China's wind industry: Leading in deployment, lagging in innovation

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ABSTRACT

China's massive carbon emissions and air pollution concerns have led its government to embrace clean energy innovation as a means of transitioning to a more sustainable energy system. We address the question of whether China's wind industry has become an important source of clean energy technology innovation. We find that in terms of wind capacity expansion, China has delivered enormous progress, increasing its wind capacity from virtually no wind capacity in the early 2000s to 140 GW by 2015. However, in terms of innovation and cost competitiveness, the outcomes were more limited: Chinese wind turbine manufacturers have secured few international patents and achieved moderate learning rates compared to the global industry's historical learning rate. Leading China-based indigenous producers are likely to remain important global players for the foreseeable future, but further progress in reducing the cost of capital equipment may slow relative to the recent past. However, opportunities in lowering curtailment rates and improving turbine quality can reduce China's overall levelized cost of electricity for wind.

1. Introduction

Given the environmental, health, and climate change costs associated with conventional electric power generation, and given the country's rich wind resources, China has embraced a 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. In 2001, China's cumulative installed capacity was only a little over 400 MW. By 2012, it had surged to 75,000 MW, allowing China to surpass the U.S. as the country with the most installed wind capacity (GWEC, 2012). Through 2008, China experienced an annual wind installation growth rate of at least 60%. From 2009–2010, the growth rate slowed down to a still impressive level of 37% and accelerated again in recent years. China's wind resources are concentrated in its northern and northeastern regions (He and Kammen, 2014), and this is also where the majority of the country's wind power capacity is located (Fig. 1).

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 market as recently as 2004. However, as

Fig. 2 shows, indigenous firms dominated the explosive growth of installed wind capacity after 2005. By 2010, these Chinese firms claimed a cumulative 90% market share. Today, five of the top ten global original equipment manufacturers in the wind turbine industry are based in China (GlobalData, 2016).

China has enacted a number of policies in recent years to boost its supply of renewable energy.[1] A key turning point arose with the Renewable Energy Law of the People's Republic of China, passed in 2005 and implemented in 2006, which empowered key government players at the national and provincial level to draft renewable energy development and utilization plans (Schuman and Lin, 2012). Currently, the government is planning for 20% of China's primary energy consumption to come from renewable energy sources by 2030 (UNFCCC, 2015).

Developments in China's wind energy industry have attracted a lot of attention, both in the popular press and in scholarly research. Many studies systematically review historical developments within the industry and relevant government support policies to explain the rapid rise of China's wind energy sector (Kang et al., 2012; Liu and Kokko, 2010; Wang et al., 2012; Zhang et al., 2013). Other studies examine the technological change of China's wind energy industry in terms of
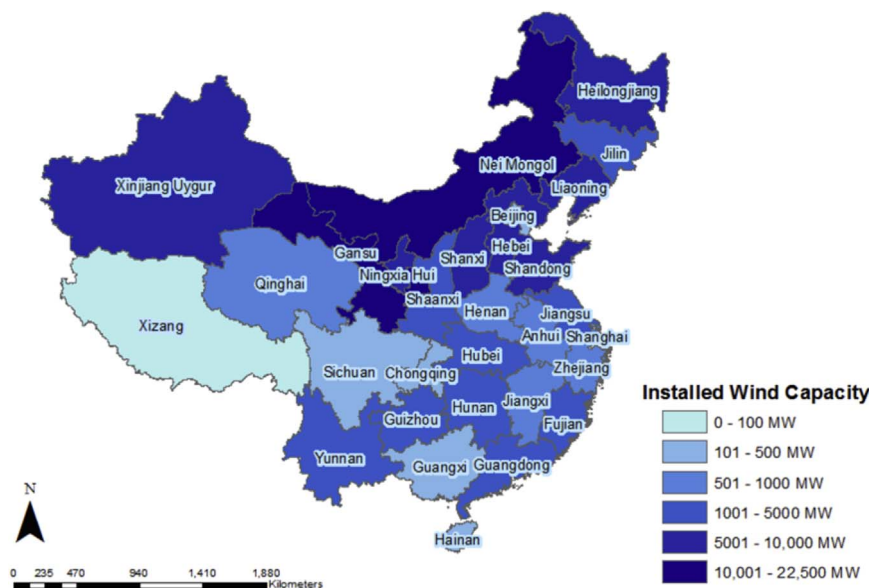
Fig. 1. China's wind power installation by province in 2014. Provinces with most wind power installed are also those that have significant wind resources. Data from CWEA (2015). Map produced by authors.
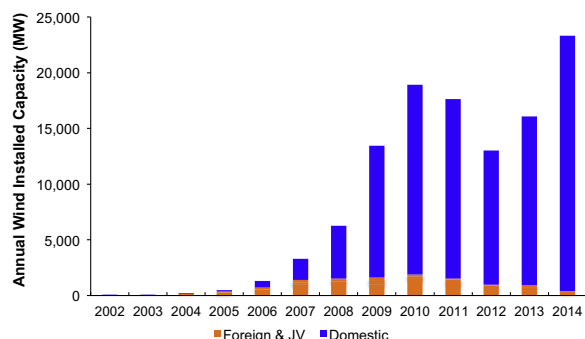

Fig. 2. Annual wind nameplate capacity installations in China by year, broken down by domestic versus foreign firms. Domestic firms dominate the market in recent years. Plot constructed by the authors using data from (CWEA, 2015).

turbine size, increases in domestic patenting and innovation activity, and cost reduction in turbine manufacturing (Lewis, 2013; Nahm and Steinfeld, 2014; Qiu and Anadon, 2012; Ru et al., 2012). The literature has consistently recognized China wind power industry's late-comer status and documented its successes in capacity building, technology transfer, and learning (Gosens and Lu, 2013; Lema and Lema, 2012; Lewis, 2013; Qiu and Anadon, 2012; Tang and Popp, 2014; Wang et al., 2012). Some studies assert that China's wind energy boom has been driven by indigenous innovation (Ru et al., 2012). Bettencourt et al. (2013) note the large number of wind turbine patents granted to indigenous producers by the Chinese Patent Office (SIPO), and conclude that these firms have engaged in robust and substantial innovation.

We build on this literature, empirically examining the contribution of Chinese wind turbine firms to the advance of the global technological state of the art. Using international patent data, we undertake an analysis of international innovation trends in wind turbine manufacturing technologies. We find that international patenting activity among Chinese firms and inventors has been minimal to date. China's top indigenous wind power manufacturers have not patented many new wind technologies in major markets outside of China. At the same time, Chinese patents are less likely to be cited than their foreign counterparts. Additionally, we find that while Chinese firms have managed to push the costs of current technology to low levels, the measured learning rate has been relatively modest, and further cost

reductions may be limited.

The rest of the paper is organized as follows: Section 2 reviews the previous literature on energy innovation, with a focus on papers that use patents and estimated learning curves as metrics for progress in China's renewable energy technologies. Section 3 explains our data and methods. Section 4 presents our results. The paper concludes with a discussion of the results and implications.

