Innovation in China's Renewable Energy Industry

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Abstract

This dissertation includes three studies that examine the remarkable rise of China's renewable energy industry and its technological contributions to the global industry. China has emerged as the world's largest carbon emitter by a large margin, and many of its cities experience high levels of air pollution. The Chinese government has turned to wind – and later solar – as alternative power sources to help decarbonize its electricity system and ameliorate increasingly urgent air pollution problems. Through these efforts, China has markedly expanded the share of renewable energy in its energy mix, and in the process absorbed a fair amount of relatively advanced technology, establishing itself as a competitive location to manufacture clean power equipment. In short order China has bolstered its international standing as a renewable energy powerhouse.

The first study evaluates the question of whether China's wind industry has become an important source of clean energy technology innovation. Results indicate that while China has delivered enormous progress in terms of wind capacity, the outcomes were more limited in terms of innovation and cost competitiveness. Chinese wind turbine manufacturers have secured few international patents and achieved moderate learning rates relative to the global industry's historical learning rate.

The success of China's transition to a low-carbon energy system will be key to achieve the global level of emissions reductions needed to avoid large negative consequences from climate change. The second study shows that China made progress in bringing down the levelized cost of wind electricity and cost of carbon mitigation. However, widespread grid-connection issues and wind curtailment rates caused much higher-than-anticipated costs of renewable energy integration.

China has emerged as the global manufacturing center for solar photovoltaic products, and Chinese firms have entered all stages of the supply chain in short order. The third study provides detailed expert assessments of the technological and non-technological factors that led to the surprised success of China's silicon photovoltaic industry. Expert judgments suggest that continued declines in in module and system costs and improvements in performance will allow solar photovoltaic to be competitive with fossil fuels in China.

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List of Abbreviations

Al-BSF	Aluminum Back Surface Field
AWEA	American Wind Energy Association
CCM	Cost of Carbon Mitigation
CDM	Clean Development Mechanism
CdTe	Cadmium Telluride
CEC	China Electricity Council
CER	Certified Emission Reduction
CF	Capacity Factor
CIGS	Copper Indium Gallium Selenide
CPV	Concentrator Photovoltaics
CREIA	Chinese Renewable Energy Industries Association
CWEA	China Wind Energy Association
DSSC	Dye-Sensitized Solar Cell
EF	Emissions Factor
EPO	European Patent Office
ERCOT	Electric Reliability Council of Texas
ETIS	Energy Technology Innovation System
EVA	Ethyl vinyl acetate
FBR	Fluidized Bed Reactor
FC	Fixed Cost
FIT	Feed-in Tariff
GHG	Greenhouse Gas

GW	Gigawatt
GWEC	Global Wind Energy Council
HCPV	High Concentrator Photovoltaic
HIT	Hetero junction with Intrinsic Thin-layer
IBC	Interdigitated Back Contact
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
IP	Intellectual Property
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized Cost of Electricity
LCPV	Low Concentrator Photovoltaics
LVRT	Low-Voltage Ride Through
MW	Megawatt
NB	Negative Binomial
NEA	National Energy Administration
NDRC	National Development and Reform Commission
O&M	Operation and Maintenance
PATSTAT	Patent Office Worldwide Patent Statistical Database
PCT	Patent Cooperation Treaty
PDD	Project Design Document
PERC	Passivated Emitter Rear Contact (or Cell)
PERL	Passivated Emitter, Rear Locally Diffused

PERT	Passivated Emitter, Rear Totally Diffused
PV	Photovoltaics
RD&D	Research, Development, and Deployment
RMB	Renminbi
RPS	Renewable Portfolio Standards
SERC	State Electricity Regulatory Commission
SIPO	State Intellectual Property Office (Chinese Patent Office)
SOE	State-Owned Enterprise
TIS	Technological Innovation System
TPT	Tedlar Polyester Tedlar
TW	Terawatt
UHV	Ultra-High Voltage
UNFCCC	United Nations Framework Convention on Climate Change
USPTO	United States Patent and Trademark Office
VAT	Value-added Tax
VC	Variable Cost
WIPO	World Intellectual Property Organization
WTO	World Trade Organization

1 Introduction

Fossil fuels have powered hypergrowth of the Chinese economy since *Reform and Opening* and are the chief source of the country's air pollution and carbon emissions. Rapid increase in economic activity has led to a seemingly insatiable demand for energy, most of which is derived from coal. By one estimate, China's consumption accounts for close to half of the world's total coal use (EIA, 2016). Emissions from coal consumption have increased 5% annually between 2000 and 2012 (Z. Liu, 2015). The country's intensive use of its abundant domestic supplies of coal made China's the world's largest emitter of greenhouse gases by the mid-2000s. China is now responsible for nearly 30% of global carbon emissions (Olivier et al., 2016). Its annual emissions have more than doubled since the early 2000s. The short- and long-term environmental consequences of the rapid expansion of Chinese energy-intensive economy have been the subject of both domestic and international attention.

Aware of the heavy toll that economic growth has exacted on the country's environment, Chinese leaders have turned to alternative sources of power. Rich hydropower resources and low marginal cost made hydroelectric generators an obvious candidate. However, constructions of massive dams failed to satiate the country's ever-growing demand for energy. At the same time fewer and fewer hydropower resources are left unexploited. After initial forays into building non-hydro renewable energy projects, the government decided that wind energy would play a central role in meeting the country's energy needs (Zhi et al., 2014). The decision to embrace wind energy made sense given the country's abundance in wind sources, particularly in the northern regions. Besides, the economic argument was on wind energy's side, when solar energy was viewed as a niche technology that only high-income countries could afford.

With the passage of the 2005 Renewable Energy Law, the central government's embrace of wind energy set in motion the greatest construction boom in the history of the global industry. In less than a decade, China went from having virtually no wind power to installing more wind turbines than any other countries in the world. In 2001 the cumulative capacity of China's wind turbine fleet was only around 400 MW; by 2010 its capacity had expanded by more than 100-fold, to 44.7 GW (CWEA, 2016). China surpassed the United States as the country with the most installed wind capacity that year (GWEC, 2012). By 2016 China's wind energy installed capacity dwarfed that of the United States, reaching more than 168 GW (AWEA, 2016; CWEA, 2016). During this time period, China successfully – and at times controversially – incubated a competitive domestic industry through various support policies and mechanisms. Playing only a marginal role not so long ago, domestic firms seized most of the Chinese wind turbine market from foreign producers and are now self-sufficient in most parts of the supply chain.

In contrast to the wind energy industry, China's solar PV industry grew up primarily on foreign demand and relied on the private sector in its early days (Gallagher, 2014; Zhang and Gallagher, 2016; Zhi et al., 2014). Kyoto signatories in Europe fueled the demand for solar PV by introducing generous feed-in tariffs (IEA, 2016). Eager to provide for the European market, Chinese private investors rushed to set up production lines purchased from foreign suppliers (la Tour et al., 2011). By 2010, Chinese PV cell production made up of more than half of the global production (CRES, 2010). In the days after the Eurozone financial crisis, European governments scaled back or even reversed FIT policies, depressing demand for PV (Schmela, 2015). New sources of growth in the post-recession U.S. and post-Fukushima Japan emerged, but they were not enough to make up for the demand slack left behind by the European market. Profit margins became tight as increasingly desperate producers fought for the limited amount of market demand (Zhang and Gallagher, 2016).

As financial conditions of the major solar power producers in China worsened, the Chinese central government began to put in place much more aggressive policies to promote the deployment of solar energy. In addition to putting in place a generous FIT regime, the government also established an installation target for solar PV. As a result, in 2015 China installed 16.5 GW of solar PV, bringing the country's total to 43 GW, stripping Germany of its global leader status (GlobalData, 2017). Hoping to take advantage of economies of scale, Chinese PV producers integrated up and down the supply chain and increased their production capacity. In short order Chinese firms dominated the global silicon PV industry. Today of every ten solar panels installed in the world, seven were manufactured by Chinese producers (CPIA, 2016a).

Recent developments demonstrate China's commitment to clean energy development and its intention to bolster its international image as a climate leader. In 2015 China led the world in non-hydro renewable energy investments, totaling $102.9 billion, more than the next three countries – the United States, Japan, and the United Kingdom – combined (McCrone, 2016). Through 2020 China plans to spend more than $360 billion on renewables (NEA, 2017b). This is remarkable given that in 2004 China devoted only $3 billion to renewable energy investment. At the Paris COP21 meeting, China pledged to increase the share of its renewable energy sources to 20% of total primary energy consumption by 2030 (UNFCCC, 2015a). Following the renewable energy development blueprint established in the 13th Five-Year Plan (2016-2020), the National Energy Administration recently released the country's 2020 installation target. Wind and solar capacity should reach 210 GW and 110 GW respectively, effectively cementing China's powerhouse status in the renewable energy sector (NDRC, 2016b).

Nevertheless, China's renewable energy undertakings are far from being an unmitigated success. The same policies that buoyed domestic firms also resulted in severe overcapacity problems, both in the production of power equipment and in the generation of electricity. Both wind and solar industries have experienced painful periods of consolidation that led to a number of high-profile bankruptcies. Overcapacity also besets the electricity generation sector. The large amount of renewable capacity coming online coupled with business-as-usual expansion of coal-fired power plants resulted in reduced utilization rates across all energy supplies. Rampant curtailment of wind and solar energy owing to political and infrastructural obstacles continues to dog the industry, calling into question the efficiency of China's energy policies.

This dissertation aims to empirically examine the progress and challenges in China's renewable energy sector, particularly from an innovation perspective. Chapter 2 accesses the extent to which China has succeeded in incubating a technologically dynamic wind turbine manufacturing industry that can make significant contributions to global emissions reduction goals. Chapter 3 evaluates the successes and shortcomings of China's policy efforts to integrate renewable energy sources into its national electricity grid in terms of reductions in levelized cost of electricity for wind and cost of carbon mitigation. Chapter 4 analyzes China's solar photovoltaic industry, detailing the technological and non-technological factors that contributed to industry's success. Additionally, this chapter outlines various development paths for China's solar PV based on expert judgments. Chapter 5 concludes the dissertation with a summary of findings and policy implications.

2 China’s Wind Industry: Leading in Deployment, Lagging in Innovation[1]

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 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.

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[1] A version of this chapter has been published as Lam, L.T., Branstetter, L., Azevedo, I.M.L., 2017. China’s wind industry: leading in deployment, lagging in innovation. Energy Policy (forthcoming).

2.1 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 to 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 (Figure 2.1).

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 Figure 2.2 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[2]. 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, 2015a).

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[2] Please see IEA (2016), Lewis (2013), and (Gallagher, 2014) for reviews of relevant renewable energy policies.

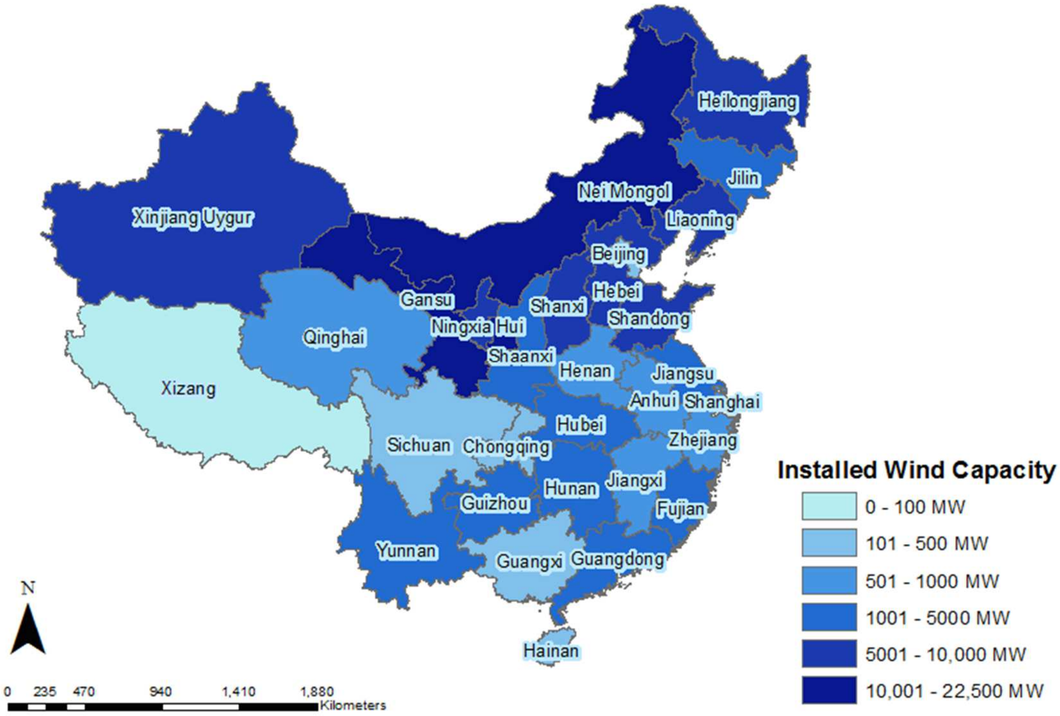


Figure 2.1: China's wind power installation by province in 2014. Provinces with most wind power installed are also those that have significant wind resources. Data from CWEA (2015). Map produced by authors.

