in recent years. Plot constructed by the authors using data from CWEA (2007-2012), Shi (2003-2006), and Alternative eTrack (2012).

However, the growth of installed capacity has clearly outstripped the ability or willingness of the national grid to absorb wind energy, at least in the short run. Curtailment issues, or problems associated with wind sector management and grid connections, can render turbines inoperable for periods of time. While there is a lack of publicly available and reliable data, the curtailment rate in China is believed to be somewhere between 10% in western Inner Mongolia, Gansu and Heilongjiang and more than 20% in eastern Inner Mongolia and Jilin.[3] The problem has worsened in recent years. At the national level, about 20% of wind-generated electricity was curtailed in 2012. In 2011, more than the 17% of wind-generated electricity was curtailed.[4] Grid connection, while improving, still remains a problem. By the end of 2012, only 61GW of

[3] These figures are cited in Greenpeace (2012). Corroboration is difficult, but field research by one of the authors (Lam) in the summer of 2013 confirmed widespread curtailment and lingering grid connection problems.

[4] These percentages come from authors's calculations based on (Qi, 2013a) and National Energy Administration (2011, 2012, 2013).

the 76 GW installed capacity, or 80%, was connected to the grid, compared to 69.9% in 2010 (Qi, 2013b; Greenpeace 2012). By comparison, in Western countries, the level of grid connection is generally very close to 100%, and curtailment rates are always less than 5% in the U.S.. The continuing lack of grid connection and the high curtailment rates mean that the Chinese taxpayer, the Chinese ratepayer, and the Chinese investor have paid for capacity that is not yet lowering Chinese carbon intensity or providing needed green energy to Chinese cities.

Evidence of overexpansion and overcapacity in the indigenous wind turbine manufacturing industry is even more apparent. The latest industry data suggest that the *majority* of producers active in the industry in 2011 have since ceased production. The top publicly traded Chinese producers have seen their stock prices decline by roughly 75% over the last two years, and the wave of apparent bankruptcies hitting the lower tier producers has not yet brought any reprieve to the market leaders in the form of a rising stock price. Leading firms have managed to raise turbine prices slightly in recent quarters, but, even so, detailed analysis of some leading producers' financial statements suggests that the money they are making on their core wind turbine manufacturing businesses is currently so low it cannot cover these firms' cost of capital. Revenue-hungry Chinese firms have sought to boost profits through exports, and some market participants have alleged that recent growth in exports to Latin American markets has been fueled by favorable loans from China's state-owned banks (Nielsen, 2012). True or not, export growth has not yet brought higher equity prices or visibly better financial health to the leading producers. And even though some market forecasters predict an

eventual improvement in the fortunes of some leading firms, this does not extend to all the current market leaders.

The existing literature contends that the remarkable growth of China's wind power industry began with successful imitation, then shifted to "cooperative innovation" through joint ventures with international firms, and has been more recently sustained by indigenous innovation (Ru, 2012). Using patent data, we undertake an analysis of international innovation trends in technologies related to wind turbine manufacturing. Our results show that invention in this domain has become steadily more incremental. Wind turbine technology is a domain where the key components and ideas are relatively mature, so, in principle, this is the kind of technical domain in which China-based manufacturers could conceivably participate in the global innovation process.

However, further analysis shows that this is not the case -- at least not yet. China's indigenous wind power manufacturers have produced virtually no technology worth patenting in the major markets outside China. While Chinese investors and foreign environmental groups may hold out hope for an unprecedented burst of innovative activity on the part of China's leading firms, the data record provides little empirical basis for that hope.

Before the recent wave of bankruptcies in the Chinese wind power industry, foreign observers might have hoped that China, while apparently unable, as yet, to advance the state of the art through significant product innovation, had nevertheless managed to reduce costs well below those achievable in Western countries. This may well prove to be true in the longer run, but it seems apparent that rampant overcapacity drove Chinese equipment prices well below economically sustainable levels, even within

China itself. For the Chinese industry to find its financial footing, equipment prices will need to rise and remain at levels well above recent lows for the foreseeable future.

The rest of the paper is organized as follows. Section 2 provides a brief technological history of key innovations in wind energy from the inception of the industry. Those primarily interested in the recent history of the wind turbine industry in China can skip this section and proceed to the next. Section 3 provides a detailed description of the policy measures employed by the Chinese government to expand installed wind power capacity and indigenous production of wind turbines. Section 4 introduces the primary methodological tools we use to analyze global innovation trends in wind energy technology. Section 5 discusses the results of this analysis as well as the state of wind energy innovation by indigenous Chinese companies. Section 6 surveys the substantial downturn in financial health of the Chinese industry over the last 18 months. Section 7 concludes.

2. A (Brief) History of Key Innovations In Wind Energy

Humans have used wind for thousands of years for boat navigation, water pumping, grain grinding, and other purposes. The first electricity-generating turbine was built in 1891 by Poul La Cour, a Danish scientist[5]. Subsequent Danish engineers studied and improved the *Klapsejler*, La Cour's original design, and created the first turbines with modern airfoils based on aerodynamics principles (Sahin, 2004). Meanwhile on the other side of the Atlantic, the American engineer Palmer Cosslett Putman built a 1250kW, two-bladed turbine in Vermont in 1941, the biggest wind turbine ever constructed at the time (Heymann, 1998). The Smith-Putnam wind turbine, as the machine is known, was

[5] See Sahin (2004) for an overview of wind power applications in earlier times.

the first to produce AC electricity fed to the grid. After 1100 hours of operation in 1943, the rotor blade broke off at a known weak point (Sulzberger, 2009).