2. Literature review

2.1. Energy innovation systems

Modern scholars view innovation as a complex process involving multiple linked stages with feedback loops between them (Kline and Rosenberg, 1986). Under this "chain-linked" model, knowledge does not flow only uni-directionally from basic science to applied technology, a sharp departure from the previous "linear model." Modern scholars also view innovation in the context of a system of multiple interacting agents and institutions. Carlsson and Stankiewicz (1991), for instance, propose a technological innovation system (TIS) framework, in which the systemic interplay of firms and other actors play key roles in the generation, utilization, and diffusion of various technologies or products. The TIS framework, which consists of seven system functions (Bergek et al., 2008; Hekkert et al., 2007) has been used widely to analyze various technologies, including clean energy (Markard et al., 2012). Some authors have taken this systems approach and adapted it to the challenges of energy innovation, creating an emerging literature on energy technology innovation systems (ETIS) (Gallagher et al., 2012). The innovation process is a collective and interactive activity that involves multiple linked stages (research, development, demonstration, market formation, and diffusion), and it is performed by a network of actors in their market, institution, and policy contexts. Systemic analysis of each phase can be important to understand the process of technological change and useful to inform policy (Gallagher et al., 2012). Elements of the Chinese energy innovation system have been characterized to various extents by previous studies (Gosens and Lu, 2013; Grubler et al., 2012; Zhao and Gallagher, 2007). When viewed in the systems perspective, this paper centers on the invention phase, or the knowledge development stage of the innovation process in China's wind turbine manufacturing industry.
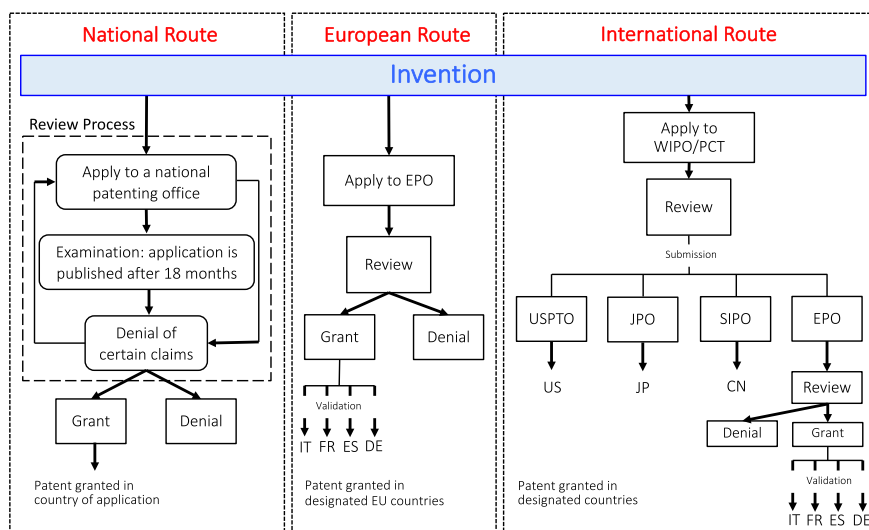
Note: The clock starts when the inventor first files an application with a patent authority.
Patent applications are typically published 18 months after they are filed.

Fig. 3. Three main patent application routes and their procedures.

2.2. Patent as an innovation metric

Patents have been used as a measure of innovation since the early 1960s in mainstream economic research (Griliches, 1990) as well as in energy innovation research. Information about the invention and the inventor is readily available in patent data and can be disaggregated into specific technological fields. Furthermore, there are few economically significant inventions that are not captured in the patent data (Johnstone et al., 2009). Broadly speaking, patent data analyses can be categorized into two approaches: patent counts and patent citation analysis. They have been used widely in the economic literature, each with its advantages and disadvantages (Jaffe and Trajtenberg, 1996). Patent counts, which tally the total number of applications or granted patents, are straightforward and a number of studies have employed this metric. Within the energy innovation literature, Popp (2005) shows that innovative activity responds to incentives, social returns to environmental research are high, and policies can be used to influence new inventions. Johnstone et al. (2009) illustrate that different environmental policies have different effects on renewable energy technology innovation. Examining wind turbine patenting activity in the U.S., Horner et al. (2013) find that RPS policies have positive effects on wind innovation, whereas tax-based incentives are not as effective. A number of studies examine the number of renewable energy patents in China (Bettencourt et al., 2013; Gallagher, 2014; Gosens and Lu, 2014) and find that Chinese patenting activity is on the rise. However, simple patent counts neither account for the differences in commercial values of various patents nor indicate whether the patented technology is adopted.

Patent citation data can address some of the limitations associated with patent counts. If we assume prior inventions cited in new patents are important fundamental knowledge on which the new knowledge is built, then the more important this knowledge precursor is, the more often it is cited. Patent citation analysis examines the number of times each patent has been cited by subsequent patents, and has been used to measure patent quality (Trajtenberg, 1990), economic value (Harhoff et al., 1999) as well as knowledge flows and spillovers across inventions (Jaffe et al., 1993). Within the energy innovation literature, Popp (2002) shows that patent citations can be used as a measure of the knowledge supply available to inventors. Nemet (2009) uses the number of times a wind patent is cited as a measure of its value. More recently, Nanda et al. (2015) use a negative binomial count model to show that patents associated with VC-backed startups are cited more often than those associated with incumbent firms. We use a similar approach in this paper to compare the quality of patents granted to Chinese inventors with the quality of patents granted to non-Chinese inventors.

2.3. Learning rate

The estimation of learning curves or experience curves constitutes an alternative approach to measure technological progress (Arrow, 1962). Accumulation of production experience in manufacturing can lead to incremental innovation in the production process that increases productivity and lowers cost. One can determine the "learning rate" parameter by linking the unit cost of wind turbine technology to cumulative production or installed capacity and track the reduction in cost for each doubling of cumulative production or capacity. The learning rate is often derived from historically observed cost reductions, and it can also be used to project the technology's future trends and progress. Since first proposed by Arrow (1962), this concept of learning-by-doing is well known in the innovation literature, and has been employed to evaluate technology improvements in the renewable energy industry in various regions across the world (Goldemberg et al., 2004; Grübler et al., 1999; Junginger et al., 2005; Qiu and Anadon, 2012; Rubin et al., 2015; Tang and Popp, 2014; Yao et al., 2015). In particular, Qiu and Anadon (2012) use data from China's national wind energy concession program between 2003 and 2007 to find that the learning rate ranges from 4.1% to 4.3%. Yao et al. (2015) use a more complete dataset from the Clean Mechanism Development and find that the learning rate is around 4.4%. In this study we use a complete dataset from CDM project database to construct an econometric model and estimate the learning rate of China's wind power industry.

3. Data and methods

3.1. Patent data and patent count

Inventors who wish to use the patent system to protect their invention first file an initial patent application (also known as "priority application") with a national patent office – usually the one in their home jurisdiction – or a regional patent office like the European Patent Office (EPO). Inventors can also protect their IP rights under the Patent Cooperation Treaty (PCT), which is administered by World Intellectual Property Organization (WIPO). Fig. 3 shows the application processes for these three patenting routes.

Under international patent rules, inventors then have up to one

year to choose to apply for patent protection abroad for the same invention. Foreign applications filed within this period will retain the same application date as the one on their initial application. This is important, because under World Trade Organization rules, patents are awarded in nearly all countries under a "first to file" principle rather than a "first to invent" principle. To evaluate the merit of the patent application, the patent office normally conducts an international search report of prior art. This search report helps the patent office assess the patentability of the invention as well as the legitimacy of the claims made by the inventors.

Upon filing an application with the United States Patent and Trademark Office (USPTO), inventors have a legal obligation to make "appropriate citations to the prior art" on which they build. During the evaluation process, patent examiners, who are experts in their respective technological fields, may modify the list of citations. These citations serve as legal boundaries, limiting the scope of the property rights eventually awarded to the patent applicant by explicitly placing related ideas outside the boundary of what the eventual patent award will protect. The inventors thus have an incentive to limit unnecessary patent citations. However, deliberate omission of relevant patent citations can be grounds for legal sanctions or even patent invalidation, so inventors have an incentive to cite all relevant patents (OECD, 2009). In major patent jurisdictions outside the United States, inventors are not required to include citations to the prior art in their initial application, but examiners add these citations to the document, thus circumscribing the range of intellectual property that can be protected by a successful application in the same manner.

