The Unsustainable Rise of the Chinese Wind Turbine Manufacturing Industry

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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." Given the strong and clear incentives these firms face to protect innovations in large markets such as Europe or the U.S., it is hard to resist the conclusion that Chinese enterprises have simply not come up with any technology worth patenting.

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 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 -- by engaging in the world's largest program of wind farm construction and by limiting those farms to domestically produced components, the Chinese authorities effectively incubated a globally significant set of domestic producers.

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 more than 10% in Jilin, Hebei and more than 20% in Gansu, western and eastern Inner Mongolia and (GTM Research) (see Figure 1b for the geographical location of the provinces).[3] The problem has worsened in recent years. At the national level, about 17% of wind-generated electricity was curtailed, and the figure rose to about 20% in 2012[4]. Grid connection, while improving, still remains a problem. By the end of 2012, only 61GW of the 76 GW installed capacity, or 80%, was connected to the grid, compared to 70% in 2010 (NEA 2013; Greenpeace 2012). By comparison, in the U.S. the level of grid connection is generally very close to 100%, and curtailment rates in regions wherever data are publicly available are typically less than 5% (Wiser 2012). 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

[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.

[3] Corroboration is difficult, but similar figures were cited by Greenpeace (2012).

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

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 2010 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 consolidation 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 they are still running losses on their core turbine manufacturing businesses. 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 consolidation 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. 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

Electricity-generating turbine have been developed and improved since as early as 1891 with Poul La Cour's invention[5], followed efforts from Palmer Cosslett Putman two-bladed design in the 1940ies, and Johannes Juul and Ulrich Hütter efforts in Europe resulting from the aftermath of World War II. 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 (Heymann, 1999). Despite these earnest efforts, these government-sponsored wind programs were largely unsuccessful.

The subsequent emergence of Denmark as wind energy leader was led by amateurs and skilled artisans (Kamp, 2004), such Christian Riisager. His success prompted agricultural machine firms, such as Bonus, Nordtank and Vestas, to enter the market and operate on a larger scale, in particular targeting California (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

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

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 (p. 134, Samaras 2009).

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 generators employ fewer moving parts, reducing maintenance cost and increasing reliability (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[6]. 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.

[6] See Table A1 in the Appendix for summary of relevant policies

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 wind farm development, the largest crash program of wind farm 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 that required that at least 70% of any wind turbine supported by the law had to be manufactured in China. Effectively, the largest crash program of wind farm development in the history of the industry was being reserved solely for products with at least 70% domestic content.

In 2004, indigenous firms and Sino-foreign joint ventures accounted for only 17% of national installed capacity. To take advantage of China's ambitious wind farm 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 (Lewis 2013). 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 yuan 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 created 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 required regulatory agencies "to set priority dispatch regulations that will give priority to renewable power generators in the

electricity dispatch sequence," with the 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 since the early 1960s, and different patent analysis methods have been documented, each with its advantages and disadvantages (Jaffe and Trajtenberg, 2002). Simple patent counts, the most straightforward method, do not account for the (enormous) 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), 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 a priority application, with the patent office in their home jurisdiction. Under international patenting rule, within a short period of time they must also begin the patent application process in all other jurisdictions in which they want their patents to be protected -- if they do not, then other firms could infringe on this intellectual property without sanction, because a patent only confers protection within the sovereign boundaries of the nation that grants it. In a global economy, most internationally active firms will seek to patent valuable patents in all the major markets in which they sell -- or hope to sell -- goods and services based on the patented technology. To evaluate the merit of the patent application, patent offices normally conduct 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 list the related existing patents of which they are aware, and the

patent examiners, the experts in their respective technological classifications, may modify the list of citations[7]. 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 "*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

[7] In the U.S., patent applicants face a legal requirement to insert "appropriate citations to the prior art" in their obligations. In other jurisdictions, this is optional. U.S. patent examiners can also add citations to patents. In Europe, applicants are not required to insert citations, but the EPO patent examiners do, based on their evaluation of the patent appliation.

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 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 (Wooldridge, 2005), the observations are weighted as follows:

$$w = \sqrt{n_{i,k} n_{i,K}} \qquad (2)$$

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.[8]

[8] Taiwan is recognized by PATSTAT as a separate patent jurisdiction and we follow this convention.