While the Smith-Putnam turbine was largely an isolated development in the US, efforts in Europe picked up speed due to energy shortages in the aftermath of World War II. Johannes Juul, an apprentice of Cour, developed the Gedser turbine using simplicity, security, and low cost principles that he developed through experimentations. (Heymann, 1995). This turbine features three blades rigidly fixed to the hub and supported by several rods, stall control, upwind rotor position, active yaw control, and a medium rotor velocity. The Gedser turbine generated about 2.2 million kWh between 1956 and 1967 (Sahin, 2004). Around the same time, the Austrian engineer Ulrich Hütter experimented with a number of turbine designs which introduced innovations like the teetering hub, which enabled blades to evade wind gusts and glass-reinforced composite rotor blades. Hütter's design principles, which feature a small number of composite blades, aerodynamic profiles and high rotor velocity, were diametrically opposite of Juul's. While Hütter's designs favored high efficiency and low weight, Juul's slower and bulkier turbines were cheaper and easier to construct (Heymann, 1998).

Interests in large-scale wind power generation waned in Europe as the energy shortages and fossil fuel rationing of the early postwar era ended, and European nations enjoyed expanding access to relatively cheap fossil energy, much of it imported from outside the region. However, strong interest in wind energy returned in the 1970s following the oil crises (Gipe, 1995). Governments in Germany, the U.S., Spain, and Denmark implemented different policies to support research and development in wind power. In the U.S., NASA started the a program that partnered NASA scientists with

leading aerospace companies to improve Hütter's design for megawatt-class wind turbines. Similarly, in 1974 the German Ministry for Research and Technology (Bundesministerium für Forschung und Technology, or BMFT) heeded Hütter's recommendations and sponsored wind power research with a focus on large-scale turbines (Heymann, 1998). BMFT provided support for the development and construction of the 3MW Growian, the largest turbine at the time, the one-bladed 640kW Monopteros turbine, and the lightweight, high-speed 270-kW Voith. Denmark followed suit and built several Gedser-inspired wind turbines of 630-kW and 750-kW capacity.

Despite these earnest efforts, these government-sponsored wind programs were unsuccessful. NASA engineers as well as subcontractors underestimated the difficulties of scaling up. The turbines that came out of the NASA programs had severe problems and none performed as well as expected (Gipe, 1995; Heymann, 1998). Problems associated with vibrations, structural fatigue, and bearing failures cut short the operations of many turbines. With the construction cost and time doubled, Germany's supposed crown jewel suffered the same fate. The Growian had to be dismantled after 420 hours in operation over a four-year period due to problems with fatigue, faulty bearings, and frost damage. (Heyman, 1998). The Monopteros and Voiths had similar endings. Denmark's rugged Gedser-inspired models proved problematic as well: one burned down due to overheating, and subsequent models had problems with material fatigue, shaft failures or economic viability.

The subsequent emergence of Denmark as a wind energy leader would not have been possible with the commitment of enthusiastic amateurs and skilled artisans committed to the development of wind turbines (Kamp, 2004). In fact, most Danish

commercial and successful wind turbines were developed independently of the government's R&D programs. The most notable of the Danish wind enthusiasts of this era was Christian Riisager, a carpenter who built and sold several efficient, Gedser-based and scaled-down models. His success prompted agricultural machine firms such as Bonus, Nordtank and Vestas, who had more manufacturing experience and capital, to enter the market and operate on a larger scale. A foreign market targeted by these Danish firms was California, which established a series of large wind farms open to all manufacturers in the 1980s (Heymann, 1998).

More recent technological advances, most notably variable speed design and power electronics, enabled manufacturers to reliably scale up wind turbine operations (Samaras, 2009). Whereas the traditional design forced wind turbines to operate at a constant speed and a fixed frequency over a narrow range of wind speeds, turbines with variable speed design can operate with higher efficiency; their optimum tip-speed ratio can maintained under a wider range of wind speed distribution. Power electronics made it possible for a turbine spinning at changing speeds to provide to the grid stable power of constant frequency (Samaras 2009, p. 134).

In the 1990s, many of the most important innovations in wind power hardware were brought into the industry from other sectors. Blade design, advanced materials, and manufacturing techniques borrowed from shipbuilding and aerospace industries produced better hardware. Automated control systems -- originally developed for other industrial uses -- enabled wind turbines to adapt more effectively to changing conditions in real time. The development of simulation and computer-aided design tools also help enhance the performance and economic viability of wind energy. More recently, innovative

designs such as direct drive permanent magnet generator employs fewer moving parts, reducing maintenance cost (Jamieson, 2011).

3. A Mighty Wind: Renewable Energy Policy in China in the 2000s

China has enacted a number of policies in recent years to boost its supply of renewable energy. A key turning point came with the Renewable Energy Law of the People's Republic of China, passed in 2005 and implemented in 2006. This law provided a regulatory framework for renewable energy, designated the key government players at the national and provincial level, and empowered them to draft renewable energy development and utilization plans (Shuman, 2010; China's Wind Power Center, 2012). The passage of this law signaled a strong central government commitment to a rapid build-up of renewable energy in China -- a commitment soon codified into ambitious renewable energy targets embraced by the State Council, China's most powerful governmental body.