Patent data used in this study come from the European Patent Office Worldwide Patent Statistical Database (PATSTAT), which includes all patents that inventors have filed in patent offices around the world. This dataset includes observations from 1980 to October 2015. To account for 2015's incompleteness, we limit our data range to the end of 2014. To identify relevant patents, we rely on a combination query method that finds wind energy patents by combining patents assigned to "wind energy" in the PATSTAT database with those that are clearly connected to wind energy based on a keyword search of the patent abstracts. Similar to Johnstone et al. (2009), we use the "F03D" International Patent 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) for wind power keywords in English, German, French, and Spanish, the major working languages of the EPO.

Patent applications, whether successful or not, are typically published 18 months after their filing dates. Our data sample only includes patent applications that are successful ("patent grant"), and it is organized by their publication years. Two types of patents are excluded from this data set: utility models and design patents. Utility models, also known as "petty patents", are incremental in nature compared to invention patents and are valid for a shorter time period. Design patents protect only the appearance of products rather than the ways in which they work. Neither category of patents is subject to an examination process that tests the idea's technological novelty. Instead, we focus on "invention patents," which undergo such an examination process. Because international knowledge spillovers and international technology transfer have played important roles in the Chinese wind turbine manufacturing industry (Lewis, 2007; Lewis, 2013), we determine the patent's "nationality" using the inventor's geographic location. If the inventor information is missing, we use the applicant's location instead. For patents whose inventors come from different countries, each country represented is counted once. In this sense, we do not report "fractional counts", thus our country-level count results may be inflated due to some double counting. We will also examine international patenting activity of leading Chinese wind turbine manufacturers.

We first focus on patents granted by the USPTO and the EPO because, compared to the Chinese Patent Office, the patent examina-

tion processes undertaken by these two organizations have been assessed to be more mature and robust. For instance, prior to 2009 Chinese patent examiners limited their search reports to only domestic prior art, thus there were no requirements for absolute global novelty (Cass, 2009). However, because inventors typically file first with their home country's patent office (though this is not always the case), this home-country bias may understate innovation progress made by Chinese inventors. Therefore, we will additionally examine PCT/WIPO patent applications. A PCT/WIPO patent application reserves the applicant the right to file for patent protection in PCT contracting states beyond his or her home state (Fig. 3), and is often of high quality. After an inventor files an application, PCT examiners conduct an international search report, where they look for relevant patent documents and other technical literature in Chinese, English, German, and Japanese. PCT's rigorous and uniform procedure minimizes some home bias effects. However, home bias may not be completely eliminated for citation data. An inventor can apply for a PCT application, but the final decision to grant protection rights is made by a national or regional patent office, and home bias may persist owing to different practices across patenting jurisdictions. We will discuss how this bias may affect our findings in the results section.

We define a "PCT patent" as a PCT application that was successfully examined and granted by any national patent office, including SIPO. These patents are organized by the years they were published by WIPO.

3.2. Patent citation analysis

To complement our patent count analysis, we perform a patent citation analysis, where we evaluate differences in patent quality across geographical areas. By assuming that citations indicate a flow of knowledge, as in Popp (2002), citation counts can be a useful metric for the value innovation; patents with a high number of citations are likely to possess high usefulness and value. For the purpose of our study, we use count data models to estimate the citation rate of a patent relative to its peers of similar characteristics. In the context of our study, we are estimating the likelihood that a wind patent granted to a Chinese inventor would be cited compared to one granted to a non-Chinese inventor.

Patent citation frequency data are count data, or non-negative integers.[2] We can run regressions using a linear model, but the small and discrete values of citation frequency, and the preponderance of zeros (in any given year, a number of patents receive no citations) imply that the distribution of the error term is quite different from the usual assumptions of the linear model. The widely used Poisson regression model is derived from the Poisson distribution by parameterizing the relationship between μ and regressors x. We assume that the observed count for observation i is drawn from a Poisson distribution with mean μ_i, and μ_i is estimated from observed characteristics:

$$\mu_i = exp(x_i\beta), \qquad i=1, \ldots, N$$

In our case, these characteristics include the patent's grant year and its nationality. The log-likelihood is:

$$lnL(\beta) = \sum_{i=1}^{N} \{y_i x_i'\beta - \exp(x_i'\beta) - ln y_i!\}$$

The Poisson maximum likelihood is the solution to the nonlinear equations corresponding to the first-order condition for maximum likelihood.

However, the Poisson distribution assumes equidispersion, or equality of mean and variance. Citation frequency data often exhibit overdispersion, and we can adjust for this by using a negative binomial

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[2] Please consult Cameron and Trivedi (2012) for a formal explanation of count data regression models.

regression model, which corrects the overdisperson by incorporating an error term *u* that follows a gamma distribution.

Our citation sample includes information for patents that are granted through the PCT process. PCT or WIPO patents can overcome some limitations associated with home-country bias, where inventors tend to file for patents in their home jurisdictions, due to their international nature as mentioned above.

Since a patent may be granted in multiple jurisdictions, PATSTAT keeps track of these various national versions and groups them into a patent family. To avoid double counting, we keep track of citations made to all patent members of a family by other patent families. For instance, if a patent is cited by two patents of the same family, then in this formulation that patent only receives one citation. Because we are interested in the technological trajectory of wind technologies, we only consider wind patents citing other wind patents. Citations made by non-wind patents and non-patent literature are excluded. We determine a patent's nationality using the geographical location of the first inventor. We will compare the likelihood of a Chinese patent being cited with patents from countries known for high wind innovation activity, namely Germany, Japan, the U.S., and Denmark. We include year fixed effects to account for the fixed differences in the number of citations across the patent year cohorts and a time exposure term to account for the time elapsed since a patent was first published. Because the Chinese wind industry began in earnest in the early 2000s, we also examine recent patent cohorts that were granted between 2004 and 2014.

3.3. Learning rate

The bulk of our data on wind projects and their costs come from the CDM, which is administered by the United Nations Framework Convention on Climate Change. Our dataset, compiled by the UNEP (2015), covers 1477 onshore wind farm projects in China from 2004 to 2012 and includes information on project name and location, turbine manufacturer and type, total investment, total installed capacity, starting date,[3] estimated utilization hours, estimated yearly and life-time generation, estimated emission factors, etc. This dataset covers a total of 81.7 GW, compared to the 75.4 GW of actual installed capacity. Summary statistics of key variables are presented in Table S3 and Table S4 in the supporting information. After 2012, Chinese developers virtually ceased applying to CDM due to the collapse of carbon price in the European carbon market. Additional CDM revenues did not justify the high costs of the application process and related consulting services.

Similar to prior studies (Qiu and Anadon, 2012; Yao et al., 2015), we estimate the learning curve by assuming that wind turbine cost reduction depends on cumulative wind turbine installation capacity, following a log-linear process $C_t=aN_t^\alpha$, where C_t and N_t are unit costs of wind turbine and cumulative installed capacity at time *t*, respectively. Thus, with every doubling of cumulative installed capacity, the relative cost reduction, or *learning rate*, is given by:

$$Learning\ rate = \frac{C_t - C_{t2}}{C_t} \leftrightarrow \frac{a(N_t)^\alpha - a(2N_t)^\alpha}{a(2N_t)^\alpha} \leftrightarrow 1-2^\alpha \quad (1)$$

The coefficient α represents the *learning factor*. The literature on learning rates uses either capital cost or levelized annual cost as the dependent variable. We use both capital cost and the levelized cost of electricity (LCOE). LCOE's depend on the plant's load factor, fixed costs and variable costs. In the case of wind power, a project would initially incur a fixed capital cost, and subsequently some variable costs in the form of operations and maintenance. The LCOE can be calculated as follows:

$$LCOE = \frac{FC + \sum_j^n \frac{VC_j}{(1+r)^j}}{\sum_j^n \frac{GE_j}{(1+r)^j}} \quad (2)$$

where FC and VC_j indicate the project's initial fixed investment cost and its variable investment costs in year *j*, GE_j is the total amount of electricity generated in year *j*, and n is the lifetime of the plant (which is assumed to be 20 years). We assume a discount rate *r* of 8%, the same as the Chinese power industry's benchmark IRR. For simplicity, we assume that the variable costs are 20% of the total investment cost. All currency values are deflated to their 2004 levels using the World Bank's Currency Deflator for China.