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[9], French[10], German[11] and Spanish[12]. 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

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

[9] ABST/((("wind power" OR (wind AND turbine) OR windmill) OR (wind AND (rotor OR blade$ OR generat$) AND (electric$)))

[10] ABST/((("windkraftanlage" OR (wind AND turbine) OR windmühle) OR (wind AND (rotor OR blatt$ OR generat$) AND (elektri$)))

[11] ABST/((("Èrgie Èolienne" OR (Èolienne AND turbine) OR moulin a vent) OR (Èolienne AND (rotor OR pale$ OR generat$) AND (Èlectri$)))

[12] ABST/((" aerogenerador" OR (eolic AND turbin) OR molino de viento') OR (eolic AND (rotor OR pala$ OR genera$) AND (electric$)))

total number of 898 patents. Of these, inventors with German addresses were awarded the most patents (365), followed by Danish (156) and American inventors (92).

There were only ***two*** patents assigned to Chinese inventors (*Fig. 4a*). Time series trends in patenting at the national level are provided 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.

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 is more likely to be cited than a patent granted in the 2000s, indicating that the marginal technological value of patents in the wind industry, in terms of spurring future innovation, has declined substantially 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.

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.

What about the growing numbers of domestic patents taken out by Chinese wind turbine manufacturers? Are these not evidence of Chinese industrial dynamism? UC-Berkeley researcher Brian Wright and a series of co-authors have examined the recent

surge in Chinese domestic patenting across a broad swath of technologies, finding that government support, at various levels, for increased domestic patent applications explains part of the surge. Chinese companies are taking out local patents because they are paid to do. What is also true is that China's immature legal system still has great difficulty distinguishing between patents that protect real innovation and patents that merely pretend to protect real innovation. This provides local firms with large portfolios of "junk" patents potential legal leverage over rivals.[13] If these patents represented economically valuable inventions, then Chinese manufacturers who are increasingly seeking to export their products outside of China would have an extremely strong incentive to patent at least their most valuable inventions outside of China. The fact that they have not done so suggests that the Chinese firms themselves regard their "inventions" as not worth the time and expense of patenting outside China.

6. Recent Developments in the Chinese Wind Power Industry

Even if Chinese wind turbine manufacturers have, at least so far, failed to generate meaningful advances to the global technological state of the art, they could still be providing an important service to the global industry if they are able to push the costs of manufacturing standard products to low levels. For decades, China-based producers have been able to expand their global market share across a wide range of manufactured goods by offering products with reasonable levels of quality at low costs. Consumers around the world have benefitted from these low costs, even as rising Chinese competition has forced a reallocation of the labor force in countries where domestic producers have been unable to withstand the onslaught of Chinese competition. Low

[13] The largest number of intellectual property lawsuits anywhere in the world are Chinese firms suing each other for intellectual property infringement.

costs in China reflect much lower wages, of course, but they also reflect the low prices of the other factors of production. In Western countries, land for production facilities must generally be purchased from private owners. In China, private land ownership, *per se*, is still effectively nonexistent. The state owns the land, and can provide it to favored firms and industries at very low cost. Likewise, the cost at which China's state-owned banks lend to industry is also arguably artificially low.[14] Of course, policy distortions that artificially reduce the cost of land and capital inputs have an economic cost, in China and elsewhere. Moreover, such subsidies, if they are product-specific and distort trade, contravene international trade rules, and could result in China facing penalties in a WTO dispute.[15] Nevertheless, it stands to reason that, given these favorable environmental factors and a fairly mature technology, China-based wind turbine manufacturers would be able to produce at a lower cost than foreign rivals. And lower priced wind turbines could expand adoption of wind energy around the world, as well as in China, leading to faster adoption and more rapid global decarbonization.

However, recent evidence on the current state of the Chinese wind power industry suggests that China's breakneck expansion pushed prices to unsustainably low levels, undermining the financial health of China's heretofore rapidly growing wind turbine manufacturing sector. Data on the most recent developments in the Chinese wind power industry is surprisingly hard to come by. The wave of bankruptcies engulfing China's solar cell industry -- former market leader Suntech has already declared bankruptcy -- has received extensive attention in the international media, but the same media outlets have

[14] See Lardy (2011) for a careful analysis and evaluation of the degree to which key input prices in China have been artificially pushed down, as well as the economic consequences.