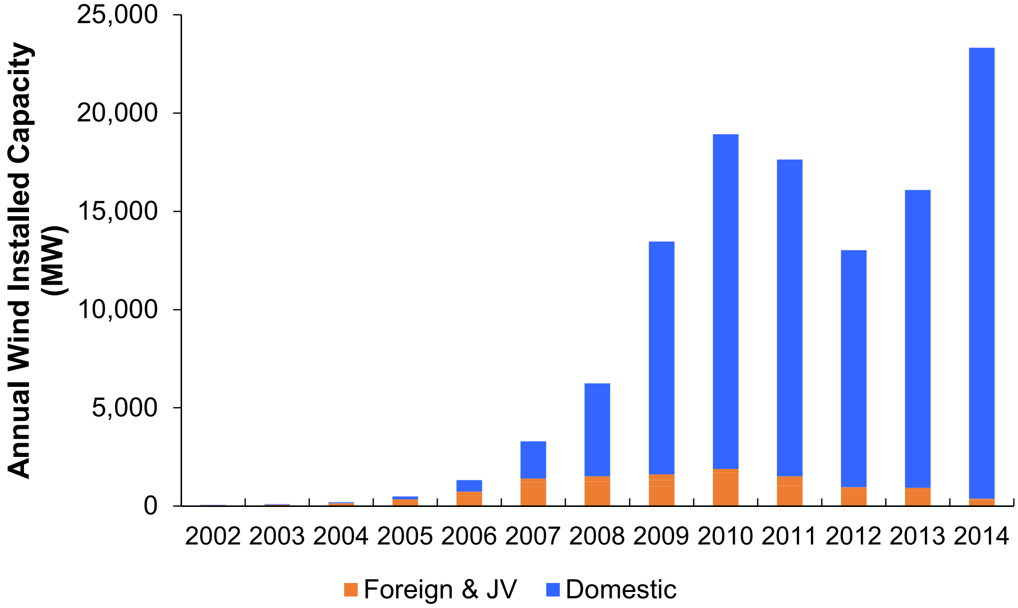


Figure 2.2: Annual wind nameplate capacity installations in China by year, broken down by domestic versus foreign firms. Domestic firms dominate the market in recent years. Plot constructed by the authors using data from (CWEA, 2015).

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 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 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.

2.2 Literature review

2.2.1 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.

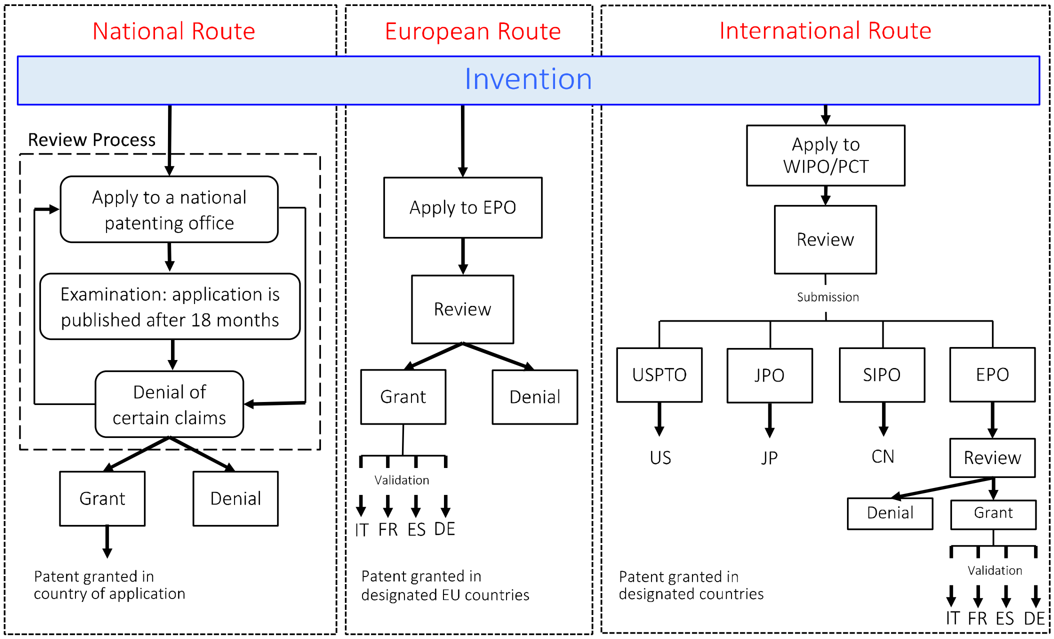
2.2.2 Patent as an innovation metric

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 by 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 the prior inventions cited in new patents are important fundamental knowledge on which 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.

2.2.3 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.



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.

2.3 Data and methods

2.3.1 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). Figure 2.3 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 a 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 examination 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 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.

2.3.2 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[3]. 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

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

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:

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

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

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

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 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.

2.3.3 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[4], estimated utilization hours, estimated yearly and lifetime 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 A.3 and Table A.4. 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:

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

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

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[4] 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.

cost, and subsequently some variable costs in the form of operations and maintenance. The LCOE can be calculated as follows:

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

[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 O&M 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[5]. 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 will report both here. 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.

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

2.4 Results

2.4.1 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 EU15, Japan, South Korea, Russia, Canada, and the United States. Figure 2.4a and Figure 2.4b show the total number of patents granted by these patent offices. We only track priority patents to avoid double counting.

Figure 2.4b 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)[6].

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.

When we restrict our sample to only patents that were by EPO member states, the total number of patents drops substantially (Figure 2.5a and Figure 2.5b). 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.

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[6] PATSTAT coverage of inventor information is incomplete for SIPO data, although examining domestic wind power patenting activity, Gallagher (2014) reports that a majority of SIPO patents were granted to domestic inventors.

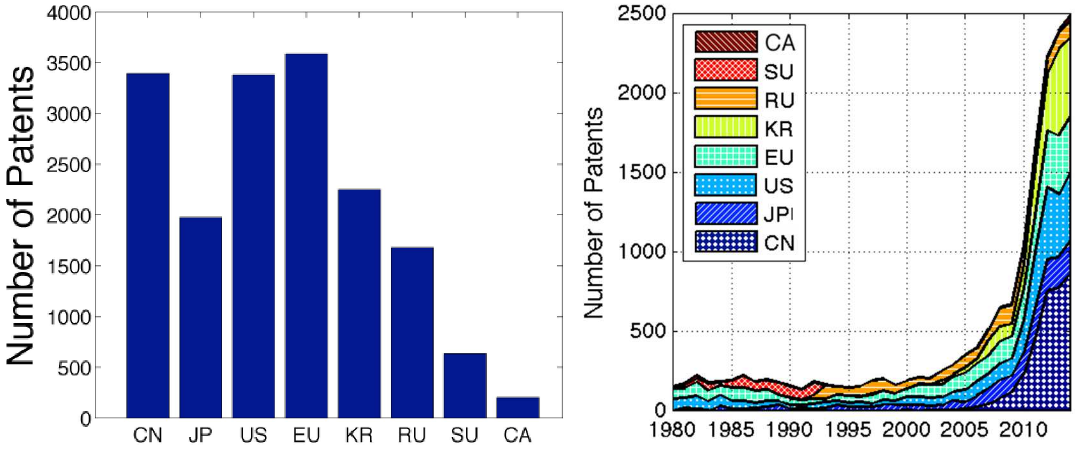

Figure 2.4: Wind power patents granted by all patenting offices: (a) total wind patents from 1980 to 2014 by country/region and (b) wind patents over time by country (China = CN, Japan = JP; United States = US; EU = European Union 15 and EPO member states; South Korea = KR; Russia = RU; Soviet Union = SU; Canada = CA). Data from PATSTAT 2015; plot produced by the authors.

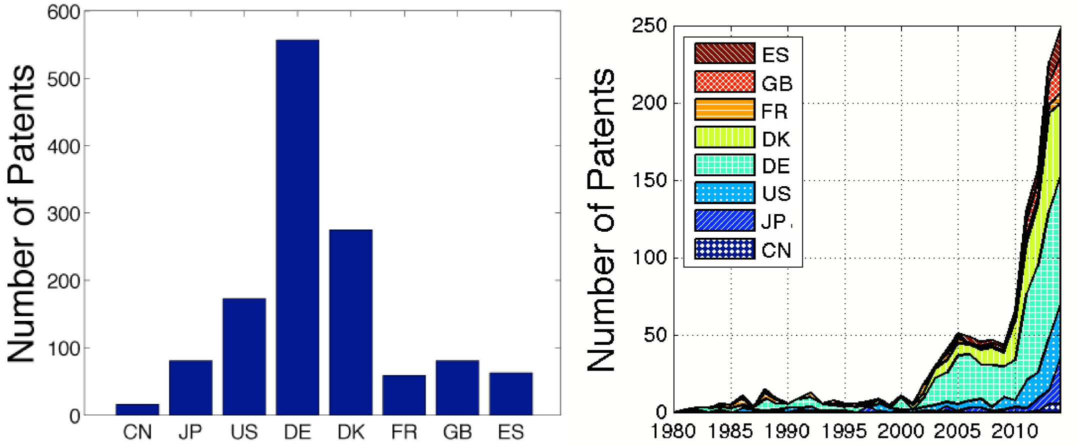

Figure 2.5: Wind power patents granted by EPO member states to inventors from China (CN), Japan (JP), United States (US), Germany (DE), Denmark (DK), France (FR), Great Britain (GB), and Spain (ES), from 1980 to 2014: (a) cumulative number of wind patents, (b) wind power patents over time by country. Data from PATSTAT 2015; plot produced by the authors.

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 (Figure 2.5a). To date, Envision and XEMC have respectively lodged 38 and 19 EPO applications, receiving respectively two and six patents (see Table 2.1). 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 (Figure 2.4a).

In Figure 2.6a and Figure 2.6b 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 firm. Table 2.1 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.

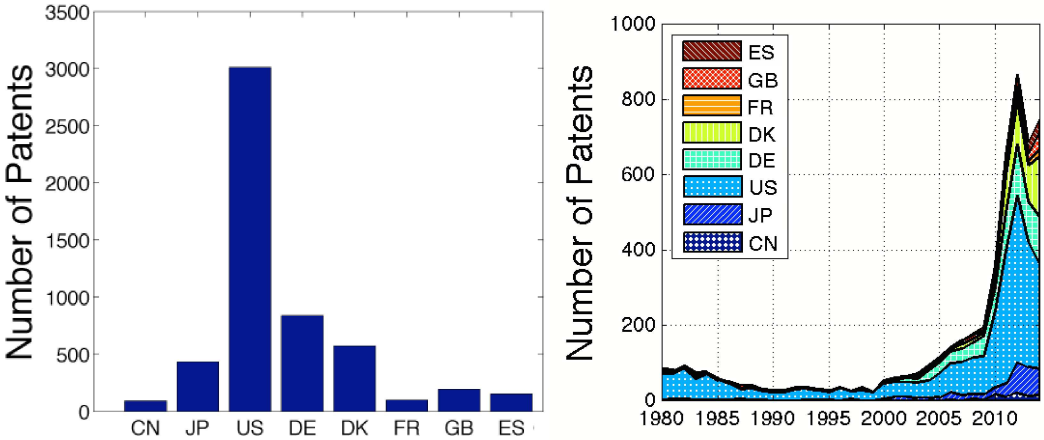

Figure 2.6: Wind power patents granted by USPTO to inventors from China (CN), Japan (JP), United States (US), Germany (DE), Denmark (DK), France (FR), Great Britain (GB), and Spain (ES), from 1980 to 2014: (a) cumulative number of wind patents, (b) wind power patents over time by country. Data from PATSTAT 2015; plot produced by the authors.

Similarly, Figure 2.7a and Figure 2.7b 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 2.1 shows more even patenting activity among the top producers, with all but one deciding to 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[7]. 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[8]. (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.

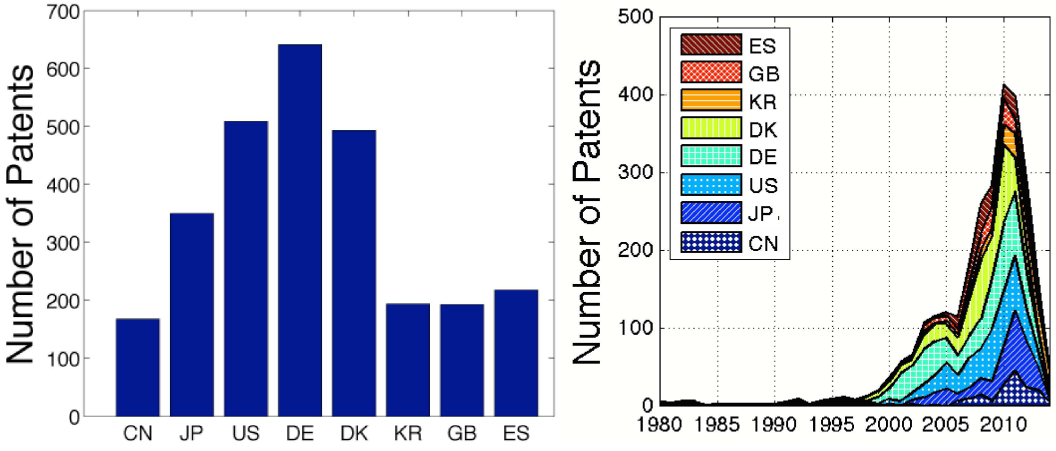

Figure 2.7: PCT wind power patents to inventors from China (CN), Japan (JP), United States (US), Germany (DE), Denmark (DK), France (FR), Great Britain (GB), and Spain (ES), from 1980 to 2014: (a) cumulative number of wind patents, (b) wind power patents over time by country. Data from PATSTAT 2015; plot produced by the authors.

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[7] One inventor has a Chinese surname, though she or he has a Danish address.

[8] Goldwind recently established a new technology development center in Denmark, hoping to tap into the European wind power knowledge pool (Snieckus, 2016a).