Soon after passage of the Renewable Energy Law, the State Council released the Mid- and Long-Term Development Plan for Renewable Energy. This document called for 10% of China's primary energy consumption to come from renewable energy sources, including hydropower, wind, and solar, by 2010. By 2020, renewable sources were to account for 15 % of primary consumption (NRDC, 2007). At the time the targets were set, the share of non-hydro renewable power in Chinese primary energy consumption was extremely low. Realization of the incredibly ambitious 2010 target set off a national frenzy of windfarm development, the largest crash program of windfarm development in the global history of the industry.

The Renewable Energy Law also aimed to prop up the domestic turbine manufacturing industry by offering research and development funds and strong deployment incentives. Most controversial of these was "Notice 1204," a rule promulgated in 2005 as part of the Renewable Energy Law which required that at least 70% of any wind turbine supported by the law had to be manufactured in China. Effectively, the lion's share of the largest crash program of windfarm development in the history of the industry was being reserved solely for domestic manufacturers.

In 2004, indigenous firms and Sino-foreign joint ventures accounted for only 17% of national installed capacity, and much of the most advanced equipment was imported. To take advantage of China's ambitious windfarm development program while meeting its requirement for local manufacturing, Western firms scrambled to transfer technology to Chinese affiliates and local joint venture partners. These efforts were supported by other Chinese government programs. The Ninth Five-Year Plan (1996-2000) had already created the National High Tech R&D Program (more commonly known as the 863 Program), under which local wind turbine manufacturers were able to use the funds provided by the Ministry of Science and Technology (MOST) to license international technology. The continuation of the 863 Program in the Tenth and Eleventh Five-Year Plan provided support for the development of megawatt-size wind turbines as well as variable speed and pitch technologies. This helped Chinese enterprises absorb the foreign knowhow required to meet China's wind energy development targets and its requirement that 70% of turbines be made in China.

The State Council's ambitious renewable energy targets were supported by a series of requirements and incentives within the national power system. The "Measures

on Grid Company Full Purchase of Electricity from Renewable Energy," issued by the State Electricity Regulatory Commission (SERC), set up a mandatory connection and purchase requirement for grid operators, as well as a priority dispatch system under which renewable generators are given priority in the dispatch sequence.

Similar to what many countries in Europe did in the past, China established feed-in tariffs to encourage the generation of renewable power. To gauge the price of wind energy projects prior to setting a feed-in tariffs system, China has held a number of concession programs where projects were awarded through a competitive bidding process. The current feed-in-tariff system for wind energy generation has four tiers, ranging from 0.51 to 0.61 Chinese yen per kilowatt-hour (CNY/kWh) -- this is roughly equivalent to US$0.08 – US$0.1/kWh -- for six years, depending on the region's wind resources and electricity demand (Hu, 2013). To help pay for the costs incurred by the new programs, the National Development and Reform Commission (NDRC), the nation's top economic planning agency, issued the Interim Measures on Renewable Energy Electricity Prices and Cost Sharing Management, which levied a RMB 0.001/kWh surcharge on consumers (NDRC, 2006). The surcharge has increased a few times since its introduction, and NRDC announced at the end of 2011 its intention to raise it to 0.008 CNY/kWh, or US$0.0013 (Walet, 2011). In order to ensure equality among the grid companies, SERC and NDRC issued the Interim Measures on Revenue Allocation from Renewable Surcharges, which created an interprovincial equalization program where grid companies could exchange their shortfall or surpluses with companies from other regions (Schuman, 2010).

The National People's Congress adopted some important amendments to the Renewable Energy Law in 2009, as the deadline for the 10% renewable energy target approached. The global financial crisis has led to a sharp decline in fossil energy prices. Even though China escaped the worst of the global slowdown, there was still a temporary decline in the growth of energy demand. This combination of lower fossil energy prices and relaxed demand made the renewable energy targets more expensive for the grid operators. Even though the grid companies were still required to connect and purchase power generated by renewable sources, they could require wind generators to consent in their power purchase agreements to grid curtailment (Schuman, 2010). Such agreement allowed grid companies to purchase only a portion of the renewable energy, freeing them to purchase electricity generated by cheaper sources. The 2009 Amendments create a central renewable energy fund through which grid companies could directly seek compensation for costs associated with purchasing renewable power and transmission (Shuman, 2010). The Amendments also require regulatory agencies "to set priority dispatch regulations that will give priority to renewable power generators in the electricity dispatch sequence," with lowest emission units being dispatched first (p.10, Schuman, 2010).

Meanwhile, the U.S. government challenged China's policy limiting its rapidly expanding domestic market to locally produced wind turbines under WTO trade rules. Rather than fight the U.S. in a trade case that it would likely lose, China rescinded the formal legal requirement that turbines supported by the Renewable Energy Law had to be 70% manufactured in China (Bradsher, 2010). However, by the time this legal requirement was formally rescinded, indigenous firms and Sino-foreign joint ventures

had come to dominate the Chinese market. The technological advantage held by foreign firms had been significantly diminished, if not eliminated, and low-cost Chinese producers were now able to produce virtually the entire spectrum of commercial products. China's ambitious wind power build-out had displaced foreign producers with apparent success.