[15] In a definitional sense, a low price sustained by WTO-illegal measures may not be sustainable, in the sense that it may not be legally defensible.

said little about China's wind turbine manufacturers. Nevertheless, data from the Chinese Wind Energy Association (CWEA) suggest that a significant consolidation is underway. At the end of 2010, there were over 80 wind turbine manufacturers in China. That number had decreased to approximately 30 by 2013, according to industry sources. CWEA numbers suggest that annual wind turbine sales fell in quantity terms by more than 30% from 2010 to 2012 as the majority of firms eventually shuttered.

This consolidation has been driven, in part, by government policy. The Ministry of Industry and Information Technology (MIIT) developed a new set of regulations, the Wind Power Equipment Manufacturing Industry Access Standards, which came into effect in June 2011, requiring that turbine manufacturers had to produce wind turbines capable of generating 2.5 MW and possess an overall annual capability of a minimum of 1 GW in order to compete for domestic contracts. Only 12% of 80 Chinese manufacturers in the industry in 2011 were judged capable of meeting those standards, so these regulations had the effect of freezing marginal producers out of the expanding domestic market.[16] Manufacturers who meet the standards will continue to receive preferential treatment, including access to equity issuance on the Chinese stock market (a process rigidly controlled by the government), simpler requirements for bank loans, and tax breaks (Liu, 2011). Many Chinese industries plagued by overcapacity have struggled on the pathway to consolidation, because local governments try to keep local producers alive, even when economic logic would require many of them to close. By prolonging the period of overcapacity, this local resistance to consolidation raises the social costs and the ultimate degree of resource misallocation. By effectively disqualifying the vast

[16] See Alternative Energy eTrack

majority of producers, regardless of local financial support, MIIT presented the local governments with a *fait accompli*.

The results have been swift, and they have quickly laid bare the weakness of the majority of producers. Some 50-odd domestic manufacturers of wind turbines had borrowed money, hired workers, set aside land, and constructed factories. Now these enterprises are no longer producing. Given the extent of the downturn in the industry, and the financial weakness of the leading firms that remain, it is likely that much of this hastily constructed capacity will lay idle for a long time to come. The leading firms are certainly in no position to absorb the excess capacity themselves -- indeed the leading firms apparently have excess capacity problems of their own. The magnitude of these costs -- the full extent of the misallocation of resources that occurred as Chinese producers scrambled to meet the State Council's ambitious goals -- will only become evident with the passage of time.

And the process of consolidation may not yet be over. Some of the large firms still remaining in the industry appear to be on shaky ground. A number of them are listed on the Hong Kong stock exchange, and are tracked by a community of equity analysts that can, perhaps, speak more freely about the underperformance of firms in a government-favored industry than domestically based analysts could. China's number three manufacturer, Sinovel, is getting especially negative reviews. Since early 2011, Sinovel's equity price on the Hong Kong market has collapsed from HK $22 per share to less than $4 HK per share. Sales of turbines fell 61% in 2012 from 2011 levels, and the company is currently recording significant losses with no clear pathway to a return to financial health. Sinovel is known to American readers as the Chinese company accused

of stealing the trade secrets of a firm known as American Superconductor. The company is under criminal investigation by the U.S. Department of Justice and remains the target of a lawsuit filed by American Superconductor.[17]

The strongest Chinese firm in the industry, Goldwind, appears to be in better shape, and equity analysts judge it to have brighter prospects. But even this enterprise is far weaker today than the market expected three years ago. In late 2010, Goldwind's shares on the Hong Kong exchange traded at a price of nearly HK $20 per share. By August 2011 it was trading below $5 per share, a decline of nearly 75%, and it was still trading at these depressed levels as of August 2013. In addition to manufacturing turbines, Goldwind has invested in a number of windfarms. More than 100% of its total profit came from these noncore investments in the first half of 2013. Operating income from the core turbine manufacturing business was still negative in the first half of 2013; market forecasts suggest that it will turn barely positive in 2013, but fall back to zero in 2015. Market commentary on Goldwind's alleged order backlog was positive, but Goldwind's production is far short of capacity now. The backlog appears to reflect delayed purchases by customers rather than current capacity constraints. Despite improving conditions, analysts project that Goldwind's return on assets will be quite low: around 1.3% in the current year, rising to only 2% in 2014. This is far below estimated average returns on investment in the Chinese private sector. Gross margins on Goldwind's turbines are rising, because prices are rising and because materials costs have