Table 2.1: Current numbers of EPO, USPTO, WIPO applications and patents granted to Chinese wind turbine manufacturers with the highest domestic cumulative installed capacities. "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	31130	6	1	10	5	15	7	3
Sinovel	2006	SOE on stock exchange	16240	21	1	22	1	9	7	5
Guodian United Power	2007	SOE	14450	0	0	2	0	5	1	0
Dongfang	2004	SOE on stock exchange	10660	0	0	0	0	0	0	0
Mingyang	2006	Public	10110	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

Table 2.2: 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

2.4.2 Patent citation likelihood

Citation descriptive statistics are shown in Table 2.2. 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 A.1) and the USPTO (Table A.2).

Results of our citation function estimation are shown in Table 2.3. 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 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[9].

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 Figure 2.7b. 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.

2.4.3 Learning rate

Our results show that over the sample period, China's wind turbine industry has a learning rate that ranges between 3.5% to 4.5%, roughly comparable to what previous studies report (Qiu and Anadon, 2012; Yao et al., 2015) (Table 2.4). We further examine how China's learning rate evolved over time. Table A.5 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

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[9] 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.

learning rate is as high as 8.7% (though the coefficient is not statistically significant), then declines to 2.2% for in the 2004-2009 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 A.1). Reported capacity factors during this period decreased as well, from 26.2% in 2004 to 23.8% in 2012 (Figure A.2), 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 suggest 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).

Table 2.3: 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<0.01, ** p<0.05, * p<0.1

Table 2.4: 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<0.01, ** p<0.05, * p<0.1

2.5 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 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 1.7GW 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. (2015) 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.[10] 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

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

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 meaningful 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. And 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 & 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 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 (Figure A.3). Nevertheless, learning rate results should be interpreted with some caution.

2.6 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 2.5).

Table 2.5: 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

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.

3 China's Wind Electricity and Cost of Carbon Mitigation are More Expensive than Anticipated [11]

The success of China’s transition to a low-carbon energy system will be key to achieve the global level of emissions reductions needed to avoid large negative consequences from climate change. China is undergoing an impressive buildup of renewable capacity, in particular wind. Using data from the Clean Mechanism Development project database between 2004 and 2012, this study shows that while China made progress in bringing down the levelized cost of wind electricity and cost of carbon mitigation, serious grid-connection issues and high wind curtailment rates resulted in a levelized cost of wind electricity that is one-half to two times higher than expected, and a cost of carbon mitigation that is four to six times higher. Sharp drop in electricity demand, utilization rate, and coal prices in recent years may lead to even higher results.

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[11] A version of this chapter has been published as Lam, L.T., Branstetter, L., Azevedo, I.M.L., 2016. China's wind electricity and cost of carbon mitigation are more expensive than anticipated. Environ. Res. Lett. 11, 1–11. http://dx.doi.org/10.1088/1748-9326/11/8/084015.

3.1 Background: Renewable energy integration in China

In 2014 China's wind energy installed capacity outstripped that of the U.S. by some 75%. However, China's wind turbines generated only 156 TWh of electricity in the same year, compared to 180 TWh in the U.S. (see Figure 3.1). This gap between the total installed capacity and electricity generation has narrowed in recent years but remains substantial. In fact, if China were to connect its entire wind turbine fleet to the grid and put them to full use at a 22% capacity factor, it would generate almost 40% more electricity from wind, or 217 TWh, an equivalent to installing an additional 32GW of capacity.

To address some of the country's serious environmental problems, China is undergoing a massive build-up of renewable capacity, in particular wind. Furthermore, global progress in reducing emissions to avoid large negative consequences from climate change hinges on China's ability to transition to a low-carbon energy system. However, efforts to integrate the country's wind power into its electrical grid and to reduce curtailment have had limited success to date.

Recently, a number of studies have tried to describe a number of barriers that restrict the full utilization of China's installed capacity. Much of the existing research highlights the inadequacy of the country's electricity grid system, specifically its inability to transmit electricity produced by renewable sources generated in remote wind- and solar-rich regions to energy load centers (Wang et al., 2010; Li et al., 2012; Li et al., 2014; Pei et al. 2015; Zhao et al., 2016). The absence of interprovincial power markets owing to the ambiguous authority of various stakeholders over transmission (Davidson, 2013), different levels of feed-in-tariffs (Zhao et al., 2012; Pei et al. 2015), the lack of a mature, and standardized exchange platform, and grid companies' conflicts of interest (Kahrl and Wang, 2014) further aggravate grid integration problems[12].

Nevertheless, little has been reported on how the pervasive lack of grid connection and widespread curtailment affect the industry's levelized cost of electricity and the cost of carbon mitigation. Using Clean Mechanism Development data from 2004 to 2012 and industry statistics, this study provides an analysis on these measures when accounting for both the capacity that has not been connected and the curtailments due to poor transmission.

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[12] Please see IEA (2016), Lewis (2013), and Gallagher (2014) for a review of relevant renewable energy policies.

3.2 Data & methods

3.2.1 Clean Mechanism and industry data

We rely primarily on data from Clean Development Mechanism (CDM) project database. Established under the Kyoto Protocol, CDM aims to stimulate sustainable development and greenhouse gas emissions (GHGs) reductions in developing countries. Through the program's framework, developing countries can earn certified emission reduction credits (CERs) by building projects that would reduce greenhouse gas emissions. Industrialized countries in turn can purchase these credits in order to meet their emission reduction targets.

The process and rules for a project to become CDM-registered and certified are standardized by the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC)[13], who collects and publishes relevant data on all low-carbon energy projects that receive financial support through CDM. Two organizations organize and compile these data (IGES, 2015, UNEP, 2015).

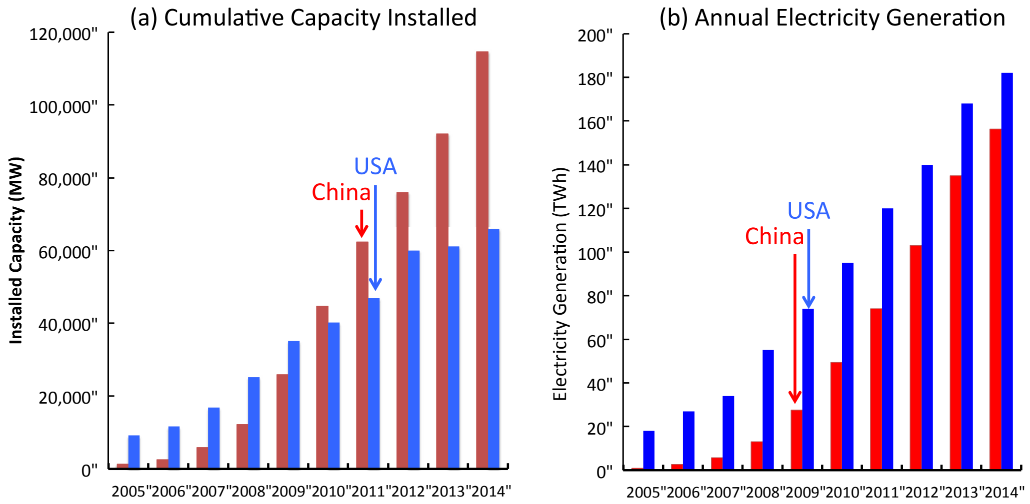

Figure 3.1: (a) Wind cumulative capacity installed (MW) over time in China and in the USA (2005-2014). (b) Annual electricity generation (TWh) from wind (TWh) over time in China and in the USA (2005-2014). The cumulative installed wind capacity in China surpassed that of the USA in 2009-2010. However, the annual electricity generation in the USA is still larger than in China. Plot produced by the authors using data from AWEA (2015), CWEA (2015), and CEC (2015).

The CDM dataset has been used to examine the learning rate in China's wind energy industry (Yao et al., 2015), the network effects of technological learning (Tang and Popp, 2014),

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

the effect of CDM on China's industry development (Stua, 2013), and the efficacy of CDM's additionality requirement (He and Morse, 2013; Chan, 2015), among other effects. Our version of the CDM project database contains data for most of China's onshore wind farm projects between 2004 and 2012. This dataset includes the project's name and location, turbine manufacturer and type, total investment, total installed capacity, starting date[14], estimated utilization hours, estimated yearly and lifetime generation, estimated emission factors, etc. Table B.1 and Table B.2 report summary statistics for the major variables of interest.

Because cost data are not publically available, we use price data as a proxy for cost data. While data quality is not of concern because the process and rules for a project to become CDM-registered and certified are lengthy and highly standardized[15], there may exist some doubts as to what extent the investment data reflect the true costs of the projects. In an extremely competitive wind turbine market like China, we may expect the turbine's price to be close to its cost. However, it is plausible that because State-Owned Enterprises (SOEs) dominate the wind turbine industry and are willing to sell products below cost to gain market share or to comply with government installation targets, the product price may be distorted. We will explore this possibility further in our sensitivity analyses.

Our 2004-2014 province-level data on installed capacity come from the China Energy Databook published by the Lawrence Berkeley National Laboratory (LBNL, 2014) and from the annual industry data published by China's Wind Energy Association (CWEA, 2015). We refer to China's Electricity Council (CEC) and National Energy Administration (NEA) for national-level electricity data, including generation and consumption amount, and utilization hours (CEC, 2015). The NEA and Chinese Renewable Energy Industries Association (CREIA) also keep track of grid-connected capacity, allowing us to compute unconnected capacity.

3.2.2 Methods to estimate CF, LCOE, and CCM

We use the CDM project database and the industry's annual statistics published by various organizations to estimate the Chinese wind turbine's capacity factor (both projected and

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[14] 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.

[15] The CDM project database's investment data tracks closely with a similar database maintained by the NDRC. See SI for more details.

actual), the levelized cost of electricity, and the cost of carbon mitigation.

Connected, unconnected capacity, and curtailment: We start by showing the amount of installed wind capacity, and whether it has been connected or not. To do so, we use province-level installed capacity data from LBNL's China Energy Databook and CWEA's monthly magazines and the grid-connected capacity from the NEA and CREIA. We also report province-level curtailment data from the NEA and CREIA from 2011 to 2015. Note that the national curtailment rate reported in this study is computed using the national curtailed wind electricity total. It is not the average of the provincial curtailment rates as sometimes publicly reported.

Capacity factors: We estimate the capacity factor (CF_t) from wind, which is defined as the ratio of actual electricity generation to the maximum possible generation assuming continuous full power operation during the same period, or:

$$CF_t = \frac{GE_t}{8760 \cdot C_t} \tag{1}$$

where t indexes the year; GE is the amount of electricity generated and delivered to the grid, C the installed capacity, 8760 is the number of hours in a year. In practice, the capacity factor depends on a number of factors, including wind resources, grid capacity and availability, generation costs and electricity prices, and equipment.

We first show the *ex-ante* capacity factor using CDM data. Each Project Design Document reports estimates for the project's anticipated capacity factors as determined by an independent third-party consulting agency using the local region's historical meteorological conditions in the past 30 years, onsite anemometric data of the previous year, and other data relevant the aforementioned factors. These estimates assume that all the electricity generated would be used, i.e., there is no curtailment or issues with connecting the wind farms to the grid. Therefore, this estimate provides an upper bound on the potential wind capacity factor. To ensure the estimations' precision, the agency also crosschecks with power plants of similar profiles within the region. The yearly capacity factor is averaged over all CDM-registered projects in that year.

Next, we use CEC annual statistics on utilization hours to compute the *ex-post* utilization factor. Utilization factor is the ratio of the number of hours during which the turbines are spinning in a year to the total number of hours in the year. The utilization factor does *not* measure actual electricity supplied to the grid. Utilization hour numbers are widely reported in official documents, but because the utilization factor does not account for efficiency factors (e.g. wind speed or equipment availability), it can be a highly misleading metric for performance. The electricity output of a wind turbine is a function of the cube of the wind speed, and a metric such as the utilization factor completely misses that point. We still include this metric given that it provides a proxy for an upper bound for the capacity factor, and because the CEC and other official reports often emphasize this metric (NEA, 2015a).

We also compute the *ex-post* capacity factor using actual aggregate wind generation data published by the CEC and NEA divided by the total installed capacity or the total connected capacity (times the number of hours in the year) published from the CEC and CWEA. Thus, we report both the capacity factors calculated using the cumulative grid-connected capacity and cumulative installed capacity.

Therefore, we present four estimations: (i) CDM reported *ex-ante* capacity factors which estimate wind electricity production if there were no connection or curtailment issues (ii) utilization factors, which represent the percentage of time the turbines were spinning, but don't provide a good proxy for the electricity produced since they do not take into account wind speeds and other factors (iii) an *ex-post* estimates of end-year capacity factors calculated based on the reported cumulative grid-connected capacity (*CF ex-post connected*) and (iv) based on the cumulative installed capacity (*CF ex-post installed).*

Levelized cost of electricity (LCOE): We also estimate the LCOE for each CFs computed according to the four estimates outlined above. LCOE is the price at which electricity can break even over the project's lifetime and can be calculated as follows:

$$LCOE = \frac{\sum_{j=1}^{n} \frac{FC_j + VC_j}{(1+r)^j}}{\sum_{j=1}^{n} \frac{GE_j}{(1+r)^j}} \qquad [2]$$

where *j* indexes the year, *FC* and *VC* indicate the project's fixed and variable costs, *GE* the total amount of generated electricity, and *r* the discount rate. A project's expected amount of electricity generation is the product of its installed capacity, averaged capacity factor, and operational time. 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. A wind farm's project is typically in service for 20 years. We assume in our analysis that the discount rate is 8%, which is same as the China power industry's benchmark internal rate of return (IRR). For simplicity, we further assume that the operations and maintenance cost accounts for 20% of the total investment cost due to the lack of better reported estimates. We report in local currency unit (yuan RMB) and when appropriate in Euro (€) for comparison[16]. All Chinese currency values are deflated to 2004 level using the World Bank's Currency Deflator for China. We report four sets of results corresponding to different capacity factor assumptions.