The estimated amount of electricity that a power plant will generate depends on its load factor, or the ratio of actual electricity generation to the maximum possible generation assuming continuous full power operation during the same period, and it can be determined by the availability of grid capacity, equipment availability, and wind speed. In order to gain approval to register with CDM, a project must successfully complete a multi-stage application and verification process, so data quality is not a concern.[4] Because cost data are not publically available, we compute the LCOE using price data. We will discuss how using price instead of cost data can affect our results. We emphasize that electricity generation is an estimate (i.e., it is not the observed electricity generation by that wind farm – such data are not reported).

To estimate the learning rate, we employ a basic econometric model where the independent variable is the cumulative installed capacity of wind power in China. For the dependent variable, we use both capital cost and LCOE. We introduce control variables for the project's location and its starting year to account for the time-invariant differences across provinces. We will also introduce the plant's load factor variable, which is a function of wind resources and technology progress.

4. Results

4.1. Wind patenting activity

We start by counting all wind patents in the PATSTAT database published by patenting offices in China and in regions with the most activity in wind turbine invention, manufacturing, and deployment, including the EPO and the EU15 nations, Japan, South Korea, Russia, Canada, and the United States. Fig. 4a and Fig. 4b show the total number of patents granted by these patent offices. We only track priority patents to avoid double counting.

Fig. 4b shows that patenting activity started in the early 1980s and accelerated in the 2000s. The most recent burst of inventive activity began in the late 1990s. At this point, a number of European countries accelerated their efforts to curb carbon emissions. The ratification of the Kyoto Protocol by Western Europe's industrial states, coupled with incentives such as feed-in tariffs in several European countries, sent a clear signal to the industry (Dechezleprêtre et al., 2011). We note the impressive increase in patents in the Chinese Patenting Office, which grew from zero in the 1980's to about 3500 patents cumulatively by 2014, the vast majority of which were granted in the last few years. This growth in domestic patents is consistent with previous findings (Bettencourt et al., 2013; Gallagher, 2014).[5]

However, this figure treats Chinese domestic patent grants as being equivalent to European or U.S. patent grants in quality. We next assess the number of patents that were awarded to inventors in the major patenting offices, i.e., the EPO and the USPTO.

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[3] Starting date refers to when a 'real' project activity takes place, typically referring to the signing date of equipment purchase contract or the construction date. The registration process for CDM usually completes some time later.

[4] For more information see https://cdm.unfccc.int/Projects/diagram.html

[5] PATSTAT coverage of inventor information is incomplete for SIPO data. Examining domestic wind power patenting activity, Gallagher (2014) reports that a majority of SIPO patents were granted to domestic inventors.
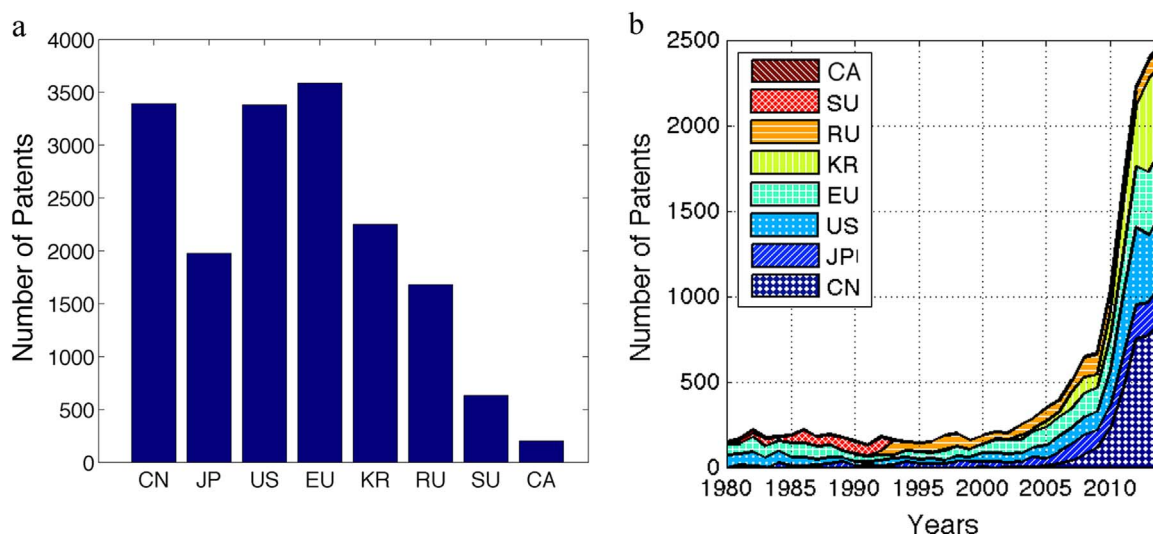
Fig. 4. a and b: Wind power patents granted by all patenting offices: (a) total wind patents from 1980–2014 by country/region and (b) wind patents over time by country (China = CN, Japan = JP; United States = US; European Union 15= EU and EPO member states; South Korea = KR; Russia = RU; Soviet Union = SU; Canada = CA). Data from PATSTAT 2015; plot produced by the authors.

When we restrict our sample to only patents that were granted by EPO member states, the total number of patents drops substantially (Fig. 5a and b). Of these, inventors with German addresses were awarded the most patents, followed by Danish and American inventors. Inventors typically file in their home-country patent offices first, and only apply to the EPO to extend protection to some or all of the 38 member countries states. Because the EPO's patent application process can be costly, EPO data filter out low-value inventions (Johnstone et al., 2009), explaining the smaller number of patents granted by the EPO member states.

Over our entire sample period, only 16 patents out of a total of 1695 wind patents (or 0.9% of the total wind patents in the EPO) have been granted by EPO member states to Chinese inventors (Fig. 5a). To date, Envision and XEMC have respectively lodged 38 and 19 EPO applications, receiving respectively two and six patents (see Table 1). Sinovel has submitted 21 patent applications to the EPO, but, of these, all but one were either subsequently withdrawn by Sinovel or deemed to be withdrawn by the EPO. Sinovel has secured one patent grant. The other seven of the top 10 Chinese wind turbine manufacturers have not obtained any EPO patents, and five of them have no records of applying for patent protection through EPO. We note that China's State

Intellectual Property Office granted over three thousand wind patents over the same time period (Fig. 4a).

In Fig. 6a and b we provide information regarding the number of wind power patents granted by the USPTO to inventors from different countries. In our sample period, Chinese inventors were granted 91 wind patents in the USPTO, corresponding to less than 1.6% of the total. A significant fraction of these patents was assigned to multinational corporations like GE or to inventors unaffiliated with any firms. Table 1 shows that USPTO patenting trends of Chinese manufacturers mirror EPO trends. Envision is aggressive in seeking protection rights for their IP, lodging 72 applications and receiving 28 patents. Sinovel comes in second with 22 applications and one patent. Five of the top manufacturers have never filed with the USPTO for patent protection.