[17] See Wright's Research Service analyst report on Sinovel, July 4, 2013.

fallen slightly. But this has not been enough to shore up the financial fortunes of Goldwind's core business.[18]

No one is predicting that the entire Chinese wind turbine industry is going to disappear, even if a majority of the active firms in 2011 have since ceased production. No one is forecasting that China's leading firms will cease to be a global force, even if some former high flyers, like Sinovel, appear to be sliding toward dissolution. But when the country's leading enterprise is earning a return on its assets that is lower than the yield on government bonds -- and that only because of income outside of its core business of turbine manufacturing -- then it is fair to ask what the broader return to China has been on the expensive experiment launched by the passage of the Renewable Energy Law. At the moment, that return does not look that good.

How did it come to this? In hindsight, it appears to be a classic validation of the ancient proverb that haste makes waste. In the mid-2000s, the Chinese government set extremely ambitious targets for renewable energy consumption by the end of the decade. It also required that all new wind turbines used to meet this target by 70% manufactured in China. This unabashedly protectionist move was not challenged by a major trading partner for years. This started a gold rush in China's wind sector as domestic firms moved in to what was the most frenetic build-out of wind energy ever attempted in any country, confident that their most technologically sophisticated and well established foreign rivals would be effectively kept out of the marketplace, except to the extent that they transferred technology to Chinese affiliates or joint venture partners. China's protected internal marketplace was primed to rapidly become the biggest wind energy

[18] These facts are taken from KGI's August 26, 2013 analyst report on Goldwind.

market in the world. Firms with limited technological capability and manufacturing scale scrambled into the marketplace to be part of China's green revolution. With the scale of this revolution fully endorsed by the State Council, it was reasonable to expect that the power generators and grid operators would be forced to buy wind power from domestic producers -- even if the prices were high -- in order to meet the mandates of the nation's most powerful governmental body.

However, as the deadlines approached, the entities that purchased and distributed energy within the national grid received crucial "wiggle room" from the central authorities. As wind farms were hastily constructed, many of them were simply not connected to the grid. When the marginal cost of wind energy increased, the grid operators were allowed to "curtail" it -- that is, reject the wind energy in favor of conventional energy that was less expensive. Full enforcement of the 10% mandate would have required the grid operators to either incur significant losses or pass large electricity price increases on to China's energy-intensive manufacturers at a time when the central government was far more determined to maintain growth in the wake of a global economic crisis than it was to enforce green power mandates, and this inclination was reinforced by a substantial drop in fossil energy prices after the global crisis. China's appetite for a surge in wind energy declined at precisely the moment that the investment boom of the 2000s was resulting in a hefty surplus of turbine manufacturing capacity. Faced with an unexpected glut, producers lowered prices below marginal cost, the financial health of the industry imploded, and the equity prices of even the leading producers collapsed.

As the scale of overcapacity and overproduction in the wind turbine sector -- especially among the smaller, less capable producers -- became apparent, MIIT seems to have become the designated Grim Reaper, implementing regulations that shut the entire lower tier of producers out of further wind farm supply contracts. The majority of producers are now apparently shut down, providing badly needed "breathing room" for the leading manufacturers, like Goldwind. As the degree of overcapacity has faded, turbine prices have modestly risen. In light of all this, it seems that China's march down the cost curve went several steps too far. The rock-bottom prices of two years ago reflected not unbeatable Chinese manufacturing dynamism but the desperation of an industry drowning in overcapacity as price fell below marginal cost. It is unclear where the equilibrium price point is, or when China's industry will reach it. Still, when the industry's top firm is losing money on its turbine manufacturing business, we may not be there yet. Here again, the Chinese wind turbine industry has fallen short of what its most ardent domestic and foreign supporters might have wished. The industry has failed to invent new technologies and it has also run into limits in terms of the degree to which it can depress the prices of products invented by others. Even in China, it seems, one cannot lose money on every item but make it up on volume.