Cost of Carbon Mitigation: The cost of carbon mitigation (CCM) using wind electricity is the difference between the wind LCOE and baseline LCOE divided by the carbon emission factor EF, or:

$$CCM_t = \frac{LCOE_t^w - LCOE_t^b}{EF_t} \qquad [3]$$

where *t* indexes the year. Because coal-fired power plants make up a large majority of China's electricity generating capacity, we use the LCOE of coal for each year as the baseline. We use E3's generation cost model to compute the LCOE of coal (E3, 2012). To be consistent with our LCOE model using CDM data, we focus on investment and operating costs and ignore related taxes. Average annual data for 5500-grade coal prices are obtained from Qinhuangdao Port's Free-On-Board Price (Qinhuangdao, 2016). We use annual national average utilization hours for coal power plants as reported by the CEC. Since a substantial portion of China's coal fleet consists of subcritical plants, we assume that the subcritical plants make up China's entire coal fleet in the baseline case. However, the number of the more efficient supercritical plants is on the rise and makes up close to 30% of the country's total thermal capacity (IEA, 2012). We will thus

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[16] We use a constant exchange rate of 1 Euro = 8 RMB throughout the paper.

also consider a scenario where the fleet consists exclusively of supercritical plants. Using CDM-register projects' data, we compute the yearly average emissions' factors (EFs) for China's grid, which range from 823 gCO_2/kWh to 929 gCO_2/kWh. All currency numbers are again deflated to 2004 prices.

3.3 Results

3.3.1 Connected and unconnected capacity

Between 2006 and 2010, China doubled its cumulative installation capacity every year. However, we find that proportion of the installed turbines that remained offline remained a very high share of the total installed capacity, ranging from 25% to 31% between 2006 and 2008. In 2010, this number peaked, with 34% of the installed turbines never spinning their blades (see Figure 3.2). For comparison, grid connection issues are not common in the U.S., where infrastructure considerations are often part of the planning process. During this period, a number of accidents occurred where turbines suddenly and unexpectedly went offline, further hampering efforts to integrate renewable energy into the Chinese electricity grid. Ming et al. (2014) report that as many as 80 accidents occurred in 2010, a number that increased to 193 in 2011, of which 54 events caused a loss of more than 500 MW in capacity. Wind farms in Gansu and Hebei have experienced some of the worst power loss accidents. On February 24th, 2011, a substation in Gansu suffered an equipment fault and resulted in a cascading failure, tripping off 598 wind turbines whose combined capacity totaled more than 800 MW (Xu and Alleyne, 2012). In the following April, another accident in Gansu caused power losses of 1006.2 MW, and on the same day, Hebei lost 854 MW of wind power (Li et al., 2012). A week later, an accident in Gansu tripped off 1278 wind turbines, resulting a total loss of 1535 MW power (Schuman and Lin, 2012).

3.3.2 Curtailment

China's installed wind has seen large curtailment rates, in particular in the North and Northeastern regions (see Figure 3.3). According to NEA, the 2013 curtailment rate was greater than 15% in Hebei and Inner Mongolia and around 20% in Jilin and Gansu (NEA, 2014). (In Table B.5, we show curtailment rates for various provinces between 2011 and 2015.)

Curtailment issues initially occurred in the "Three North" regions[17], though they subsequently emerged in other provinces as well. While some provinces seemed to leave their curtailment issues behind by 2015, the Three North provinces have been continually dogged by curtailment. There were some improvements in 2014, when the average national curtailment rate dropped to 8%, though the total amount of curtailed electricity was comparable to that of 2011 amount. Latest industry data underscore that the problem is far from being resolved. In 2015, as much as 33.9 TWh of wind electricity was discarded, an equivalent of 17.3 billion RMB (€2.2 billion) loss in revenue using the lowest FIT rate of 0.51 RMB/kWh (€6.38 cents/kWh) (NEA, 2015a). In fact, with the exception of Inner Mongolia, curtailment rates actually worsened for all concerned provinces between 2011 and 2015.

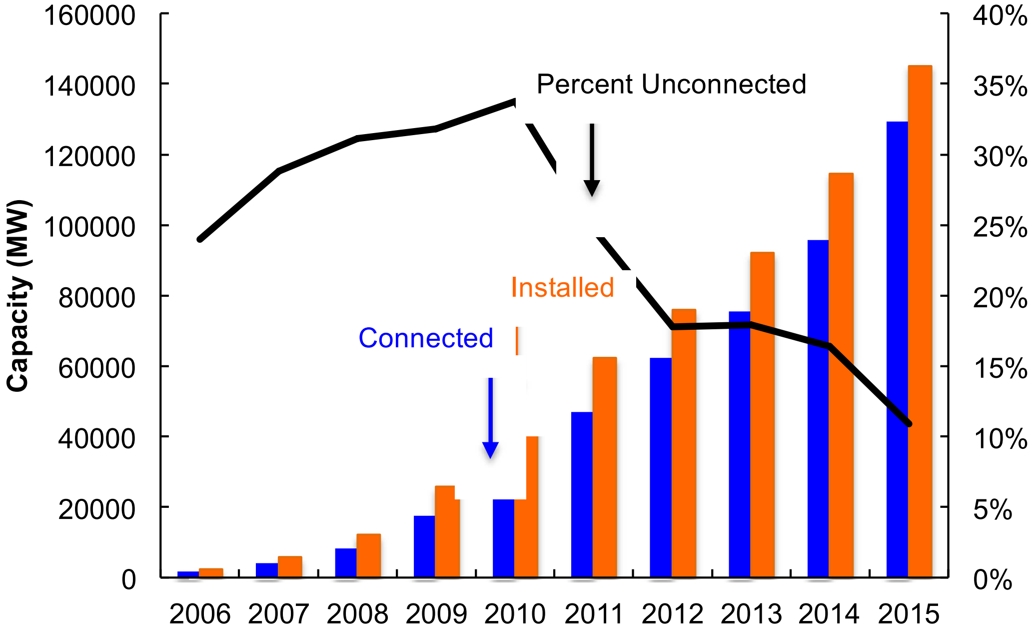

Figure 3.2: China's cumulative installed and connected capacity between 2006 and 2015 (left axis). The line tracks the percentage of China's wind base that is not connected to the grid (right axis). Figure produced by authors using data from CWEA (2015), LBNL (2014) for installed capacity and from CEC (2015) for connected capacity.

Curtailment problems also happen in other parts of the world, but not to the extent that they do in China. For instance, Wiser and Bollinger (2014) report that the U.S. wind curtailment rate is approximately 2%. The highest curtailment rate ever recorded in the U.S. was 11% peak

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[17] China's "Three Norths" refers to Hebei, Bejing, Tianjin, Shanxi, Shandong, West Inner Mongolia (North); Heilongjiang, Jilin, Liaoning, East Inner Mongolia (Northeast); Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang (Northwest).

in 2009, though curtailment quickly decreased to levels far below this historical peak. At the regional level, the Electric Reliability Council of Texas (ERCOT), one of the nine U.S. independent system operators, reported a peak curtailment rate of around 17% in 2009. By 2014, only 0.5% of potential wind energy generation within ERCOT was curtailed. In comparative perspective, the magnitude and persistence of curtailment rates in China seem quite high.

In Figure 3.3 we show the relationship between cumulative installed capacity (represented by the size of the circles), penetration rate (defined by the ratio of electricity produced by wind to total electricity produced), and curtailment rate for all provinces. Provinces with the highest wind penetration rates tend to have the highest curtailment rates. For instance, Inner Mongolia, a vast province with abundant wind resources, has become one of the focal regions for wind development, and at 10%, its wind penetration rate was the highest in the country in 2014. Inner Mongolia has also been a wind curtailment hotspot in China. Similarly, electricity grids in provinces with high wind penetration rate such as Gansu, Heilongjiang, Jilin, and Xinjiang all had to reject a high proportion of electricity produced by wind.

3.3.3 Relationship between unconnected capacity and curtailed electricity

Figure 3.4a and Figure 3.4b respectively show the amount of China's 2014 unconnected capacity and curtailed electricity in all provinces. At first glance, provinces in the "Three North" region that have high amount of curtailed electricity also have large unconnected capacity. However, once adjusted for the provinces' total capacity and electricity generation, a different picture emerges. The curtailment rates, or the ratio of curtailed electricity to total electricity produced by wind, are highest in the "Three North" region, but the rates of disconnected capacity are highest in the Central and Southern provinces (Figure 3.4c and Figure 3.4d). The initial focus of China's wind power development was in the "Three North" region, provinces abundant with wind resources. Both grid connection and curtailments hindered integration efforts in the early days of wind development. Though the country has made much progress connecting turbines to the grid, curtailments continued to dog the industry. Disconnection rates in provinces with high wind development decreased in the past five years, but disconnection and curtailment problems persist (Table B.5 and Table B.6). As curtailment worsens, the central government turned the focus to other provinces (NEA, 2016a), and these provinces have some of the highest disconnection rates in recent year. In 2015 42% of wind turbines in Guangxi was not connected, compared Qinghai's 47%, Sichuan's 37%, and Hunan's 37%.

We also show in Table 3.1 the actual amount of generated electricity between 2010 and 2012 (when the data are complete) and how much curtailment issues caused the electricity output to deviate from the expected amount. If all of China's installed wind turbines were put to use at capacity factors that were estimated by the CDM, the country could have produced as much as 153 TWh in 2012. In reality, the country's turbines only generated 103 TWh of electricity, or around 33% less. Curtailment alone accounts for 20.8TWh of the shortfall in the same year, or 42% of the discrepancy between expected and actual amount of generation.

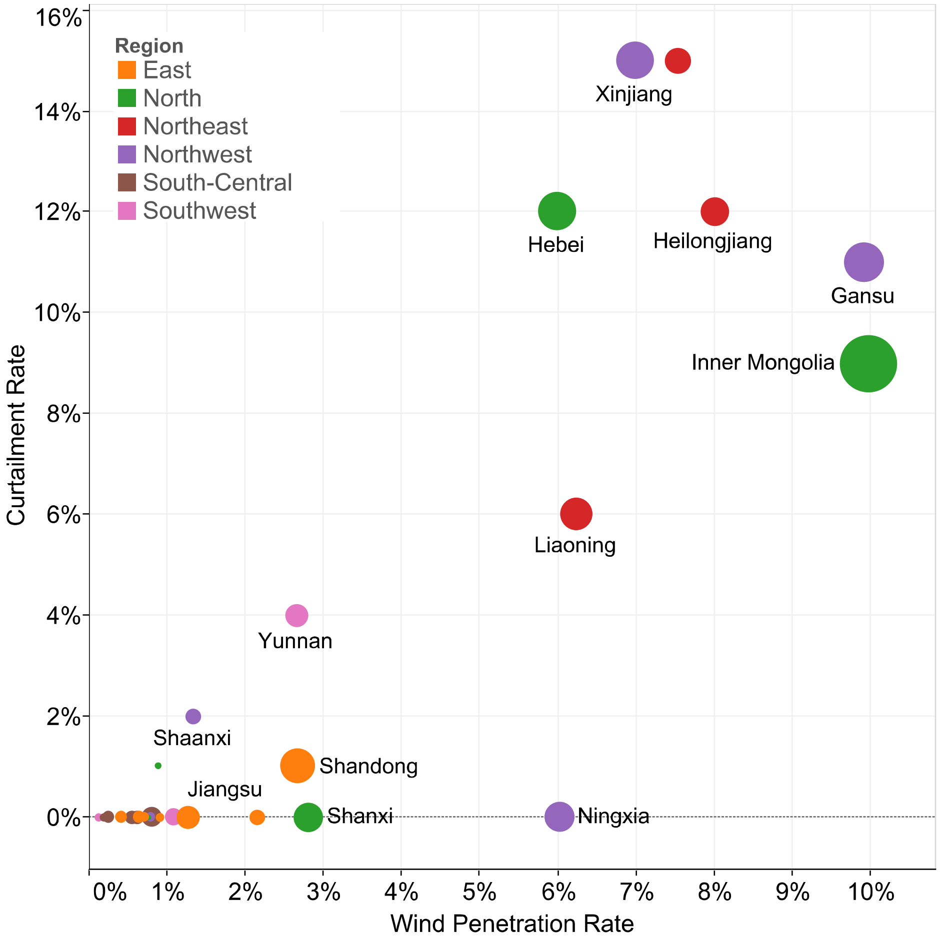
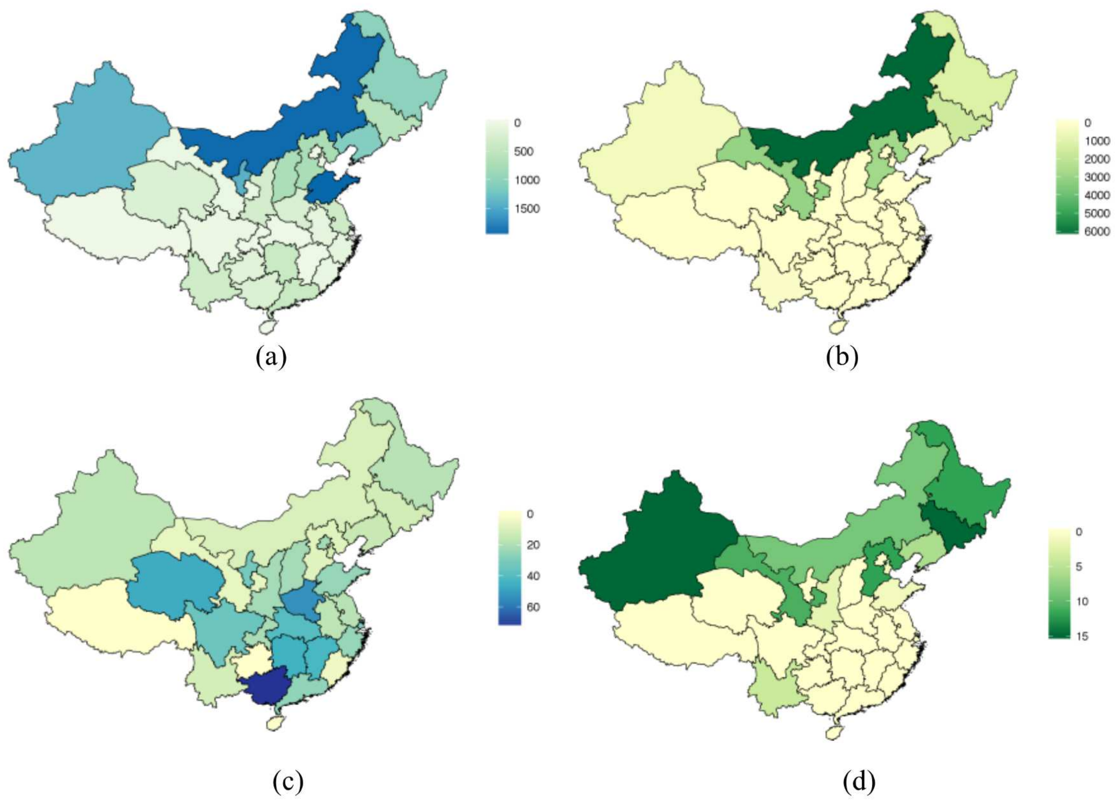


Figure 3.3: 2014 wind curtailment rates in various provinces (the circle areas are proportional to the installed capacity). Provinces with high wind penetration rates tend to have high curtailment rates as well. Plot produced by authors using data from CWEA (2015) for wind installed capacity, NEA (2015a) for electricity generated by wind, and NBS (2014) for total electricity generation.