Similarly, Fig. 7a and b show the number of wind power patents granted through the PCT process. There is an increase in the number of patents granted to Chinese inventors (175) as well as their overall share (5%). However, when filtering out patents that were granted only by SIPO, the number of patents decreases to 96. Table 1 shows more even patenting activity among the top producers, with all but one deciding to
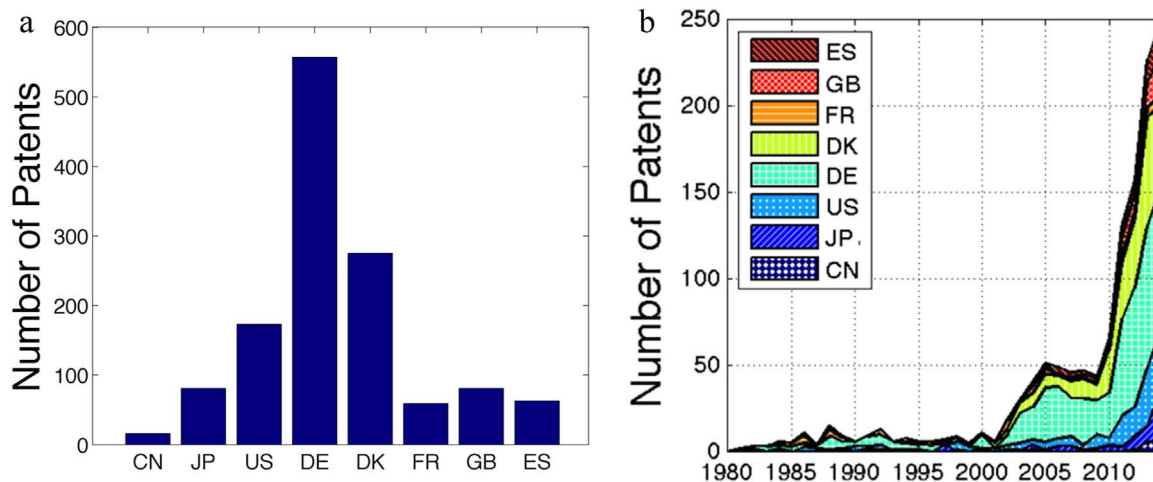

Fig. 5. a and b: Wind power patents granted by EPO member states to inventors from China (CN), Japan (JP), United States (US), Germany (DE), Denmark (DK), France (FR), Great Britain (GB), and Spain (ES), from 1980 to 2014: (a) cumulative number of wind patents, (b) wind power patents over time by country. Data from PATSTAT 2015; plot produced by the authors.

Table 1

Current numbers of EPO, USPTO, WIPO applications and patents granted to Chinese wind turbine manufacturers with the highest domestic cumulative installed capacity from 1980-2016. "Foreign" indicates the number of PCT patents that were granted by non-SIPO patent authorities. XEMC's patent numbers include Darwind; Goldwind's numbers include Vensys' patents that were filed after 2008. Data from Klagge et al. (2012), companies' websites, CWEA (2016), Google Patents (2016), and EPO (2016).

| Firm	Year Founded	Ownership structure	2015 Cumulative Capacity (MW)	EPO		USPTO		PCT/WIPO		
				Apps	Patents	Apps	Patents	Apps	Patents	Foreign
Goldwind	1998	SOE on stock exchange	31,130	6	1	10	5	15	7	3
Sinovel	2006	SOE on stock exchange	16,240	21	1	22	1	9	7	5
Guodian United Power	2007	SOE	14,450	0	0	2	0	5	1	0
Dongfang	2004	SOE on stock exchange	10,660	0	0	0	0	0	0	0
Mingyang	2006	Public	10,110	0	0	0	0	5	0	0
Shanghai Electric	2004	SOE on stock exchange	7330	0	0	0	0	5	0	0
XEMC Windpower	2006	SOE	7040	19	6	2	1	4	0	4
Envision	2007	Private	6890	38	2	72	28	11	7	7
CSIC Chongqing	2004	SOE	5300	0	0	0	0	1	1	0
Windey (Yunda)	2001	SOE	4160	1	0	0	0	3	2	0
Total				85	10	108	35	58	25	19
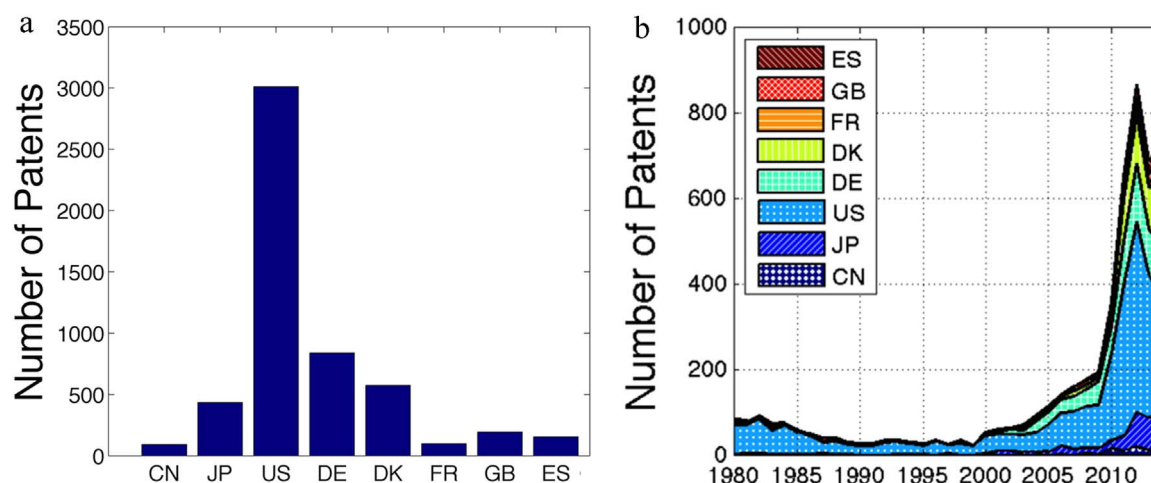
Fig. 6. a and b: Wind power patents granted by USPTO to inventors from China (CN), Japan (JP), United States (US), Germany (DE), Denmark (DK), France (FR), Great Britain (GB), and Spain (ES), from 1980 to 2014: (a) cumulative number of wind patents, (b) wind power patents over time by country. Data from PATSTAT 2015; plot produced by the authors.

use the PCT route to protect their intellectual property.

Our results also indicate that Chinese turbine manufacturers increasingly rely on R & D centers outside of China to generate international patents. For instance, in 2010 Envision Energy, a Jiangsu producer, established its Global Innovation Center in Denmark, and all of its EPO, USPTO, and PCT patents were assigned to its Danish counterpart, Envision Energy (Denmark) ApS. The Danish entity filed for all but one of these applications. Significantly, all of the listed inventors were Danish nationals.[6] Likewise, all of XEMC's patents were assigned to its Dutch subsidiary, XEMC Darwind, and all of the listed inventors have Dutch nationality. Goldwind in 2008 acquired the majority stake in Vensys, a German firm, and since then, Goldwind/Vensys together have obtained one EPO patents, five USPTO patents, and seven international patents.[7] (Three EPO patents, one USPTO patent, and one international patent were filed by Vensys prior to the acquisition, and we do not attribute these to Goldwind).

The recent uptick in patenting activity is clearly evident across different patent authorities, and the final years of the data sample were when Chinese firms 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 find a

limited number of patents granted to indigenous Chinese firms outside of their home market.

4.2. Patent citation likelihood

Citation descriptive statistics are shown in Table 2. PCT patents filed by Chinese inventors on average receive fewer citations than their German, Danish, and U.S. counterparts. Using EPO data, we also observe that wind energy patents filed by Danish and German inventors in the EPO on average have higher citation rates than both their Chinese and U.S. counterparts, suggesting the presence of home bias. Interestingly, the home bias is not as strong for USPTO patents as Danish and German patents on average receive more citations than U.S. patents. In the supplemental material we also provide citation statistics for inventors of different nationalities in the EPO (Table S1) and the USPTO (Table S2).