7. Conclusions

China established itself as a major global 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 in the Western media 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 little 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 the European Patent Office, a major patent jurisdiction 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, especially when compared against the increasing intense patenting activities outside China of Chinese firms in other sectors. 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, the industry's rapid development can be attributed to a highly supportive policy environment. 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 possible 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 three years ago. The latest industry data suggest that the *majority* of producers active in the industry in 2010 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 consolidation 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 stabilize and raise turbine prices slightly in recent quarters. 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 insufficient to cover their full costs of production, including capital costs. 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 consolidation 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 among domestic manufacturers. 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.

Despite the current situation facing the industry, we believe that leading Chinese firms are likely to remain important global players in the near future. By singling out clean energy as one of the seven priority industries, China government signaled its firm commitment to clean energy development in its 12th Five-Year Plan (2011-2015). With the continuation of friendly policy environment, China's wind power industry is likely to rebound. However, even as the industry regains its financial footing, further progress in terms of cost reductions is likely to slow substantially relative to the recent past, as is the growth rate of the indigenous industry.

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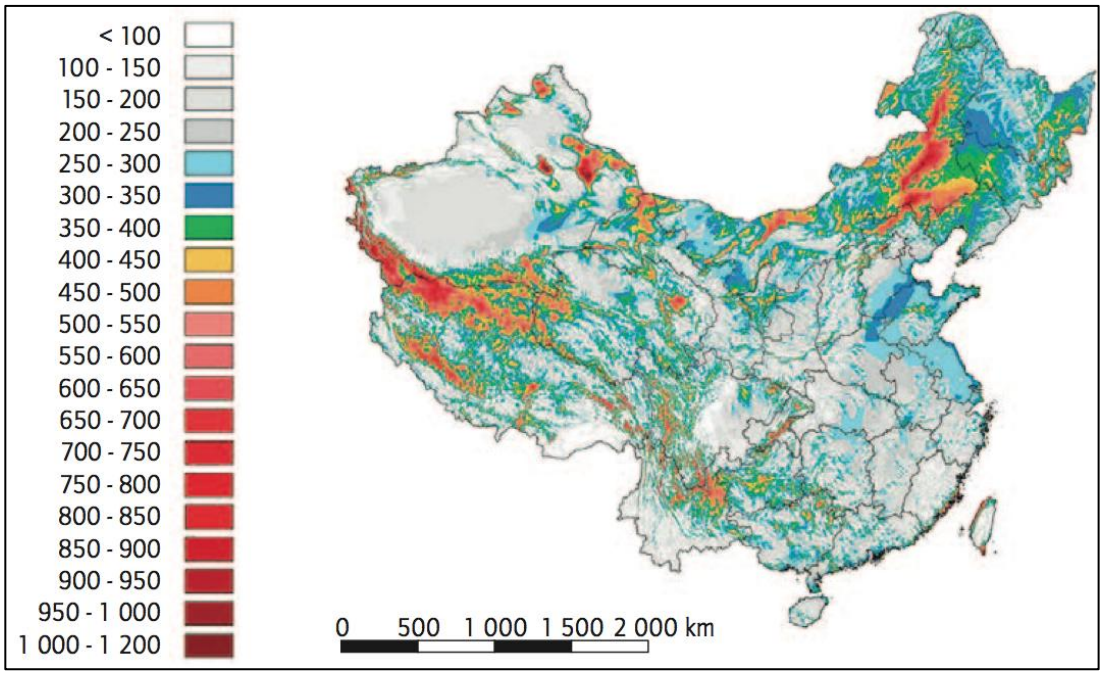


Figure 1a: Distribution of China's wind resource potential. The country's northern and northeastern regions are among the windiest. Wind power density is expressed in W/m^2, measured at 70m height. *Source*: Figure from *IEA, 2011* .