But had China succeeded in creating a cadre of local firms that could not only produce standard products at low cost, but also participate in the advance of the global state of the art? Addressing that question is the subject of the next section.

4. Innovation in Wind Power: A Citation Function Approach

Mainstream economic research has been using patents as a measure of innovation as early as the early 1960s, and different patent analysis methods have been documented, each with its advantages and disadvantages (Jaffe and Trajtenberg, 2002). There are several strategies to measure innovations using patents, including application and patent counts, citation count and analysis. The simple patent count, the most straightforward method, does not account for the difference in values of various patents. Patent citation analysis, which examines the number of times each patent has been cited by subsequent patents, is a more robust alternative, and it has been use to measure patent quality (Harhoff et al., 2002) as well knowledge flows and spillovers (Jaffe et al., 1993), serving as an established proxy for the patent value. There are two immediate problems associated with patent analysis: truncation and obsolescence. Compared to a patent issued at a later date, an earlier patent has been around longer to diffuse in the knowledge stock, increasing its probability to be cited. On the other hand, the older patent may protect a technology that is no longer as relevant in its field, i.e., it becomes obsolete. This

knowledge obsolescence issue has the opposite effect of truncation on a patent's citation probability. A citation model was established by Caballero and Jaffe (1993) to resolve these limitations (see below). In our analysis, we follow such citation analysis model, which can provide useful information in our context.

Firms who wish to use the intellectual property system to protect their invention first file a patent application, also known as priority application, with the patent office in their home jurisdiction. To evaluate the merit of the patent application, the patent office normally conducts an international search report of prior arts. This search report helps the patent office assess the patentability of an invention as well as the legitimacy of their claims. Upon filing an application inventors have to list the related existing patents that they are aware, and the patent examiners, the experts in their respective technological classifications, may modify the list of citations[6]. The citations serve as legal boundaries, limiting the scope of the property rights awarded. The inventors then have an incentive to both limit unnecessary cited patents and to cite all relevant patents, placing them outside the realm of the current patent (OECD, 2009).

In this paper we assume, as in Popp (2002), that citations indicate a flow of knowledge, and they are evidence of existing technologies when the patent application is filed. As a result, patents with high number of citations signify their high usefulness and value. Problems associated with data truncation – we cannot look past the present date for the total number of citations –prevent simple citation counts from being a useful metric. Thus, in addition to assessing patent counts and citations, we follow the model used by Caballero and Jaffe (1993) and Jaffe and Trajtenberg (1996) to estimate the likelihood (or

[6] EPO patent examiners assign citations to patents, though applicants can optionally add their own.

"*citation frequency function*", as denoted by Jaffe) that a particular patent will be cited by subsequent patents as a function of the time elapsed between the two patents as well as the characteristics of the citing and cited patents. The likelihood that any particular patent in group *K* granted in year *T* will cite some particular patent in group *k* granted in year *t* is assumed to be determined by the combination of an exponential process by which knowledge diffuses and a second exponential process by which knowledge becomes obsolete. The functional form of the citation function is given by:

$$\Pr(k, K) = \alpha(k, K) \cdot \exp(-\beta_1(t - T))(1 - \exp(\beta_2(t - T)) \qquad (1)$$

In equation (1), the dependent variable is the estimated probability that patent K will cite previously granted patent K. β_1 represents the rate at which knowledge becomes obsolete and β_2 the rate at which knowledge diffuses through society. The coefficients α correspond to categorical variables associated with the salient characteristics of the citing patent group K and the citing patent group k. In previous applications of the citation function, researchers have used dummy variables for the technology classes of the citing and cited patents, the grant years of the citing patents, and the grant years of the cited patents. The latter coefficients measure the relative technological usefulness of different patent cohorts, as reflected by the propensity for later generations of inventors to cite them in patent documents. In this paper, we are only examining one technologies related to wind energy, so there is no need to include technology class dummies. Instead, we will focus on the coefficients associated with cited and citing grant year dummy variables, with an emphasis on the former. We use a nonlinear least squares estimator. To adjust for heteroskedasticity problems associated with grouped data (Wooldrige, 2005), the observations are weighted as follows:

$$w = \sqrt{n_{i,p} n_{i,P}} \qquad (2)$$

The patent data used in this analysis comes from the European Patent Office Worldwide Patent Statistical Database (PATSTAT). We start with data on patent applications from 1976 through 2011, then restrict our analysis to those patents eventually granted by the patent offices of China, the EU15 nations, Japan, South Korea, Taiwan, and the U.S, which are the regions with the most activities in wind turbine manufacturing and construction.[7]

To identify the relevant patents, we rely on combination query method that finds wind energy patents by combining patents assigned to "wind energy" in the EPO's patent classification system with those that are clearly connected to wind energy based on a keyword search of the patent abstract. Similar to Johnstone et al. (2009), we use the "F03D" classification as an indicator of a wind power patent. We then append this dataset with results from a scan of the PATSTAT patent abstracts using a query similar to Nemet (2009) in English[8], French[9], German[10] and Spanish[11]. The patent's "nationality" is determined by the geographic location of the inventor. If the inventor information is missing, we use the applicant's location instead.