Results of our citation function estimation are shown in Table 3. For brevity's sake, we report only the nationality coefficients. These coefficients measure the relative "citedness" of patents of different countries, relative to a base category (in this case, Chinese patents). As such, the coefficients provide an indication of the relative impact of Chinese patents compared to patents of other countries. Using WIPO patent data, we find that there are 156 patents whose first inventors are Chinese nationals. Between 1980 and 2014, the likelihood of a Chinese wind turbine patent being cited by subsequent patents is less than that of a German, Japanese, Danish, or American patent, and this trend is

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[6] One inventor has a Chinese surname, though she or he has a Danish address.
[7] Goldwind recently established a new technology development center in Denmark, hoping to tap into the European wind power knowledge pool (Snieckus, 2016).
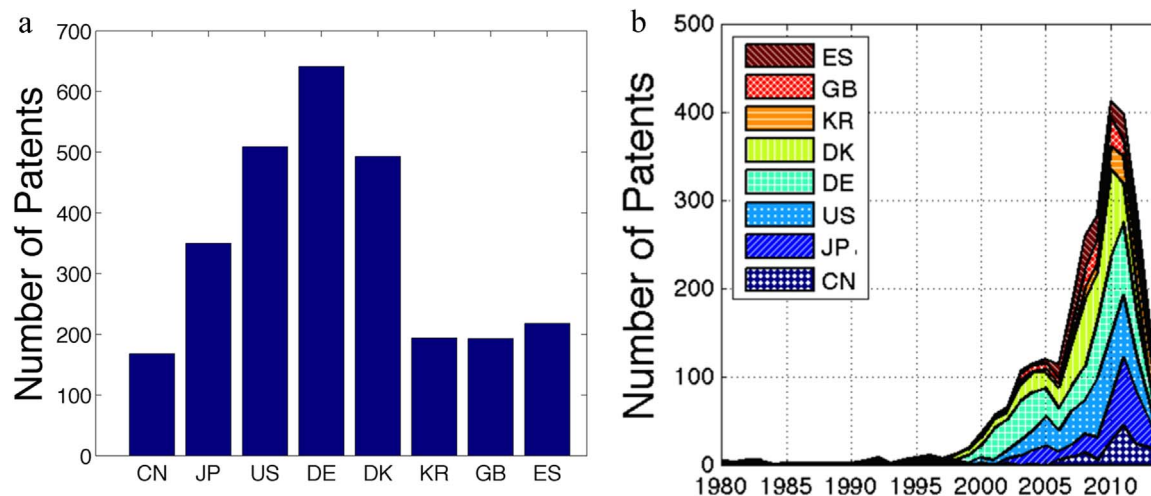
Fig. 7. a and 7b: PCT wind power patents to inventors from China (CN), Japan (JP), United States (US), Germany (DE), Denmark (DK), France (FR), Great Britain (GB), and Spain (ES), from 1980 to 2014: (a) cumulative number of wind patents, (b) wind power patents over time by country. Data from PATSTAT 2015; plot produced by the authors.

Table 2
Patent citation statistics for 1980–2014 patents granted through PCT.

Nationality	N	Mean	SD	Min	Max
All	3328	2.99	3.78	0	37
CN	156	1.53	2.24	0	15
DE	570	3.15	3.82	0	34
JP	327	3.35	4.02	0	37
US	443	4.37	5.19	0	37
DK	440	3.8	3.86	0	34
ROW	1392	2.31	3	0	24

significant and robust. For example, when interpreted as an incidence rate ratio German wind patents are associated with approximately 2.3 times higher citation rate than Chinese patents, and U.S. patents are three times more likely to be cited than Chinese patents.[8]

To account for the fact that Chinese wind turbine manufacturing industry has only been active since the early 2000s, we narrowed our sample period to include only patents granted between 2004 and 2014. Again, our results show that among regional patent groups, Chinese wind patents are the least likely to receive citations. German patents in this period are associated with a 2.2 times increase in citation rate relative to Chinese patents. Finally, the patent examination process may be lengthy and can require a few years to complete as illustrated by the sharp drop off at the end of the sample period in Fig. 7b. To account for the fact that a number of patents may still be under examination, we restricted our sample period to 2002–2012. Our results show again that Chinese patents are less likely to receive citations than patents from other countries.

These results place the recent global surge of wind turbine patents in perspective. A simple count of global patents might lead the observer to believe that China is a leader in wind turbine innovation. However, if Chinese inventions were impactful, we would not have observed a significant difference in the "citedness" between Chinese patents and German, Danish, Japanese, or American patents. The number of Chinese international patent applications has increased, but not many

have progressed all the way to the point of receiving a patent grant in major markets outside China, and their value is fairly limited.

4.3. Learning rate

Our results show that in the sample period, China's wind turbine industry has a learning rate that ranges between 3.5–4.5%, roughly comparable to what previous studies report (Qiu and Anadon, 2012; Yao et al., 2015) (Table 4). We further examine how China's learning rate evolved over time. Table S5 reports the two-factor learning rates for different time periods, where the dependent variable is the levelized cost of electricity. In the 2004–2005 period, the learning rate is as high as 8.7% (though the coefficient is not statistically significant), then declines to 2.2% in the 2004–2009 period before bouncing back up to 4.1%.

The learning rate as measured by the levelized cost of electricity is driven primarily by capital costs and capacity factors. During the 2004–2012 period, China's installed wind capacity increased over 100 times, and capital cost per unit capacity decreased approximately 25% (Figure S1). Reported capacity factors during this period decreased as well, from 26.2% in 2004 to 23.8% in 2012 (Figure S2), suggesting that there may be fewer sites with abundant wind resources.

In fact, Lam et al. (2016) show that the actual average capacity factor is several points lower than what developers anticipated due to widespread grid connection and curtailment issues. When these factors are taken into account, the learning rate may be even lower.

Between 1981 and 1990 Denmark went through a similar rate of capacity expansion as China did, increasing its capacity 100-fold, achieving an 8.8% learning rate (Neij et al., 2003). At a similar development rate between 1991 and 2000, Germany expanded its wind capacity 60-fold, reaching a 12% learning rate. China's learning rate is moderate compared to those of Germany and Denmark during similar development stages. This may be because China is a late-comer to this sector, and there is little room for significant technical improvement. Many Chinese manufacturers adopted wind power technology from abroad (Lewis, 2013), where wind turbines were widely deployed. In the beginning of the study period, 73% of the turbines installed in China were made by foreign manufacturers, a portion that decreased to 8% by the end of the study period. Though beyond the scope of this study, it would be interesting to compare learning rates across different countries in this time period. We note, however, that recent studies show that China's solar PV industry, which also obtained its technologies abroad and went through similar development stages over the same time period, has been following the industry's historical learning rate of about 22% (Chen et al., 2014).

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[8] We also estimated the double exponential citation function used in Jaffe and Trajtenberg (1996) and Popp (2002) using data from PATSTAT2012, and we obtained similar results indicating Chinese patents are less likely to be cited than non-Chinese patents. However, because the dependent variable is a citation that patent year cohort K received from patent year cohort k in year t, the number of observations is much smaller. We therefore opted for the more standard and more widely used count regression instead.

Table 3

This table reports the estimation results for Negative Binomial and Poisson using PATSTAT data on PCT/WIPO patent grants between 1980 and 2014, between 2004 and 2014, and between 2002 and 2012. The dependent variable is the count of cumulative citations received by each patent. The coefficients can be interpreted using incidence rate ratio as a percentage quality discount relative to the reference group, China. All regressions include fixed effects for the patent's grant year and control for the time elapsed after the patent was granted. Numbers in parentheses report robust standard errors.