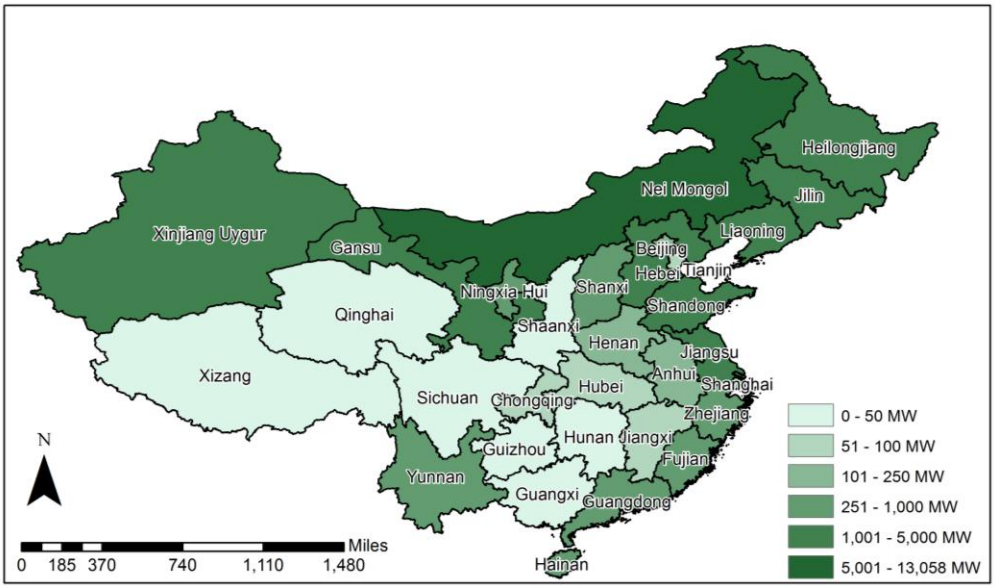


Figure 1b: China's wind power installation by provinces. *Data Source*: Figure from CWEA (2012).

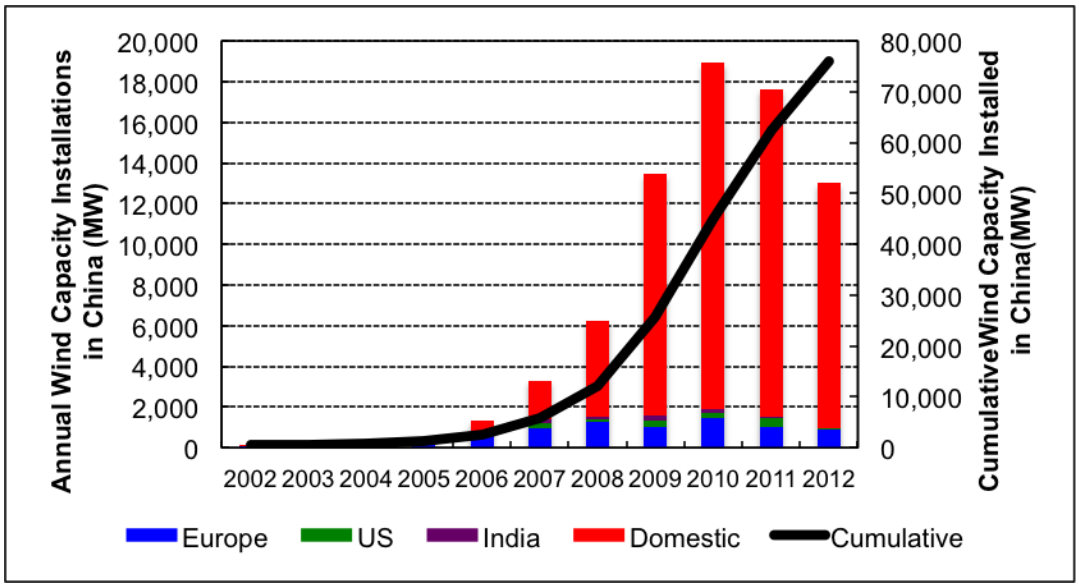


Figure 2a: Annual and cumulative wind nameplate capacity installations in China by year. Plot constructed by the authors using data from*:* CWEA (2007 - 2012), Shi (2003 - 2006), and Alternative eTrack (2012).