(a) (b)

(c) (d)

Figure 3.4: Maps (a) and (b) show the disconnected capacity (MW) and curtailed electricity (GWh) for 2014, whereas maps (c) and (d) the disconnection and curtailment rates (%) for the same year. Maps produced by authors using data from CEC (2015) and CWEA (2015) to compute the unconnected capacity and from NEA (2014, 2015a) for curtailment rates.

Table 3.1: 2010-2012 wind electricity generation (TWh). Expected generation is the product of the total installed capacity and the CDM's estimated capacity factor. CEC and NEA report the actual generation and the total amount of curtailed electricity. Sources: CWEA (2015), UNEP (2015), CREIA (2012), SERC (2013), CEC (2015).

Year	Expected	Actual	Actual, if no curtailment
2010	94.0	49.4	54.3
2011	131.1	74.1	86.4
2012	153.0	103.0	123.8

3.3.4 Capacity factors

In Figure 3.5, we show that China's wind capacity factor is much lower than developers anticipated in their *ex-ante* estimates. The CEC reported that the country's 2012 average wind utilization factor is about 22%, though when accounting factors that can affect turbine's performance such as wind conditions and curtailments, the 2012 *ex-post connected* capacity factor drops to 19%, close to five points lower than the CDM *ex-ante* capacity factor. At 15%, the *ex-post installed* capacity factor is four points lower than the *ex-post connected* capacity factor, a difference that can be attributed primarily to grid connection issues. For comparison, the average capacity factor in the United States during the same time period is approximately 27% (EIA, 2015a), nearly twice as high.

Importantly, we estimate that had all of the wind turbines installed been connected and operated at the CDM estimated capacity factor, China could have generated as much as 243 TWh of electricity, or 56% more than it actually did in 2014. Surprisingly, the CDM capacity factors actually decreased from 25% in 2008 to 24% in 2012, and the utilization factor also follows this trend during the sample period. To account for the industry's high expansion rate, we substituted the yearly reported cumulative capacities by the averaged midyear capacities. Under this adjustment, the *ex-post* capacity factors are higher, though they still exhibit a downward trend (see Table B.3).

We could alternatively use the CDM project's success rate – ratio of forecasted CERs to issued CERs – to gauge the performance of Chinese wind farms. CDM forecasts the number of carbon credits that a project will earn in its qualified period based on its design parameters, and the number of issued credits depends on the actual and verified amount of offset carbon. China wind projects' success rate between 2004 and 2012 averages out to about 87% (see Table B.4).

It has been suggested that a back-up generation fleet that could comprise of hydropower plants with adjustable load-following capabilities can help with renewable integration (Kahrl et al. 2011; Yang et al., 2012; Wang, 2013; Zhao et al., 2016). However, we find evidence that the presence of high hydropower cannot help completely mitigate wind curtailment problems. In 2013 hydropower plants generated proportionally more electricity than wind turbines in Yunnan (76%), Gansu (28%), Jilin (15%), and Xinjiang (12%), and yet these provinces were still prone to have high wind curtailments (see Table B.7).

3.3.5 Levelized cost of electricity

China's wind capital equipment unit costs fell 26% between 2004 and 2012, from 8.9m yuan/MW to 6.6m yuan/MW (or €1.1m-€0.83m/MW), and are among the lowest in the world. For comparison, the 2012 US average project cost per unit capacity was approximately \$1.7m/MW (Wiser and Bollinger, 2013), or 10.71m yuan/MW at 6.3 yuan to a dollar exchange rate[18]. Similarly, the average levelized cost of electricity during this period decreased significantly, owing to a sharp reduction in investment costs and a slight increase in capacity factor.

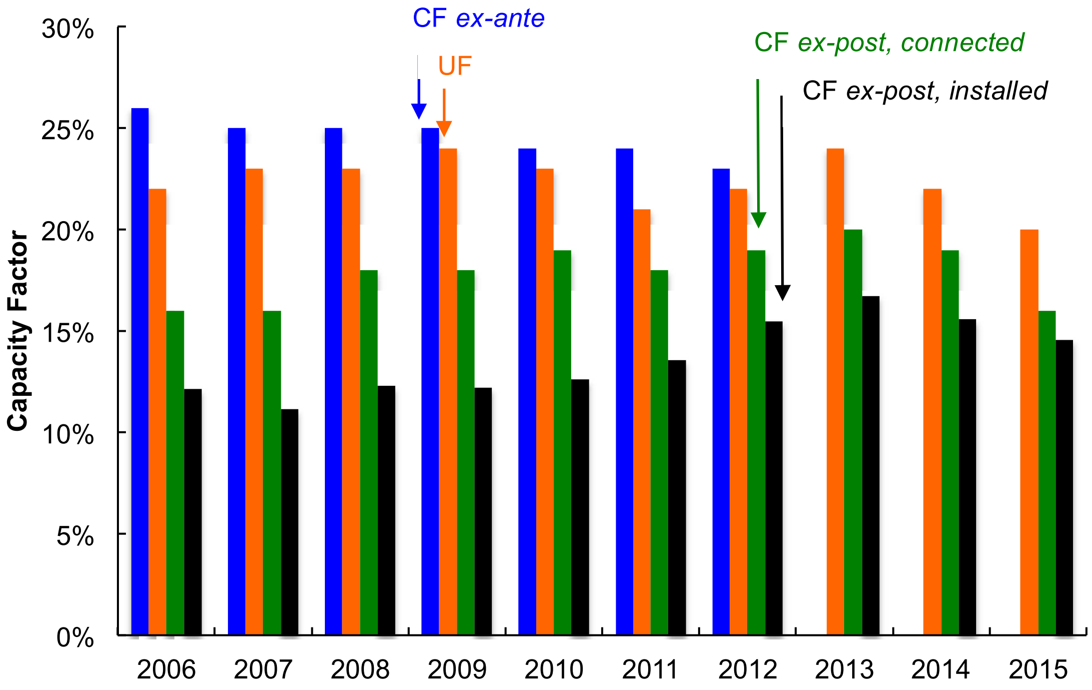


Figure 3.5: Wind farm's utilization factor (UF) and *ex-ante* and *ex-post* capacity factors (CF) in China. The *ex-post* capacity factors are consistently smaller than the *ex-ante* capacity factors. The difference between *CF ex-ante* and *UF* is due to unanticipated time that wind turbines stand idle; the difference between *UF* and *CF ex-post, connected* is primarily due the unanticipated curtailments and wind conditions; the difference between *CF ex-post connected* and *installed* is due to unconnected capacity. Plot produced by authors using data from UNEP (2015) and CEC (2015). The CDM data are only available up to 2012.

In Figure 3.6 we show the LCOE using different assumptions about the capacity factors. For instance, using CDM *ex-ante* capacity factor yields an LCOE of 0.49 yuan/kWh in 2006 (or €6.13 cents/kWh), which decreased to 0.39 yuan/kWh (or €4.88 cents/kWh) in 2012. When taking into account the significant fraction of the wind base that was not connected during this period, the 2006 LCOE (computed using *ex-post installed* capacity factor) more than doubles the

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[18] The CDM initial investment costs include turbine cost and other related expenses, such as grid connection, civil works, and other miscellaneous items. Wiser and Bollinger's (2013) reported project costs "reflect turbine purchase and installation, balance of plant, and any substation and/or interconnection expenses" (page 34).

ex-ante estimate, at around 1.02 yuan/kWh. As grid connection problems improved, the corresponding LCOE decreased at a fast rate, though at 0.59 yuan/kWh (€7.4 cents/kWh), it is still around 50% higher than the *ex-ante* estimate in 2012. The overall downward trend over the sample period is consistent across different assumptions.

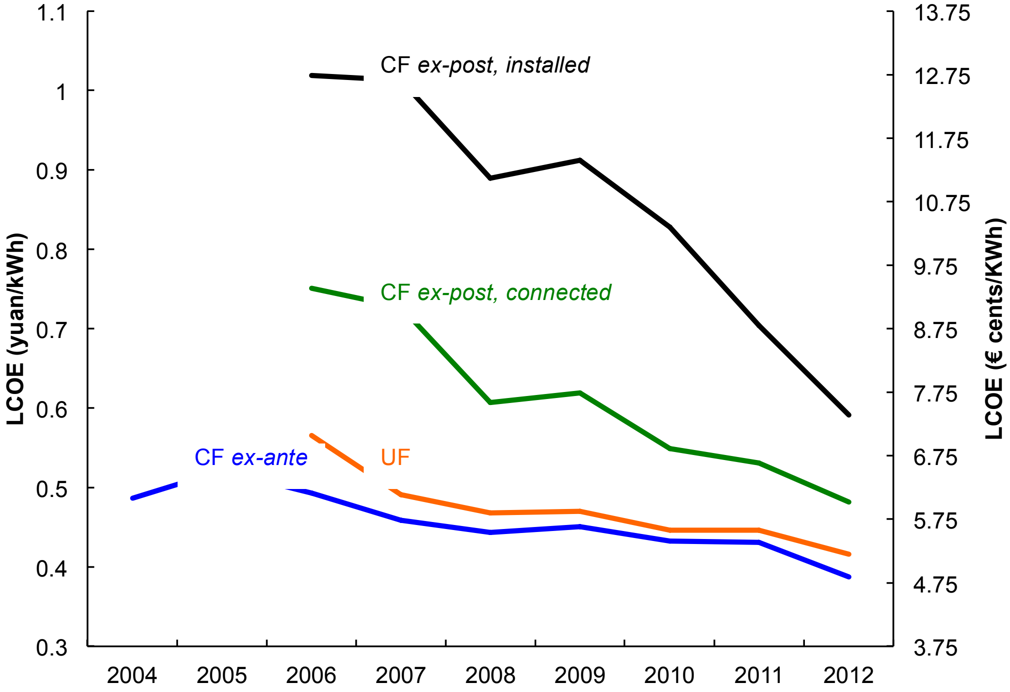

Figure 3.6: Wind levelized cost of electricity (LCOE) under different assumptions about the capacity factors in RMB/kWh (left axis) and in Euro cents/ kWh (right axis). Computed LCOE using *ex-post* capacity factor is consistently higher than using *ex-ante* capacity factor. CEC did not release wind electricity generation data prior to 2006. Plot produced by authors using data from CEC (2015) and UNEP (2015).

3.3.6 Cost of carbon mitigation

China also made significant inroads in driving down the cost of carbon mitigation using wind energy. Using CDM *ex-ante* estimates for capacity factors, we find that mitigation costs range from 151 yuan/tCO$_2$ in 2004 to 33 yuan/tCO$_2$ in 2012 (or €18.9-€4.1/tCO$_2$) for the baseline case (assuming all subcritical plants). Again, results are sensitive to capacity factor assumptions (see Figure 3.7) as well as the assumption about the composition of China's coal fleet. Under the *ex-post installed* capacity factor assumption, the CCM is four to six times higher than the ex-ante estimates, ranging from 207 yuan/tCO$_2$ in 2012 to 618 yuan/tCO$_2$ in 2006 (or around €25.8-€77.3/tCO$_2$). The 2012 CCM is comparable to the European Emission Allowance nominal price at its peak, though it is several times higher than the current market price.

The downward trends are again consistent across all assumptions. However, the CCM reductions are steeper than the LCOE reductions due to the increase in coal prices in the first half of the sample period and the sharp decrease that followed. We expect the CCM in recent years to be much higher given the recent precipitous drop in coal prices (Figure B.4). Likewise, the recent lower capacity factors are likely to push up the corresponding CCM.