5. Patents and Innovation in Wind Energy -- Global Trends and Chinese Activity

[7] Taiwan is recognized by PATSTAT as a separate patent jurisdiction and we follow this convention.
[8] ABST/(("wind power" OR (wind AND turbine) OR windmill) OR (wind AND (rotor OR blade$ OR generat$) AND (electric$)))
[9] ABST/(("windkraftanlage" OR (wind AND turbine) OR windmühle) OR (wind AND (rotor OR blatt$ OR generat$) AND (elektri$)))
[10] ABST/(("Ènergie Èolienne" OR (Èolienne AND turbine) OR moulin a vent) OR (Èolienne AND (rotor OR pale$ OR generat$) AND (Èlectri$)))
[11] ABST/((" aerogenerador" OR (eolic AND turbin) OR molino de viento') OR (eolic AND (rotor OR pala$ OR genera$) AND (electric$)))

We examine the number of patents available in the PATSTAT database using two filters: the patents published by EU15+ countries and the patents published by the European Patent Office. *Fig. 3* shows the total number of patents taken out by EU15+ countries. Patenting activities accelerated in the early 1980s and again in the 2000s, as seen by the two peaks in these periods, which correspond to the times of renewed interests in wind power. While counting patents published by EU15+ countries may be inclusive, the EPO patent count eliminates inconsistencies in technical and logistical standards across various countries. Between 1976 and October 2012, the EPO granted a total number of 898 patents. Of these, inventors with German addresses were awarded the most patents (336), followed by Danish (148) and American inventors (114).

There was ***one*** patent assigned to Chinese inventor (*Fig. 4a*). Time series trends in patenting at the national level are provied in *Fig. 4b*. The recent uptick in patenting activity is clearly evident, and the final years of the data sample are ones in which Chinese firms have displaced foreign rivals in their home market. Despite the growth in Chinese production and the inception of Chinese exports of wind power equipment to other major markets, we see essentially no patents granted to indigenous Chinese firms. There is a global patenting surge in this domain, but China's indigenous producers are not participating in it.

Could Chinese firms be creating useful new-to-the-world technology but not patenting it outside their home country? This would seem to defy economic logic. At current exchange rates, both the U.S. and the EU remain much larger economies than China, and they will retain that status for years to come. Unless Chinese firms patent their inventions in these jurisdictions, they have no way of preventing other inventors

from infringing on their intellectual property rights. Chinese firms in other sectors have, in recent years, become increasingly aggressive about patenting inventions outside China -- the total number of patents taken out in the U.S or the E.U. by indigenous enterprises now exceeds one thousand per year. It is hard to interpret the stunning lack of international patents on the part of China's indigenous wind turbine manufacturers as signifying anything other than their lack of any innovation sufficiently novel to merit patenting outside China.

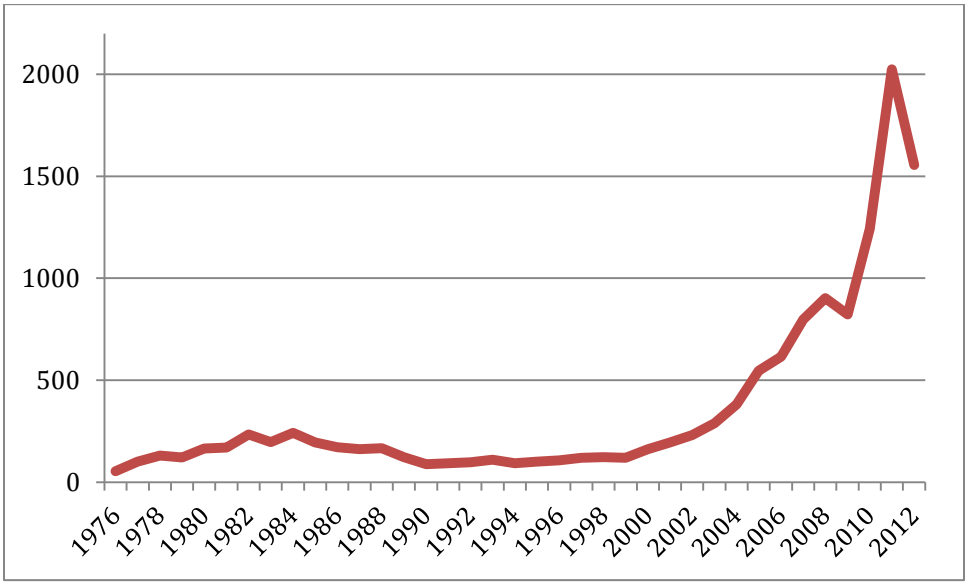


Figure 3: Total wind power patents granted by EU15+ countries, sorted by the year the patent is granted from 1976 to October 2012. *Source*: PATSTAT 2012.