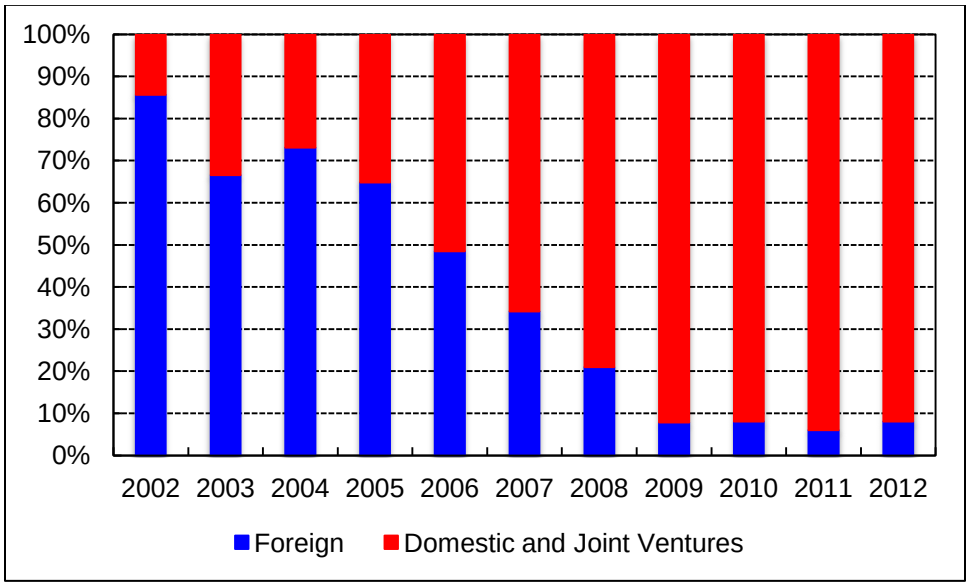


Figure 2b: Market share of China's wind turbine installed capacity. Domestic and joint ventures dominate Chinese wind turbine market in recent years. Plot constructed by the authors using data from CWEA (2007 - 2012), Shi (2003 - 2006), and Alternative eTrack (2012).

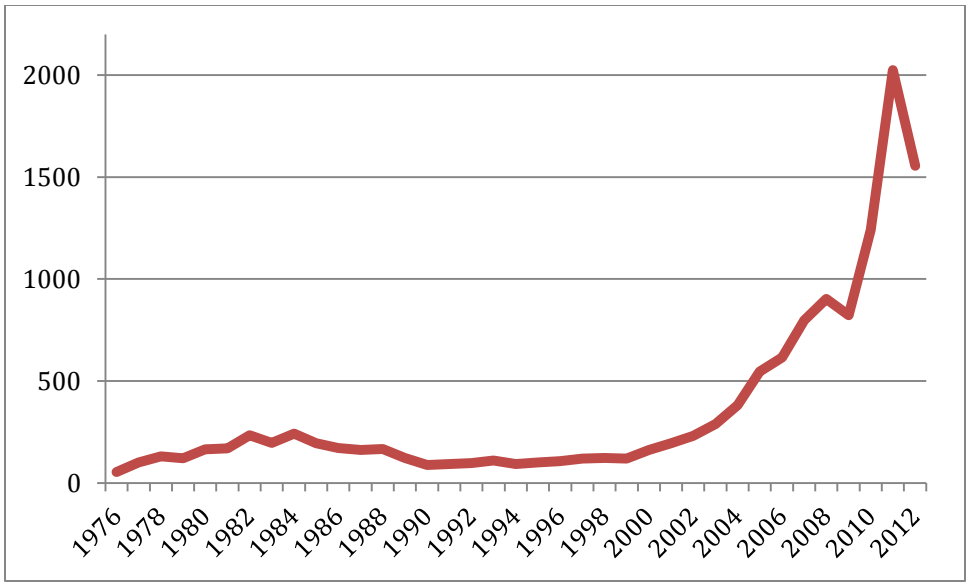


Figure 3: Total wind power patents granted by EU15+ countries, sorted by the year the patent is granted from 1976 to October 2012. *Source*: PATSTAT 2012.