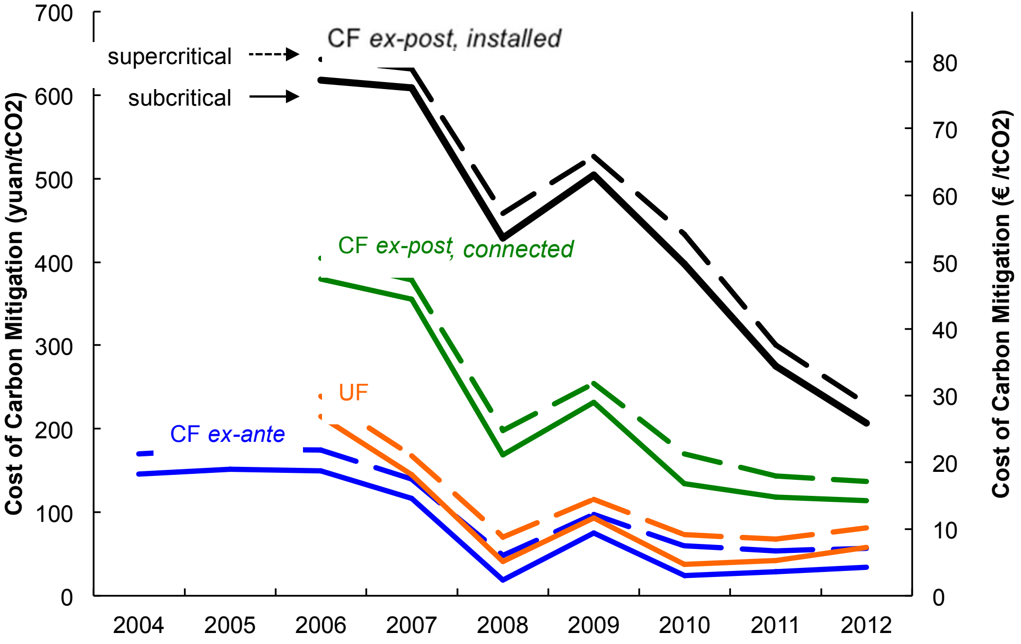

Figure 3.7: Cost of carbon mitigation (CCM) under different assumptions about the capacity factors and the baseline LCOE in yuan/tCO2 (left axis) and €/tCO2 (right axis). In each capacity factor scenario, we assume the coal plants replaced by new wind power plants are either all subcritical or all supercritical. Plot produced by authors using data from CEC (2015) and UNEP (2015) for wind LCOE, E3 (2012) and Qinhuangdao (2016) for coal LCOE, and IGES (2015) for emission factors.

3.4 Discussion and conclusion

In this paper we illustrate the scale of connection and curtailment problems of China's wind energy industry across provinces, their effect on China's wind capacity factor, levelized cost of electricity produced by wind, and the associated cost of carbon mitigation. We show that China's wind capacity factor is much lower than developers anticipated in their *ex-ante* estimates. As a result, the corresponding wind LCOE and CCM in reality are also higher than expected.

This work has some caveats and limitations. First, CDM data on capital investment costs do not necessarily reflect the real costs of wind turbines in the Chinese markets. It could be the case that SOEs, which make up more than 90% of the market in recent years, intentionally distorted product prices to gain market share. The LCOE and CCM estimates are then higher in this case. We explore this possibility by varying the investment costs and the O&M costs in more detail in the appendix (Table B.8). The LCOE is more sensitive to the capital investments and the capacity factors. For instance, in the scenario where the capital investment is 30% higher, the lowest LCOE is 0.51 yuan/kWh, which occurred in 2012 using CDM *ex-ante* capacity factor, 0.12 yuan/kWh or 24% higher than the corresponding baseline case. Using the *ex-post* capacity results in a 0.63 yuan/kWh LCOE for the same year, 0.24 yuan/kWh or 38% higher than the corresponding baseline case.

Estimates for the first half of our sample period may be more accurate, when foreign and private firms still had a substantial market share, and the industry was not as competitive. Additionally, Chinese wind farms bear a number of tax burdens, and of these, income tax, value-added tax (VAT), urban maintenance and construction tax, and education surcharges are not reflected in the total investment costs. Chinese wind farms enjoy full income tax exemption in the first three years, half exemption in the following three years, and a preferential 15% income tax rate thereafter (Liu et al., 2015). However, given the large discrepancy between the expected generation and the actual generation of wind electricity across the country as well as the widely reported delays in payments to the generators, many generators during this the sample period operated at very tight margins, and would not have to pay significant income taxes. Based on the FITs for wind, we estimate that the VAT, urban maintenance and construction tax, and education surcharges total to approximately 0.047-0.056 yuan/kWh (nominal).

Second, in calculating the CCM, we assume that wind power plants replace coal-fired power plants. While smaller in its contribution to electricity generation, hydropower was still responsible for 14-17% of China's electricity in our sample period (CEC, 2015), thus the actual baseline LCOE would have to account for hydropower's LCOE as well.

Third, we consider scenarios where China's coal fleet is made up exclusively of subcritical or supercritical plants. Thus the results reported here are likely the lower and upper bounds. Finally, we do not consider how integrating electricity produced by wind could affect the CO_2 emissions and the associated CCM of the rest of system. When a traditional (mostly coal-fired in China) generator ramps up and down to compensate for wind's intermittency and variability, it may require more fuel use than when it is operated at a steady level, thus wind integration may increase CO_2 emissions and CCM (Katzenstein and Apt 2008; Zhang et al., 2015).

The success of China's transition to a low-carbon energy system will be key to achieve the global level of emissions reductions needed to avoid large negative consequences from climate change. On the surface, the rapid build-out in the past decade appears to represent a triumph of China's centralized government-directed approach to investment. However, China has struggled to utilize this massive installed base effectively. In 2015 alone wind curtailment exceeds 33.9 TWh. Had all of these spilled electrons been used, and assuming that would be able to avoid the generation from the average electricity mix, about 29.5 million on of CO_2 would have been avoided – roughly the same amount of CO_2 Connecticut produces (EIA, 2015b). Between 2011 and 2015 China's grid systems curtailed approximately 96.5 TWh of wind electricity, missing the opportunity to avoid 84 million tons of CO_2. Moreover, because the actual amount of electricity consumption determines how much revenue and the number of CDM emission reduction credits wind farm owners can earn, wind farm owners have lost billions of RMB due to these large production shortfalls.

The still-large gap between installed capacity and renewable energy usage helps explain one of the painful realities of China's green energy push: after a decade of unprecedented expansion, renewables have risen from 6% to only 9% of China's total primary energy consumption, and 7% of this total is generated by hydropower (BP, 2015). Macroeconomic trends also present daunting challenges as China pushes forward with its ambitious renewable energy development plans. China's economy has slowed substantially in recent years, and the electricity consumption growth rate has suddenly come to a virtual halt. In 2015 China's economy grew 6.9%, but the electricity consumption rate increased merely half a percentage point (see Figure B.1). Nevertheless, the country's energy supply has continued to expand at a rapid pace. Last year, thermal capacity (mostly coal) grew by 8% (see Figure B.3), hydropower 6%, and wind 36%. The slowdown in energy demand coupled with a business-as-usual increase in supply have led to sharp reductions in utilization rates across all energy sources (see Figure B.2).

Nevertheless, China has decided to redouble its efforts and press on with its renewable energy development plans. The country now wants to lift its wind power target to 250 GW, or twice the current capacity, by 2020. By the same year, it aims to install 150 to 200 GW of solar power (Reed, 2015), and 58 GW of nuclear power (WNA, 2016a). At the COP21 meeting, China committed to a 20% non-fossil primary energy consumption target by 2030, an ambitious target. In order to achieve these goals and successfully integrate renewable energy into the country's existing power generation system, serious reform efforts are needed.

Interprovincial power exchange markets and improvements in transmission infrastructure are likely key to the successful growth of low carbon electricity in China. Between 2011 and 2014, Inner Mongolia's electric power generation capacity grew by 18.69 GW, of which 4.76 GW came from wind power. (Thermal power accounted for most of the remainder.) Assuming a 60% capacity factor, the new thermal capacity alone could provide Inner Mongolia with 73.2 TWh of energy, some 18 TWh more than the increase in consumption during this period. Put differently, Inner Mongolia could satisfy its energy needs without renewables. Exporting its excess electricity production using non-UHV lines to the energy-thirsty coastal region to alleviate some of Inner Mongolia's curtailment problems remains difficult without a robust electricity network and a mature market exchange. Similar problems exist in other provinces with high wind curtailment rates such as Gansu and Jilin. As per the NEA's mandate, wind turbine construction in these provinces had been halted until curtailment problems are adequately addressed (NEA, 2016a).

Some have called for a more flexible power generation system that would consist of pumped hydro storage and electric boilers (Lu et al., 2016). Indeed, Zhang et al. (2015) demonstrate that the deployment of pumped hydro storage and electric boilers can be a cost-effective method to reduce curtailments of wind power in a power system that heavily relies combined-heat-and-power plants. The NEA is pushing Northern provinces to use wind energy that would otherwise go to waste for residential heating instead, and a pilot project is expected to complete in Inner Mongolia in 2020 (C. Liu, 2015). However, significant challenges remain as the government manages competing interests among the stakeholders, and there are questions regarding the economics of a provincial or national deployment program.

Traditionally, China follows an "equal shares" system, where coal-powered generating plants are given contracts with fixed electricity prices, and the operating hours are allocated equally across the generators. This policy effectively shuts out renewable energy by carving out and reserving a significant chunk of the electricity market for expensive and inefficient coal plants. In principle, a priority dispatch system where priority is given to renewable energy in the dispatch sequence can increase the demand for electricity produced by renewable sources. The amendments to the *Renewable Energy Law* require grid operators in five provinces to move past the generation guarantee quota system and establish a priority dispatch sequence, though grid operators are still allowed to curtail wind electricity output under certain system constraints. Recently China announced its intention to commit to a national green dispatch program (The White House, 2015), though neither the program's timeline nor its implementation is clear. China is also considering a power generation quota system where provinces must generate a certain fraction of their electricity from renewable sources, though enforcement methods are again unclear (NEA, 2016b).

Finally, an emissions trading system can bring China closer to a more cost-effective and efficient mechanism for emissions reductions. Senior policymakers have embraced this as a long-run goal, and pilot emissions trading systems have been introduced in several areas. Plans to establish a national ETS are under way, and China plans to roll out the national trading system in 2017 (The White House, 2015). While challenging, such a trading system can significantly reduce China's carbon emissions and boost its utilization of renewable energy if successfully implemented.

4 A Sunny Future? Expert Elicitation of China’s Solar Photovoltaic Technologies

China has emerged as the global manufacturing center for solar photovoltaic products in short order. Chinese firms have entered all stages of the supply chain, producing most of the installed solar modules around the world. Meanwhile, production costs are at record lows. The decisions that Chinese solar producers make today will influence the global product flow for years to come. We interviewed 16 Chinese and non-Chinese experts to provide detailed assessments of the technological and non-technological factors that led to the surprised success of China’s silicon photovoltaic industry. Experts evaluated key solar photovoltaic quantities such as efficiency, costs, and commercial viability of 17 silicon and non-silicon solar photovoltaic technologies by 2030. Judgments from experts suggest that continued declines in module and system costs coupled with steady efficiency gain will allow solar photovoltaic to be competitive with traditional energy resources like coal in China. Silicon photovoltaic will remain the mainstream product for large-scale electricity generation application in the near future, though the industry’s future developments may be affected by overinvestment, overcapacity, and singular short-term focus.

4.1 Introduction

Progress in solar photovoltaic (PV) technology has caught many by surprise. From a niche product for small-scale applications, solar PV has become an attractively cheap candidate for countries around the world to reduce greenhouse gas emissions. In the past ten years, global solar installed capacity has grown more than 45 times, from 5.1 GW in 2005 to 229 GW 2015 (Schmela, 2015). Currently, solar PV meets about 1.3% of the global electricity demand, a small but rapidly growing percentage (PVPS, 2016). Production costs have plummeted at an unprecedented rate to levels that many experts previously deemed unlikely at an unprecedented rate (Baker et al., 2015; Curtright et al., 2008). Central to these developments stands China, which has emerged in recent years as the global behemoth in terms of both PV production and deployment (Schmela, 2015). Of the 50.6GW of solar PV installed in 2015, a third was in China, making it the world's largest solar PV market (Schmela, 2015). Chinese firms dominate every stage of the supply chain, from polysilicon to modules. Chinese polysilicon producers provide half of the global polysilicon supply (BNEF, 2016b). For every ten PV modules installed in the world, about seven were manufactured by Chinese PV producers (CPIA, 2016a).

Previous studies aim to examine the competitiveness of China's solar PV industry. (Yu et al., 2011) studies the decline in solar module costs using an input-output model and concludes that raw material prices (polysilicon, silver), scale effect, and high learning-by-doing rate are responsible for this price drop. Gallagher (2014) attributes the competitive advantage of Chinese firms to global and national climate policies, human capital mobilization – an argument that (Luo et al., 2013) also makes – internal manufacturing optimization, and vertical integration (Zhang and Gallagher, 2016). Furthermore, the Chinese PV industry drew crucial support from market formation policies (Gallagher, 2014; Grau et al., 2012). In a bottom-up engineering economics model, (Goodrich et al., 2013) shows that economy of scale and supply-chain specific factors such as discounts in material and equipment confer a China-based factory cost advantages over a US-based factory.

Using expert elicitation, this paper seeks to understand how Chinese solar PV technology will evolve in the next few years. In addition to detailing specific technological factors and non-technological factors that contributed to the fall of PV production costs in China, we also seek to determine the current status and future prospects of China's solar PV industry. Expert elicitation has wide application and enjoys high popularity in the technology forecasting community (Baker et al., 2015; Verdolini et al., 2016). Previous studies have used expert elicitations to quantify future progress of solar PV globally (Anadon et al., 2011; Baker et al., 2009; Bosetti et al., 2012; Inman, 2013), though they did not feature China. China will continue to play an important role in the future progress of solar PV, and developments in China will reverberate far beyond its borders. By focusing on China, this study paints a more detailed picture of the solar PV industry's current status as well as its future technological trajectories.