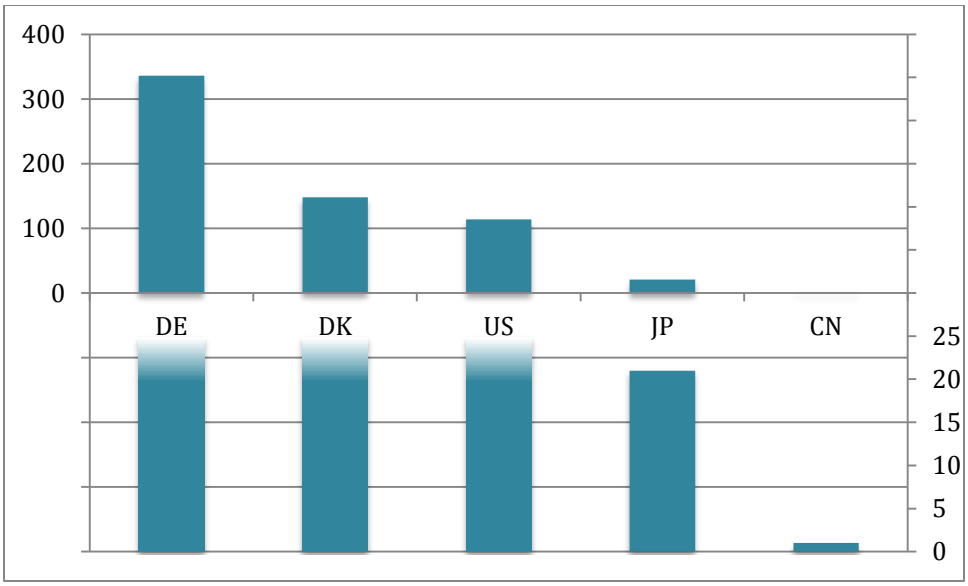


Figure 4a: Total number of wind power patents granted by the EPO to inventors from Germany, Denmark, US, Japan and China.

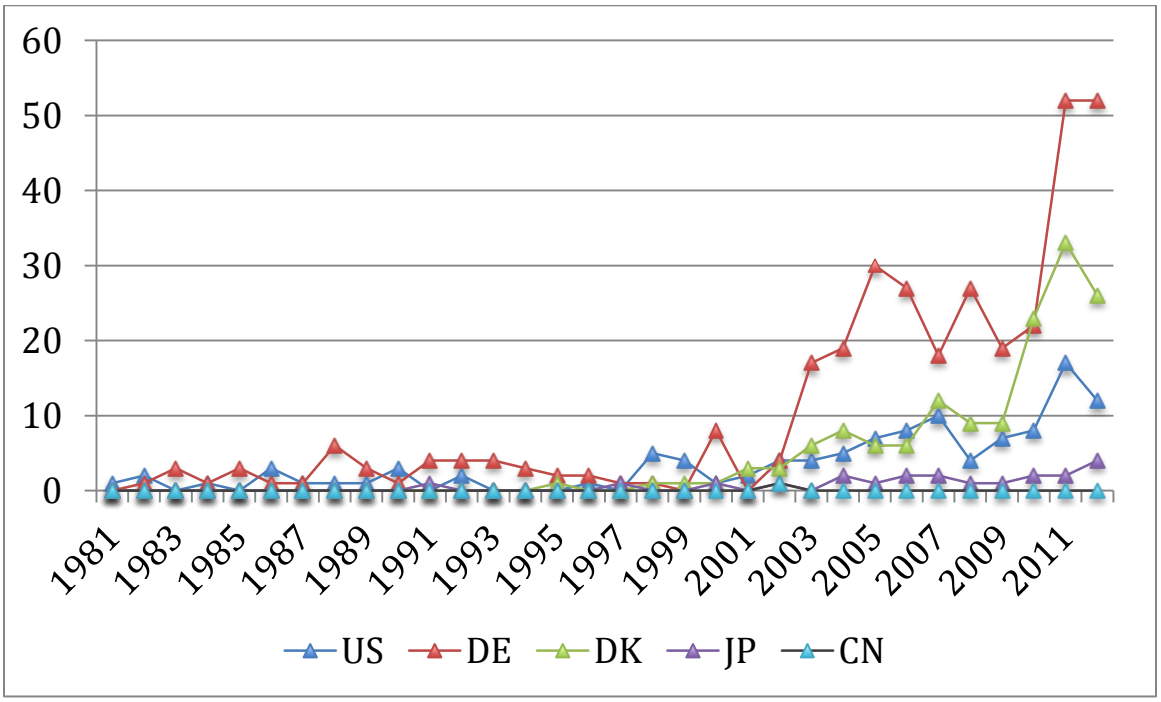


Figure 4b: Number of wind power patents granted by the EPO to inventors from Germany, Denmark, US, Japan and China by year.

To perform patent citation analysis, we use the EU15+ patent sample because the EPO patents' small sample size causes convergence issues. The citation function results

are shown in *Tables 1* and *2*. We grouped the years together by two and by four because single year citation data do not yield convergence. The results indicate that the likelihood of a patent being cited decreases over time. For example, *Table* 1 shows that the 1986-1987 cohort is 60% less likely to be cited than the 1976-1977 cohort. The trend is more consistent and stronger when we use four-year cohorts (*Table 2*). This suggests that controlling for the truncation and obsolescence issues, the likelihood of a wind patent being cited by other wind patents decreases over time. In other words, a patent granted in the 1980s are more likely to be cited than a patent granted in the 2000s, indicating that the marginal productivity of patents in the wind industry decreases over time. Given the renewed interests in wind power as well as the growing market size, the citation analysis results suggest that the technological developments in wind industry have slowed down, signs of a mature industry.