	1981–2014		2004–2014		2002–2012	
	NB	Poisson	NB	Poisson	NB	Poisson
Germany	2.322[***]	2.300[***]	2.157[***]	2.168[***]	2.239[***]	2.221[***]
	(0.297)	(0.292)	(0.284)	(0.284)	(0.305)	(0.298)
Japan	2.256[***]	2.251[***]	2.379[***]	2.353[***]	2.043[***]	2.052[***]
	(0.303)	(0.303)	(0.326)	(0.323)	(0.287)	(0.287)
US	3.009[***]	3.078[***]	3.223[***]	3.234[***]	2.943[***]	2.979[***]
	(0.392)	(0.403)	(0.430)	(0.433)	(0.407)	(0.411)
Denmark	1.658[***]	1.671[***]	1.674[***]	1.696[***]	1.577[***]	1.604[***]
	(0.203)	(0.204)	(0.210)	(0.212)	(0.206)	(0.208)
ROW	2.530[***]	2.554[***]	2.548[***]	2.592[***]	2.387[***]	2.433[***]
	(0.323)	(0.326)	(0.334)	(0.339)	(0.323)	(0.326)
Constant	0.000	0.000	0.140[***]	0.137[***]	0.109[***]	0.110[***]
	0.000	0.000	(0.024)	(0.024)	(0.021)	(0.021)
Year Dummies	Y	Y	Y	Y	Y	Y
Exposure	Y	Y	Y	Y	Y	Y
Observations	3328	3328	2700	2700	2748	2748
Pseudo Log-likelihood	−7189.471	−9246.003	−6203.965	−7910.894	−6325.228	−8163.777

* $p < 0.1$, ** $p < 0.05$.

*** $p < 0.01$.

Table 4

This table reports the estimation results for the basic learning curve model using LCOE (1) and capital cost (3) as dependent variables. Model 2 uses LCOE and controls for the plant's load factor using data for China's wind farm projects from Clean Development Mechanism. All variables are in logarithmic form. The learning rate is $1 − 2$^(coefficient of cumulative capacity). All regressions include fixed effects for the project's starting year and location. Numbers in parentheses report robust standard errors.

Variable	(1)	(2)	(3)
Cumulative Capacity	−0.051[***]	−0.060[***]	−0.066[***]
	(−0.012)	(0.008)	(0.007)
Plant's load factor		−0.607[***]	
		(0.036)	
Constant	−0.387[***]	−1.213	2.527[***]
	(−0.131)	(0.099)	(0.074)
Year Effect	Y	Y	Y
Province Effect	Y	Y	Y
R-Squared	0.613	0.716	0.604
Observations	1477	1477	1477

* $p < 0.1$, ** $p < 0.05$.

*** $p < 0.01$.

5. Discussion

In this paper we show that since the Chinese government prioritized wind power development in the past decade, Chinese turbine manufacturers have become important players both in the foreign and domestic markets. During this period, the number of wind patents granted by SIPO has exploded, the majority of which was granted to domestic inventors. This suggests that Chinese firms in this industry have acquired a substantive capacity to generate novel, indigenous innovations. However, we find that few wind power patents are granted to Chinese inventors, and even fewer are granted to leading Chinese manufacturers by the member states of the EPO or by the USPTO. Chinese inventors have filed a higher number of PCT or international applications, but a significant portion of these international applications have not been granted by patent offices outside of China. Comparing the patent citation likelihood, we find that Chinese patents are less likely to be cited than patents from Germany, Japan, Denmark, and the U.S. It is unknown whether this trend will continue in the future because only recently has China been active in patenting wind technologies.

At 145 GW of wind capacity, China is the largest wind turbine market, accounting for about a third of the global market by the end of 2015. From 2011–2014 Chinese firms exported a total of 1.7 GW of wind turbine to the U.S., South American, and European countries, although the export amount is a small fraction of domestic demand (CWEA, 2015). Furthermore, government incentives to patent domestically were attractive (Li, 2012), so Chinese producers may choose to prioritize securing domestic patents over international patents. These factors may explain the small number of EPO and USPTO patents granted to Chinese inventors. However, the U.S. and the top six European markets together make up 43% of the global market, down from 45% from the year before (GWEC, 2016). As far as wind turbine makers are concerned, these are not insignificant markets. China's wind turbine export follows larger industry trade patterns. Turbines are large, and shipping them is costly. Therefore, producers can either expand and build their operations in a new market or license their technologies. There is a decent amount of cross licensing in the wind industry, and patents can serve as an effective means of protection, deterring the other party from violating licensing terms. If a Chinese producer has come up with a useful technology but chooses not to file for patent protection, it stands to lose money when another producer decides to imitate that technology. Unless Chinese firms patent their inventions in these jurisdictions, they cannot prevent foreign inventors from infringing on their intellectual property rights.

The leading German firm Enercon pursues this strategy. Enercon's European portfolio accounted for 87% of its turbines in 2015 (GlobalData, 2016). Enercon historically does not have a strong U.S. presence – it has not sold any turbines to the U.S. market in the past five years – but that did not stop the company from filing patents with the USPTO. In addition to 138 EPO patents, Enercon also obtained 136 U.S. patents through the company's founder and owner Aloys Wobben. This patent portfolio allows Enercon to license out its technologies even though it is not an active participant in the U.S. market.

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 China indigenous enterprises across all sectors per year is now in the thousands (Branstetter et al., 2015). Indeed, we find evidence that, as with other sectors, Chinese wind turbine producers intend to turn to patent offices outside of China for IP protection. However, the majority of patents assigned to Chinese manufacturers were invented by their foreign subsidiaries or research centers with limited Chinese presence,

suggesting that Chinese wind industry has yet to transition to "indigenous innovation" mode as previously argued (Ru et al., 2012).

Protectionism is on the rise in renewable energy sectors (Lewis, 2014), and this phenomenon may affect firms' patenting behaviors. Firms may wish use their patents to create non-tariff barriers to market entry. Nevertheless, in order to be granted patent protection, a firm's application must satisfy the technical novelty requirements, a decision made by patent examiners through a rigorous process. We also note that even though GE has been accused of practicing defensive patenting, at least 44% of U.S. turbines were manufactured by non-U.S. firms (Marcy, 2016).

What about the growing numbers of *domestic* patents taken out by these Chinese manufacturers? Are these not evidence of Chinese innovative dynamism? Lei et al. (2013) 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. Similarly, Li (2012) shows that subsidy programs at the provincial level are partly responsible for the increased rate of domestic patenting activity. Chinese companies are taking out local patents because they are paid to do so. Additionally, patent grant numbers are also used as criteria for personnel evaluation both in government and private research institutes (Gosens and Lu, 2014). What is also true is that China's evolving legal system still has 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 which carry potential legal leverage over rivals.[9] If these patents represented economically valuable inventions, then Chinese manufacturers would have a strong incentive to patent them outside of China as they look to export or manufacture their products outside of China.

Chinese wind turbine producers may not be generating patented product or process innovations, but they have dramatically ramped up their manufacturing capabilities in a relatively short period of time. Qiu and Anadon (2012), Wang et al. (2012), Gosens and Lu (2013), Lewis (2013), Nahm and Steinfeld (2014), and Tang and Popp (2014) examine this rapid acquisition of manufacturing capabilities from a range of perspectives. There is little question that this represents a substantial technological achievement. Chinese enterprises can now manufacture a full spectrum of wind turbine products, including the largest and most challenging, and they are the cheapest builders of solar PV modules in the world. The best Chinese firms achieve reasonably high levels of quality, and continue to price their products at levels well below those of the major Western manufacturers. Clearly, Western technology has been successfully absorbed and effectively applied in a context where low factor and input prices enable cost-effective manufacturing on a large scale.

But can we call this innovation in the usual sense of the word? To the extent that the global state of the art is not advanced by the development of new products and/or processes that could be applied outside of China, we would suggest that this process is better characterized as technology transfer or technology absorption, rather than innovation. Some scholars have examined the sustained decline in product prices in the Chinese alternative energy hardware industries and have interpreted this as *prima facie* evidence of dynamic "cost innovation" – intentional, cumulative refinement of the manufacturing process, coupled with small changes in the product itself (Nahm and Steinfeld, 2014). These changes are individually too minor to merit a patent but, collectively, result in steady, sustained, significant cost reductions. However, sustained price reductions could also emerge from a process of gradual absorption of Western best practice and its application in a context in which factor and input prices are lower than in those Western locations where the technology was originally invented. Prices and costs could fall even in the absence of a mean-

ingful capability on the part of Chinese firms to refine, improve, and change production processes in significant ways. Even without innovation, this process generates economic value by creating a low-cost center of production – a value that potentially benefits users of green-tech hardware far from China's borders. On the other hand, to the extent that low wages, low effective land prices, a low cost of capital rise over time, the low costs could be temporary rather than permanent; once Western best practice is fully absorbed, that also implies a deceleration or a cessation of the decline in costs.