4.2 Methods

The overall goals of the expert elicitation are to: (i) understand the factors that affected the cost of crystalline Silicon PV modules between 2005 and 2015; (ii) to identify the major barriers to the future success of PV; (iii) to assess the state and economic viability of different PV technologies by 2030 under current R&D funding. In order to do so, we developed an expert elicitation survey following the traditional approach established by Carnegie Mellon University over several decades (Morgan et al., 1992; Morgan, 2014; Morgan and Keith, 1995). Please refer to the Supplemental Information for a general description of the approach as well as alternative methods to estimate future technology costs. A full version of the protocol used for this elicitation is also available in the Appendix.

The elicitation is organized as follows: the interviewer first introduces the method of expert elicitation and explains the goal of the study to the expert. The interviewer then explains the elicitation procedure as well as biases associated with this type of study and strategies to address them. After that, the expert is asked to rank his or her levels of expertise towards different solar PV technologies. The formal elicitation then consists of two parts: an assessment of silicon technologies and another for non-silicon technologies. The emphasis is on silicon-PV technologies, because they make up an overwhelmingly large portion of the global market (Fraunhofer, 2016), and Chinese firms predominantly compete in this technology space. The expert is asked to identify technological and non-technological factors that led to the decline of production cost of silicon PV modules from 2005 to 2015. The expert then assesses technological barriers and potential advances before estimating module efficiency and costs by 2030[19]. He or she is asked to perform the same assessment and estimation tasks for non-silicon

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[19] We elicited in-house production costs instead of blended costs. For a discussion of the difference between the two, please refer to the Supplemental Information.

technologies. Finally, to check for consistency, the expert is asked to assign probabilities that any technology for each major technological group achieving certain system costs by 2030.

The elicitation includes questions for 17 solar PV technologies. Table 4.1 lists these technologies. Solar PV module is chosen as the unit of analysis because modules are often sold commercially and installed as electricity-generating units, even though progress at the cell level may attract more attention.

This study focuses on cost as opposed to price to minimize the number of market uncertainty factors such as overcapacity in the supply chain. Furthermore, instead of eliciting directly the levelized cost of electricity (LCOE), which is location-specific, we compute it using elicited results. This approach allows us to perform sensitivity analysis on key parameters such as balance of system, capacity factors, and discount rate. For simplification, we consider utility-scale solar only.

Previous studies also consider various Research, Development, and Deployment (RD&D) scenarios (Anadon et al., 2011; Bosetti et al., 2012; Curtright et al., 2008; Inman, 2013). However, eliciting how increasing or decreasing public RD&D can affect costs and performance of PV technologies decades from now creates an extra dimension of uncertainty and adds an additional set of tasks to an already-long protocol. Thus, we designed less ambitious research questions and focused simply on understanding the performance of solar PV assuming current levels of R&D.

Because the Chinese market is the focus on this study, we elicited costs in local currency (yuan RMB per Watt peak) in current year value. Many experts preferred to express their estimates in U.S. dollars, the currency used by large firms and some industry trade groups. We report both values, assuming an exchange rate of 6.5 yuan RMB to a dollar.

Overall, we recruited 16 participants from industry, academia, and national laboratories with expert knowledge of solar PV technologies and China's solar industry[20]. All but three are Chinese nationals. Participation was voluntary and anonymous. Table C.1 summarizes demographic and background information of participating experts. One interview was conducted via Skype call, and two via telephone. The remainder of the interviews were conducted in person. All interviews were conducted in Chinese or English, depending on the expert's

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[20] Please see the SI for a full description of the protocol and its development.

preference. (One Chinese expert decided to respond in English.) We interviewed 16 additional subjects in person. These individuals engaged in various parts the PV industry but did not formally participate in the survey due to time constraints or lack of expert knowledge of some aspects of the industry. These discussions were guided by open-ended questions at the end of the protocol. The study was conducted between June and December 2016.

Table 4.1: 17 technologies featured in study. We provided definitions of each category and technology to experts as needed. They are also available in the protocol in the SI.

Crystalline Si	**Thin Film**	**CPV**	**Excitonic**	**Emerging**
Mono-Si	CdTe	LCPV	DSSC	Hot carrier
Mc-Si	CI(G)S	HCPV	Organic, molecule	Multiple electron-hole pair
Novel	Amorphous Si		Organic, polymer	Multiband/impurity
				Up/down converter
				Thermophotovoltaic
				Perovskite

4.3 Results

4.3.1 Technological factors for Chinese silicon PV 2005-2015 cost decline

Experts agreed that the sharp decrease of polysilicon price was the single most important factor in reducing the overall costs of PV in the past decade[21]. Figure C.1 and Figure C.2 in the SI show experts' rankings of the importance of different components to cost reduction of PV module and system. Chinese investors led the effort to ease the global polysilicon shortage that peaked in the late 2000s. In 2016 the global production capacity totaled over 400,000 tons, half of which was owned by Chinese producers (BNEF, 2016b). Fifteen years earlier seven firms made up of over 90% of the world market of about 18,000 tons, and none was Chinese (Woditsch and Koch, 2002). Polysilicon price as of 2016 has fallen to \$12 to \$17 per kilogram (EnergyTrend, 2016), a precipitous drop from \$350 per kilogram in 2008. (Table 4.2 summarizes technological factors that influenced the cost of solar PV.)

Chinese producers improved wafer quality by controlling the distribution of grain sizes and bringing down the level of dislocation density through a seed-assisted crystal growth method (Zhu et al., 2014). Commercial raw mc-Si seeds placed at the bottom of the crucible act as

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[21] Please refer to Section 6 of the SI for a detailed discussion of relevant technological advancements.

starting points for the growth of silicon crystal, yielding mc-Si crystals with fewer defects. A standard cell can gain up to 0.5% in efficiency. As much as 60% of the mc-Si ingots were made using this process in 2015[22], and non-Chinese manufacturers are exploring and adopting this technique as well[23]. Ingot makers also built larger furnaces, thus increasing the proportion of unpolluted ingot blocks.

Wafer makers replaced multi-wire slurry sawing with diamond wire to produce more wafers with smaller thickness at a higher throughput (N. Watanabe et al., 2010). Because diamond wires are thinner than steel wires, there is less kerf loss, or sawdust from slicing. Diamond wire can slice a kilogram of silicon into 60 wafers, compared to steel wire's 51, thus delivering substantially more efficient production. By one estimate, diamond wire sawing can lower module cost by about 2.6 cents/W (Xing, 2016).

Improvements in key material inputs such as silver paste allowed manufacturers to further increase cell efficiency. Better silver paste recipes and improved printing methods reduced silver use: a solar cell in 2015 contained 0.10 gram of silver compared to 0.30 gram five years prior (BNEF, 2014a; ITRPV, 2016). At the same time, profiles of cell conductors became taller and more narrow, resulting in lower shading loss and higher overall efficiency[24].

Chinese cell makers added more busbars to their solar cells, increasing the overall cell efficiency. Early cells contained two busbars, though the majority of solar cells now have three. Four-busbar technology can increase cell efficiency by 0.3% (BNEF, 2014a; ITRPV, 2016). Recently, Canadian Solar recently launched their five-busbars mc-Si and mono-Si products with cell efficiency as high as 20% (CanadianSolar, 2016).

Module makers have been aggressive in cutting costs as well. Previously, Chinese module assemblers relied on international suppliers for main components, but new domestic entrants allowed them to source these components locally at a fraction of the cost of international brands. For example, ethyl vinyl acetate (EVA) sheets, front glass covers, and aluminum frame are all produced domestically. Chinese producers have been forceful in fabricating inexpensive alternatives to more complex components. For instance, Jolywood (Suzhou) Sunwatt, a Chinese firm, offers backsheet at half the cost of DuPont[25].

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[22] Interview #2

[23] Interview #34. (Some experts were interviewed in two sessions.)

[24] Interview #16

[25] Interview #2

The indigenization of capital equipment was one of the most important factors in driving down PV module costs. Early Chinese PV entrants purchased turnkey production lines from Western equipment makers, who in turn trained local employees to operate the machines (la Tour et al., 2011; Zhang and Gallagher, 2016). Small-scale producers, who were more price-conscious, opted to purchase domestic equipment. Early equipment was rife with quality issues, but through iteration and learning, often alongside with customers, equipment makers were able to iron out technical kinks and fine tune their designs.

Investment costs have dropped significantly thanks to the proliferation of domestic equipment. For example, an expert from a leading Chinese equipment maker estimated that a 25 MW production line in the mid 2000s costed 100-300 million yuan RMB to set up. A production line of the same capacity currently costs about 40 million yuan RMB. Automation also helped to reduce labor costs. Five years ago operating a 500MW module manufacturing plant required around 2000 employees, but a new plant of the same capacity can be run with 400 people (Zheng, 2016). Similarly, as Suntech emerged from its bankruptcy, the company was able to reduce its work force from 10,000 in 2011 to 3000 in 2016 while maintaining the same level of production capacity[26].

Table 4.2: Key technological improvements mentioned by our experts that influenced the cost of solar PV.

Stage	Key Factors
Polysilicon	Investment and scaling up of production plants; hydrochloronation technology upgrade; increase number of seed rods in furnace; reduction in electricity use; investment in fluidized bed reactor technology
Ingot/Wafer	Seed-assisted growth method using crystalline Si and quartz; larger furnace and larger ingots; diamond wire sawing; black Silicon; direct wafer
Cell	Improved efficiency; improved silver paste recipe; efficiency use of silver paste; higher number of busbars; high-efficiency cells (PERC/L/T, IBC, HIT)
Module	Domestic production and reduction of material use of key components (EVA sheets, glass, backsheets); replacement of TPT backsheets
Equipment	Indigenization of equipment for aluminum back surface field; automation; gradual domestication of key equipment for high-efficiency cells

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[26] Interviews #27, #28

4.3.2 Non-technological factors for Chinese silicon PV 2005-2015 cost decline

Our interview subjects agreed that policies aimed at creating market demand for solar PV technologies – what Gallagher (2014) terms "market formation policies"– were critical to the development and success of China's solar industry. These policies included generous feed-in-tariffs (FIT) in Europe before the financial crisis and in post-Fukushima Japan; and renewable energy portfolio, net energy metering laws, investment tax credits in the U.S.[27] The Chinese government also used demonstration projects and FIT to promote domestic deployment of solar. Promotion of solar energy not only brought the promise of jobs and exports, but it also dovetailed with the central government's official commitment to environmental protection and clean energy[28].

We confirm that access to capital and technology was not a constraint (Gallagher, 2014). Financial aid from the local governments in the form of cheap loans, tax breaks, low-cost land-use rights, and subsidized electricity made investment in solar PV more attractive, even at times bringing the market to a "feverish frenzy"[29].

Additionally, we also confirm that economies of scale, agglomeration effects, learning-by-doing, and human capital mobilization – especially in the form of intellectual returnees – contributed to the competitiveness of Chinese PV industry (Gallagher, 2014; Goodrich et al., 2013; Luo et al., 2013; Yu et al., 2011). Flexible management, especially among small firms, enhanced the industry's competitiveness. Additionally, a number of firms pursued vertical integration to improve their financial prospects (Zhang and Gallagher, 2016), though this strategy has left some firms exposed and vulnerable to market and policy shifts and caused firms great financial duress that sometimes led to bankruptcies.

Some experts stated that characteristics particular to silicon PV technology and the industry's organization allowed silicon PV to be competitive over other types of solar PV technologies[30]. Compared to thin-film, the silicon PV industry is highly modular in its organization. Improvements can come from cell or module makers or from material and

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[27] Please see IEA/IRENA Joint Policies and Measures Databases (2016) for a full summary of relevant policies.

[28] In addition to GDP growth, evaluation and promotion criteria for local officials now include metrics on environmental management and clean energy development (Interview #17).

[29] Interview #12

[30] Interviews #9, #13

equipment suppliers. Changes in one part of the supply chain does not necessarily compromise the operation or technical specifications of another. A design change in the doping process does not impinge on the cleaning process. A new profile for cell conductor does not affect how backsheets are made. “Drop-in” equipment replacements do not require manufacturers to modify their entire existing production line[31]. These incremental improvements can occur independently, but when added together, they deliver large cost reductions. In contrast, CdTe and CIGS makers follow a more integrated approach. In addition to designing and producing cells and modules, thin-film producers often build their own equipment[32].

The modular and open nature of silicon PV technology further drives product specialization and knowledge spillover within the industry. In a mature industry with standard products, improvements that result in price reduction can translate to rapid adoption, an outcome that can be accelerated by leading firms’ embrace of the improved technology. For example, a major Chinese silicon PV firm, in partnership with a domestic tool maker, successfully developed a technology that would prevent light-induced degradation in modules. As soon as the partnership ended, the tool maker introduced the technology to other module producers, and the technology quickly became an open secret[33]. Compared to the thin film industry, whose technologies are often closely guarded, the silicon PV industry is more open, and this openness can accelerate the standardization process.

4.3.3 Cost and performance elicitation results: Silicon PV

Under current RD&D scenario, experts anticipated continued improvement in efficiency for all silicon-based PV technologies from Chinese producers (Figure 4.1). Median estimates show that mono-Si modules will reach an average efficiency of 21.2% by 2030 (solid line in Figure 4.1), about 4% higher than the average mono-Si module sold today (dashed line). Average efficiency for mc-Si modules will be one percentage point lower, and average efficiency for novel silicon-based technology will reach 23%. Some experts anticipated that in the most optimistic scenario novel technology would be close to the theoretical maximum efficiency of about 30% (Shockley

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[31] Interview #36

[32] On the other hand, this integrated strategy affords thin film producers independence from equipment suppliers, and thin-film producers can customize their production lines and incorporate secret nuances in the production process.