Table 1: Results for two-year cohorts using PATSTAT

Citing Year	Coefficient (error)	Cited Year	Coefficient (error)
d1979	3.77	e1978	0.03
	(10.71)		(0.20)
d1981	1.91	e1980	-0.25
	(6.54)		(0.17)
d1983	2.51	e1982	-0.33*
	(7.88)		(0.17)
d1985	1.27	e1984	-0.34*
	(5.11)		(0.18)
d1987	0.97	e1986	-0.59***
	(4.44)		(0.17)
d1989	0.81	e1988	-0.55***
	(4.09)		(0.19)
d1991	0.98	e1990	-0.46**
	(4.47)		(0.23)
d1993	1.49	e1992	-0.22
	(5.61)		(0.27)
d1995	0.96	e1994	0.022
	(4.43)		(0.31)
d1997	1.51	e1996	-0.44
	(5.67)		(0.27)
d1999	0.63	e1998	-0.41
	(3.70)		(0.30)
d2001	0.51	e2000	-0.33
	(3.43)		(0.34)
d2003	0.14	e2002	-0.22
	(2.60)		(0.43)
d2005	0.94	e2004	1.73
	(4.40)		(0.00)
d2007	0.49	e2006	-1.22**
	(3.37)		(0.52)
b1	0.10***	b2	0.00
	(0.01)		(0.00)
Observations	149		
R-squared	0.99		

Each year denotes a two-years cohort. For example, d1979 means the citing cohort of 1979-1980. The base cohort is 1977-1978 for citing and 1976-1977 for cited years. Coefficients with *** denote that it is significant at 1% level, ** is at 5% level and * is at 10% level.

Table 2: Results for four-year cohorts using PATSTAT

Citing Year	Coefficient (error)	Cited Year	Coefficient (error)
d1981	-0.53***	e1980	-0.27*
	(0.10)		(0.15)
d1985	-0.63***	e1984	-0.63***
	(0.10)		(0.10)
d1989	-0.58***	e1988	-0.78***
	(0.12)		(0.07)
d1993	-0.33*	e1992	-0.70***
	(0.17)		(0.07)
d1997	-0.15	e1996	-0.85***
	(0.22)		(0.05)
d2001	-0.12	e2000	Omitted
	(0.25)		(0.00)
d2005	0.34	e2004	Omitted
	(0.00)		(0.00)
b1	0.19***	b2	0.00***
	(0.01)		(0.000
Observations	33		
R-squared	0.4592		

Each year denotes a four-year cohort. For example, d1981 means the citing cohort of 1981-1984. The base cohort is 1977-1980 for citing and 1976-1979 for cited years. Coefficients with *** denote that it is significant at 1% level, ** is at 5% level and * is at 10% level.

If innovation in this sector is increasingly incremental, as our citation function results suggest, then we might expect wind power to be the kind of technical domain in which emerging manufacturers in a "latecomer country," like China, could begin to innovate successfully at the global level. So far, though, we see no signs in the international patent data supporting this view.

6. Recent Developments in the Chinese Wind Power Industry

7. Conclusions

China established itself as a major player in the wind energy industry in less than a decade. From an installed capacity of just over 400MW in 2001, China surpassed the US to become the country with the most wind capacity in the world, totaling

approximately 76GW as of 2012. As they have ramped up output, indigenous producers have increasingly undercut the prices maintained by producers outside China. This growth path, some argue, suggests that Chinese wind power manufacturing firms have developed innovative indigenous technological capabilities. Indeed, some Chinese wind turbine manufacturers have been profiled as the kind of dynamic "green innovators" that might save the world from the consequences of China's expanding emissions of carbon dioxide and other industrial pollutants.

Unfortunately, we find no evidence that Chinese firms in this industry have acquired a substantive capacity to innovate. Using patents as a measure of innovation, we find that there are almost no wind power patents granted to Chinese inventors by major patent jurisdictions outside China. While Chinese wind power firms had a strong focus on domestic market in the beginning of the last decade, the top firms have shifted focus to the international market in recent years. These firms have every incentive to protect any inventions they create by taking out patents in the international markets that are an increasingly important component of their expansion strategies. Furthermore, our citation analysis results suggest that recent technological improvements in wind power, even at the global level, have been increasingly incremental. Wind power is therefore exactly the kind of technological context in which we might expect emerging manufacturers from a latecomer country to successfully participate in the advance of the global state of the art. That makes the near total absence of international patents on the part of Chinese firms all the more striking. It is hard to interpret this as evidence of anything other than the reality that, to date, Chinese wind turbine manufacturers simply have not produced inventions worth patenting outside their home countries.

These two factors lead us to conclude that it is not innovation that has fueled the rise of China's wind power industry. Rather, a highly supportive policy environment has done so. As it raced to meet incredibly ambitious renewable energy targets, China embarked on the greatest crash windfarm development program in the global history of the industry. For several crucial years during this rapid build-out, China violated international trade rules by limiting participation in this build-out to products that were mostly manufactured in China. Faced with a U.S. challenge at the WTO, China rescinded its formal requirements for domestic manufacture in 2010, but, by then, China's efforts at import-substituting industrialization had "succeeded."