Furthermore, sacrifices in product quality and performance that are made in pursuit of cost reduction could limit the value of those cost reductions for end users. This is especially true for power generating equipment, where one equipment failure may result in cascading system failure, affecting the reliability and security of the entire electricity grid. For instance, the absence of low-voltage ride through (LVRT) technologies in the earlier models of Chinese wind turbines has been subject to wide examination. LVRT technology allows wind turbines to maintain continuous operation in the event of a sudden sharp drop in voltage, ensuring the safety and stability of the grid. A series of power loss incidents in 2011 and the following investigations highlighted the importance of LVRT systems (Xu and Alleyne, 2012), which many manufacturers opted to bypass in order to make their products cost competitive. China's wind power industry had to grapple with widespread quality problems that resulted in internal equipment failures. A number of turbine equipment failures occurred between 2010 and 2012, the most common ones related to frequency converters and generators, gearbox, pitch and yaw systems (Lin et al., 2016), and the quality gap with turbines made by international leaders remains substantial (Gosens and Lu, 2014; Lu et al., 2016).

While there is evidence of sustained reduction in wind turbine prices, this reduction is relatively modest once normalized for the scale of the Chinese industry, as indicated by the low learning rate in China relative to the global industry's historical learning rate as well as Denmark's and Germany's during similar development stages. Furthermore, it is unclear if these kinds of cost innovations could continue indefinitely or be replicated elsewhere. The average estimated capacity factor in China actually decreased in the sample period, suggesting that the industry's swift expansion has run into location and infrastructural constraints. The actual annual capacity factors are several percentage points lower than expected, owing to widespread curtailment in the industry, so if we adjusted for the actual capacity factor, the learning rate results would be lower. However, these challenges can be learning opportunities for the Chinese wind turbine industry. When grid connection and curtailment issues are addressed, the levelized cost of electricity will accordingly decrease. Average turbine size in China is still smaller than in the U.S. and Europe (Gosens and Lu, 2014; IRENA, 2016), and this is yet another area where the industry can improve.

It is important to note that, because cost data are difficult to come by, the data used in this study are price data – not cost data. This is a limitation to our analysis. In order to be eligible for CDM, Chinese wind projects must fulfill the "additionality" requirement, meaning that without the CDM support the projects would not have been constructed. Developers may therefore intentionally over-report project costs in order to be qualified for CDM. Chan (2015) provided evidence that manipulation indeed occurred. Such manipulations may influence the actual learning rates as a result. On the other hand, estimated electricity generation data used in our analysis may bias learning gains because actual generation of wind electricity across the country has been much lower than anticipated due to grid connection and curtailment issues (Lam et al., 2016). Neither CDM investment data nor estimated generation data capture product quality. When unaccounted for, inferior turbine quality that caused a number of equipment failures (Lin et al., 2016) can inflate estimated learning rates. Finally, a number of state-owned enterprises operate in the wind turbine sector, and they may be willing to offer products at artificially low prices to undercut their competitors in

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

Table 5
Primary energy consumption in China, by fuel source, 2007·14 (million tonnes of oil equivalent). Figures in parentheses indicate percentage of total annual consumption. Data from BP (2015).

Fuel source	2007	2008	2009	2010	2011	2012	2013	2014
Oil	369.3 (17.3)	376.0 (17.0)	388.2 (16.8)	437.7 (17.7)	460.0 (17.2)	482.7 (17)	503.5 (17)	520.3 (18)
Natural gas	65.6 (3.1)	75.6 (3.4)	83.2 (3.6)	99.4 (4.0)	121.4 (4.5)	136.0 (5)	153.7 (5)	166.9 (6)
Coal	1573.1 (73.7)	1598.5 (72.2)	1679.0 (72.6)	1740.8 (70.4)	1896.0 (70.8)	1922.5 (69)	1961.2 (68)	1962.4 (66)
Nuclear	14.1 (0.7)	15.5 (0.7)	15.9 (0.7)	16.7 (0.7)	19.5 (0.7)	22.0 (1)	25.3 (1)	28.6 (1)
Hydro	109.8 (5.1)	144.1 (6.5)	139.3 (6.0)	163.4 (6.6)	158.2 (5.9)	197.3 (7)	208.2 (7)	240.8 (8)
Non-hydro renewables	1.9 (0.1)	3.6 (0.2)	6.9 (0.3)	13.1 (0.5)	24.6 (0.0)	33.8 (1)	46.1 (2)	53.1 (2)
Total	2,133.7	2,213.3	2,312.5	2,471.2	2,679.7	2,794.5	2,898.1	2,972.1

order to gain market share or to meet government targets. If this is indeed the case, actual learning gains would be lower. While the CDM project database has these limitations, it is the most comprehensive database that is publicly available. Furthermore, it is similar to a database curated and maintained by the National Development and Reform Commission (NDRC) between 2006 and 2010. Comparing the two databases, we find that the overall trends are similar, where average investment costs peaked in 2009 (Fig. S3). Nevertheless, learning rate results should be interpreted with some caution.

6. Conclusion and policy implications

With generous and sustained government support, China's wind industry has enjoyed much success with technology transfer, capacity building, learning, and cost reduction. As China has ramped up its wind turbine output, indigenous producers have increasingly undercut the prices maintained by foreign producers. This growth path, some argue, suggests that Chinese wind power manufacturing firms have developed substantial 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.

Our results suggest a less optimistic view. Low prices in recent years have reflected an imbalance of supply and demand as well as cost-reducing innovation. Industry data indicate that the majority of producers active in the industry in 2010 have since ceased production (GWEC, 2012). The wave of consolidation hitting the lower tier producers is only now bringing significant financial improvement to the surviving incumbents. Before the recent wave of consolidation in the Chinese wind power industry, foreign observers might have hoped that Chinese producers, while apparently unable, as yet, to advance the state of the art through significant product innovation, had nevertheless found a way to generate sustained reductions in production costs. This may well prove to be true in the longer run, but it seems apparent that overcapacity drove Chinese equipment prices well below economically sustainable levels, even among domestic manufacturers.

Despite the current situation facing the industry, we believe that leading Chinese firms are likely to remain important global players in the near future. The Chinese government signaled its firm commitment to clean energy development in its 13th Five-Year Plan (2016–2020), and in the recent Paris COP21 meeting, the government pledged to have 20% of the country's primary energy consumption come from renewable energy sources by 2030. As of 2014, about 10% of China's primary energy consumption is attributable to renewable energy sources, 8% of which to hydropower (please see Table 5).

With the continuation of a friendly policy environment and policy targets to include more "indigenous" innovation (Gosens and Lu, 2014), China's wind power industry is likely to expand. 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. At the same time,

China needs to introduce significant industry reforms to address issues that continually dog the industry, namely grid connection and curtailment. By our estimate, if China were able to connect all of its wind turbines and place them in full use at 22% capacity factor, it could generate almost 40% more electricity from wind, the equivalent of installing about 32 GW capacity (Lam et al., 2016).

China has markedly expanded the renewable share of its energy mix, absorbed a fair amount of fairly advanced technology, and established itself as a competitive location in which to manufacture clean tech hardware. But in the absence of significant technological breakthroughs to substantially reduce carbon emissions, the ability of indigenous manufacturers to continue to deliver substantial cost reductions may have its limits.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2017.03.023.

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