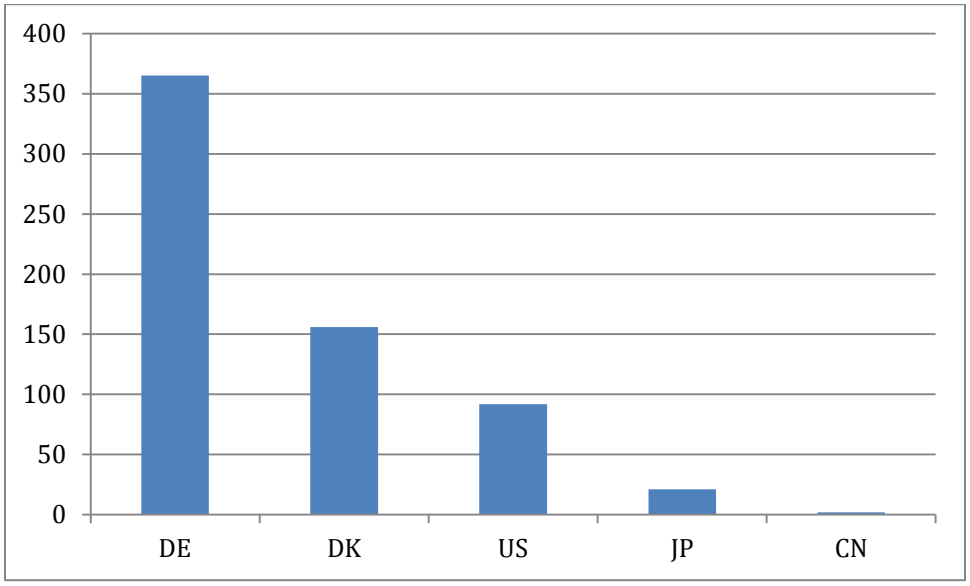


Figure 4a: Total number of wind power patents granted by the EPO to inventors from Germany, Denmark, US, Japan and China.

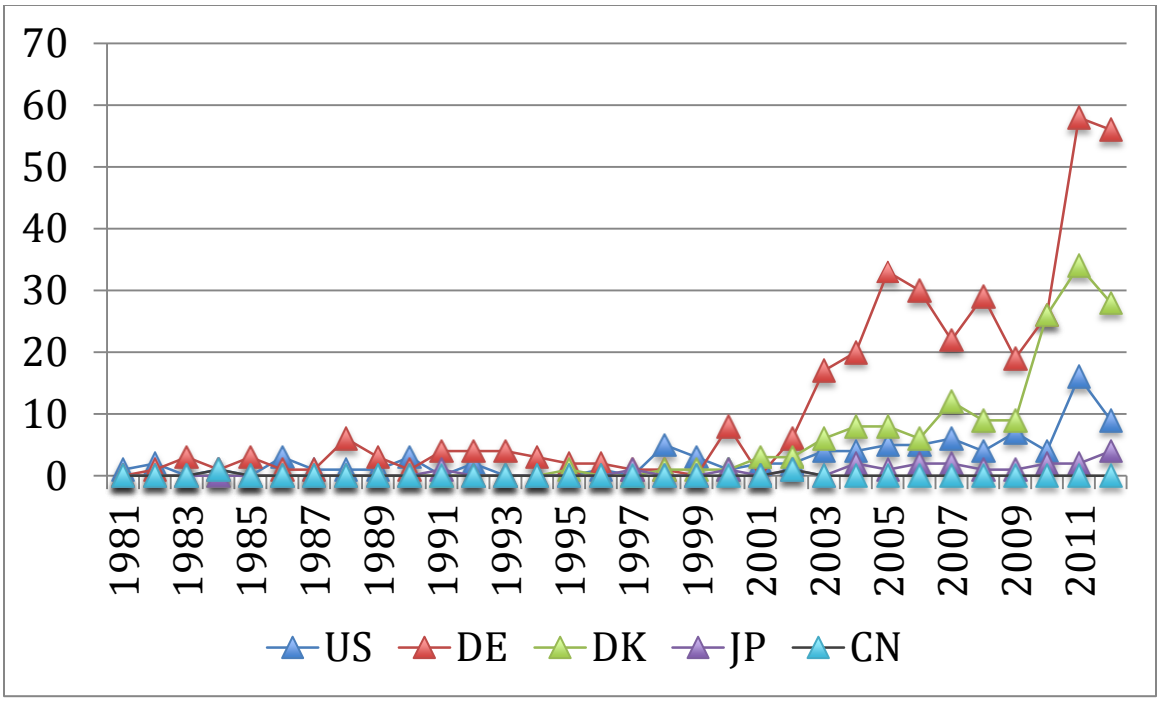


Figure 4b: Number of wind power patents granted by the EPO to inventors from Germany, Denmark, US, Japan and China by year.

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.

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