On the other hand, the domestic industry China has created looks far less healthy today than it did two years ago. The latest industry data suggest that the *majority* of producers active in the industry in 2011 have since ceased production. The top publicly traded Chinese producers have seen their stock prices decline by roughly 75% over the last two years, and the wave of apparent bankruptcies hitting the lower tier producers has not yet brought any reprieve to the market leaders in the form of a rising stock price. Leading firms have managed to raise turbine prices slightly in recent quarters, but, even so, detailed analysis of some leading producers' financial statements suggests that the money they are making on their core wind turbine manufacturing businesses is currently so low it cannot cover these firms' cost of capital. Revenue-hungry Chinese firms have sought to boost profits through exports, and some market participants have alleged that recent growth in exports to Latin American markets has been fueled by favorable loans from China's state-owned banks (Nielsen, 2012). True or not, export growth has not yet brought higher equity prices or visibly better financial health to the leading producers.

And even though some market forecasters predict an eventual improvement in the fortunes of some leading firms, this does not extend to all the current market leaders.

Before the recent wave of bankruptcies in the Chinese wind power industry, foreign observers might have hoped that China, while apparently unable, as yet, to advance the state of the art through significant product innovation, had nevertheless managed to reduce costs well below those achievable in Western countries. This may well prove to be true in the longer run, but it seems apparent that rampant overcapacity drove Chinese equipment prices well below economically sustainable levels, even within China itself. For the Chinese industry to find its financial footing, equipment prices will need to rise and remain at levels well above recent lows for the foreseeable future.

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Table A1: Major government policies to support the growth of the renewable energy sector. Adapted from Liu et al.

Date	Policy	Details
2002	Taxation Notice on Value-Added Tax	Electricity generated from wind power is exempted from 50% of the value-added-tax
July 2005	Notice 1204	70% of wind turbine must consist of local content starting 2006
Jan 2006	Renewable Energy Electricity Price Sharing and Management	Electricity generated by renewable energy is priced by the government, and the part over the market price for conventional electricity will be shared by all electricity consumers
Sept 2007	Medium and long-term development plan for renewable energy in China	(a) Construct large-scale wind farms in Northern China and small to medium sized wind farms in other areas. (b) Set up off-shore wind power generation pilot projects with at least 100 MW capacity by 2010, and 1000 MW capacity by 2020. (c) Target 1000 roof-top solar PV projects nationwide by 2010, 20,000 by 2020
2008	National Energy Bureau created	(a) Promote policymaking on energy development and reconstruction, manage national oil reserves, natural gas, coal and electricity(b) Propose strategic policies in renewable energy and energy conservation. (c) Manage international cooperation and ensure adequate supplies of oil
2008	Corporate Tax Law	Wind farm projects are exempted from corporate tax for the first 3 years, and exempted from 50% of corporate tax for the next 3 years
Mar 2008	Tenth Renewable Energy Five-Year Plan	(a) Increase the economy of scale of wind farms, promote domestic production of wind technologies, reduce costs and improve global competitiveness. (b) Set a target for the aggregate installed capacity of wind energy to be at least 10 GW, and that for solar PV energy to be at least 0.3 GW
Aug 2008	Wind Turbine Special Fund Management	(a) Subsidize Chinese wind technology companies. (b) Funded enterprises receive 600 RMB/kW (85.7 USD/kW) for their first 50 WTGS.
Dec 2008	Taxation Notice on Value-Added Tax	Electricity generated from wind power continues to be exempted from 50% of the value-added tax
2009	Amendment to the Renewable Energy Law	(a) Impose a renewable portfolio standard to grid wind power suppliers. (b) Introduce feed-in tariffs; levels depending on regional wind resources
2009	State Council Notice on Energy Conservation and Emission Reduction	(a) Enforce the use of renewable energy in new residential and office buildings. (b) Reconstruct and upgrade industries with high energy consumption and high emissions. (c) Merge or shut down small inefficient power generation plants
March	Solar Energy	(a) Subsidize 20 RMB ($2.94)/Wp. (b) The subsidized solar

2009	Construction Subsidy Funds Management	PV products need to have at least 50 kWp installed capacity. (c) Priority is given to solar PV products applicable to new buildings, schools, hospitals and other public infrastructure
July 2009	Notice on the Golden Sun Model Project	(a) Subside 50% of the total investment for qualified solar PV generation, 70% if the project is in remote areas with no electricity. (b) The subsidized projects must operate no less than 20 years. (c) The solar PV generation units must have at least 0.1 billion RMB ($14.7 million) registered capital. (d) Single projects must have installed capacity over 300 kWp
July 2009	Renewable Energy Construction Model City Plan	(a) Select and subsidize qualified model cities, with 50–80 million RMB ($7.35–11.76 million) per city. (b) Model cities must have renewable energy coverage over 30% of the newly constructed area
January 2010	National Energy Committee created	(a) Directly supervise the Energy Bureau. (b)To unify national strategy for energy, ensure energy security, and coordinate energy development
Dec 2011	Twelfth National Energy Technology Five-Year Plan	(a) Set the target for obtaining key production technologies of 6–10 MW WTGS and critical parts, achieving ocean and land wind power generation. (b) Reduce the costs of solar PV energy to be comparable with conventional energy. (c) Create research and development capability for solar PV facilities with at least 1 MW capacity. (d) Construct grid solar PV power generation system with 100 MW capacity