[33] Interview #10

and Queisser, 1961). Estimations are fairly consistent with some exceptions. Experts F and K expected significantly higher efficiency for mono-Si and mc-Si modules, while most experts saw limited prospects for these technologies. Some experts anticipated that aluminum back surface field (Al-BSF) solar panels for the most part would be replaced by high-efficiency panels, though low-cost, low-efficiency products would continue to exist in the market.

Experts stated that the module cost would continue to decline (Figure 4.1). Median estimates for mono-Si module costs range from \$0.16/W to \$0.46/W, with an average cost of \$0.27/W (solid line). For comparison, mono-Si module *price* in early 2016 was \$0.64/W (dashed line). Due to oversupply, mono-Si module *price* had already fallen by 30% within one year to \$0.41/W (EnergyTrend, 2016), reaching the lower range of results in recent studies (Anadon et al., 2011; Inman, 2013). The average of median estimates for mc-Si module production costs is \$0.24/W, \$0.15/W lower than its current price. Novel modules will be more expensive relative to mono-Si and mc-Si modules, reaching around \$0.30/W.

Estimated ranges for costs are wider than those for efficiencies. Overall, the estimated ranges are narrower than previous studies (Baker et al., 2015; Curtright et al., 2008). Efficiencies for silicon PV modules have improved over the past decade, but the theoretical efficiency ceiling remains unchanged. Similarly, decrease in module cost has been dramatic, but future system cost reductions will depend more on non-module components.

Figure 4.2 shows elicited system costs for different silicon PV technologies by 2030. Average of median estimates for mono-Si PV system cost is \$0.72/W, about four cents higher than mc-Si system. PV system using novel modules is \$0.03/W more expensive than mono-Si-based system. Two experts anticipated no difference in system costs across the three technologies (Experts L and O); two stated novel PV systems would be cheaper (Experts B and F). Novel modules may be more expensive, but their higher efficiency drives down area- and weight-related component costs. Such offset can be more pronounced as module becomes a smaller fraction of the system costs.

All experts were confident that by 2030 system costs would fall below six yuan RMB per Watt (\$0.92/W) (Table C.2)[34]. Likewise, all but three experts assigned a better-than-chance probability that 2030 system costs would fall below four yuan RMB per Watt (\$0.62/W). This

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[34] This is roughly the same as the cost target set by the U.S. SunShot initiative for U.S. solar PV.

translates to an LCOE of about $40/MWh (Table C.4). At $40/MWh, LCOE for solar energy is comparable with the current LCOE for coal in China (Salvatore, 2013). Using experts' estimates for module prices, we also compute LCOE for solar under different assumptions about balance of system costs (Table C.5 and Table C.6). We find that LCOE for solar can reach as low as $34/MWh, half of the LCOE that (Bosetti et al., 2012)) report. However, these LCOE estimates do not account for integration costs. The assumed capacity factor of 20% is optimistic for China: in 2015 the industry's utility factor for solar PV was 12.9%, and its capacity factor was 10% (NEA, 2016c).

Improvements in both efficiency and production costs can come from a number of sources. New cell designs such as PERC/L/T, IBC, and HIT can help Chinese producers boost cell efficiencies. These high-efficiency cells were invented and developed elsewhere, but Chinese cell makers hope that they can scale up operations and indigenize equipment to drive down costs in a similar manner as Al-BSF cells.

Advances in polysilicon and wafering process can further lower production costs. Recently the industry has turned to Fluidized Bed Reactor (FBR) as a cost-effective alternative technology to produce polysilicon material. Adoption of diamond wire sawing technology for mc-Si application in conjunction with black silicon technology can reduce kerf loss and increase mc-Si cell efficiency.

Direct wafer technology, pioneered by the Massachusetts firm 1366, has the potential to revolutionize the wafer manufacturing process. Using proprietary technologies, 1366 produces standard silicon wafers directly from molten silicon, bypassing the capital-intensive ingot and wafering parts of the supply chain.

Experts believed that China would remain a strong player in silicon PV, but they envisioned two scenarios for the industry's long-term evolution. In the first scenario, improvements across the supply chain through specialization of material and equipment will continue, though with some degree of industry consolidation. In the second scenario, major organizational and technological changes will take place, resulting in a shortened supply chain and substantial reduction in capital intensity. For example, a new technology that would enable direct growth of the absorber layer from raw polysilicon could allow producers to bypass multiple upstream production processes.

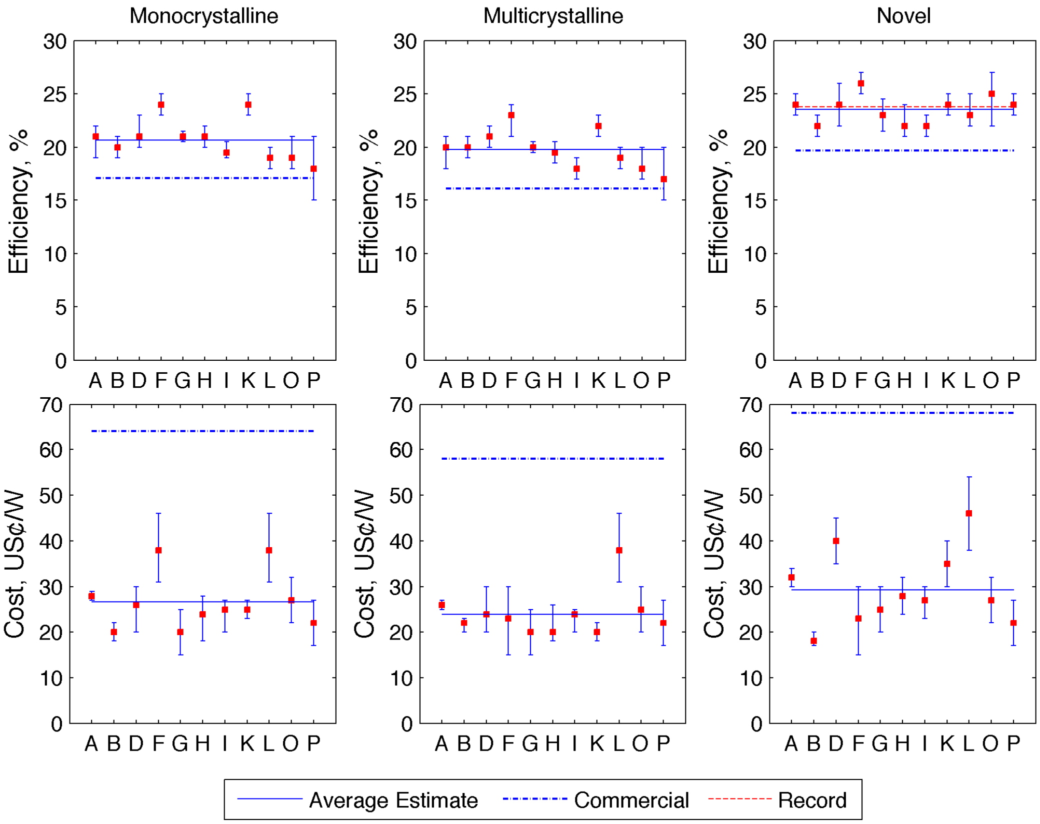

Figure 4.1: Expert judgments of efficiencies and costs in 2030 for monocrystalline, multicrystalline, and novel silicon technologies. Each expert responds with their best, upper, and lower estimates. We also report the average of the best estimates and 2015 commercial values. Panasonic HIT panel holds the lab record module efficiency of 23.8% (Green et al., 2016); its commercial efficiency is 19.7% (Panasonic, 2016). Data for commercial efficiency of mono-Si and mc-Si modules are from (BNEF, 2016a); data for commercial prices of mono-Si and mc-Si modules are from (BNEF, 2016a); data for commercial price of novel modules is from pv magazine (Schachinger, 2016).

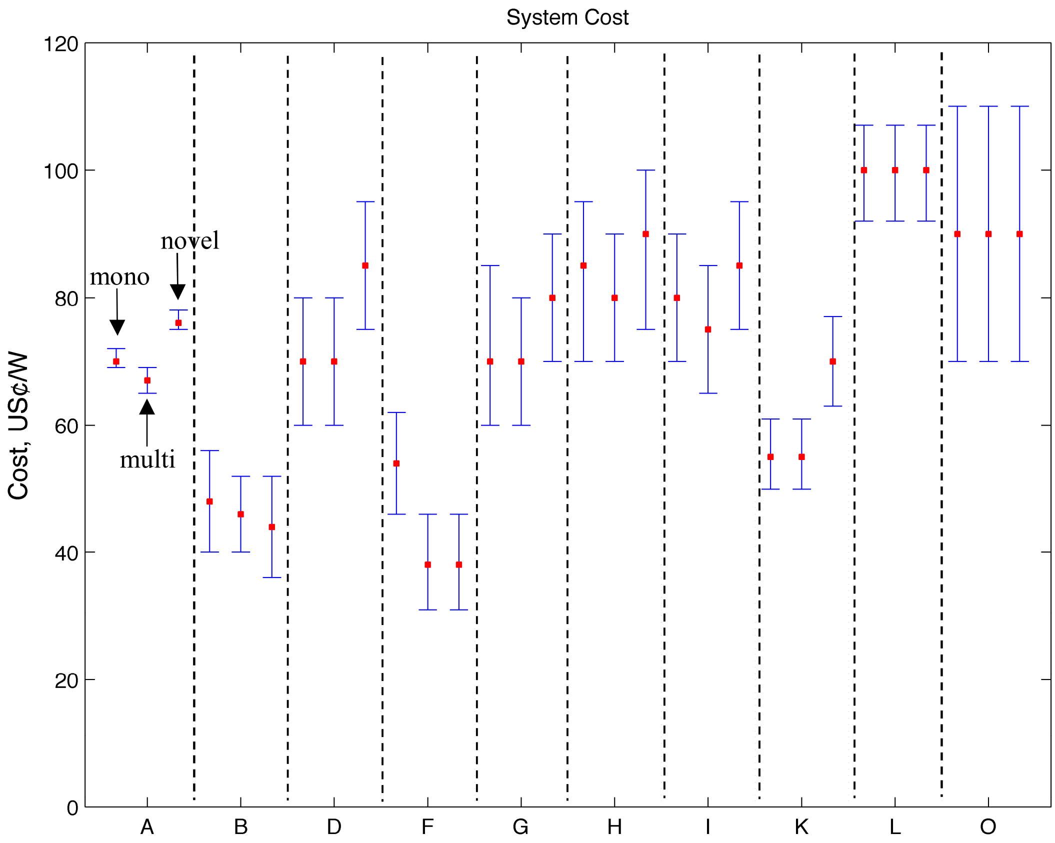

Figure 4.2: Experts judgment of expected costs for PV systems using mono-Si, multi-Si, and novel Si modules by 2030. Each expert responds with their best, upper, and lower estimates.

4.3.4 Cost and performance elicitation results: Non-Silicon PV

Experts stated that silicon PV would continue to be the mainstream electricity supply technology for at least the next ten years. Some experts expected that demand for non-silicon PV technologies would remain relatively small, but others offered a more positive outlook, believing demand would rise. Differences in technical characteristics and application requirements can result in wide segmentation of PV products. Furthermore, China may continue to be a strong player in silicon PV cell and panel production, but the U.S., Germany, and Japan may focus on non-silicon technologies[35].

Of the non-silicon PV technologies, thin film is the most promising candidate that can challenge silicon both on efficiency and cost. A few Chinese firms are engaged in thin film module production, but they command only a small fraction of the domestic solar PV market.

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[35] Interview #34

Amorphous silicon's market share has diminished substantially in recent years, and experts concluded that it was essentially eliminated from the market.

Historical module efficiency and learning rates for thin film technologies are lower than c-Si PV (Chen et al., 2014), but most experts expected thin film technologies to maintain its competitiveness. Median estimates show efficiency for cadmium telluride (CdTe) modules will reach 22% by 2030 with production cost of $0.27/W (Figure 4.3). For comparison, modules made by the world's largest CdTe maker, First Solar, have a 16.8% efficiency and cost $0.40/W (FirstSolar, 2016; Martin, 2016). CdTe manufacturers need to scale up their production size without sacrificing efficiency and reliability. Copper-indium-gallium-selenide (CIGS) modules will achieve lower efficiency and cost reduction than CdTe. CIGS technology may not be able to compete with silicon-based PV on a cost basis, but CIGS module's lightweight and highly flexible features allow them to compete in other market segments.

A number of concentrator photovoltaic (CPV) demonstration projects have gone online around the world (Philipps et al., 2015), though experts generally expressed skepticism toward CPV's future viability. One expert did not see commercial viability for CPV systems and declined to provide CPV's future costs and efficiency. The collapse in polysilicon price made low concentrator photovoltaic (LCPV) less attractive. A leading firm in LCPV, SunPower offers a tracker system using its high-efficiency solar cell, but the product has not been successful due to the precipitous fall in prices of traditional silicon PV panels. High concentrator photovoltaic (HCPV) system uses high-efficiency multi-junction cells, but challenges in tracking and alignment mechanisms and high system costs remain. One expert posited that CPV systems could be competitive in sunny regions close to big population centers with high electricity price. For example, CPV systems could be installed in North Africa to provide electricity across the Mediterranean to Europe.

Excitonic technologies have enjoyed wide academic interests in China, though their commercial prospects remain bleak. According to experts, gain in efficiency for dye-sensitized solar cells and organic photovoltaic technologies would continue, though reliability issues would preclude them from replacing silicon crystalline PV. Silicon PV technologies typically last between 20 to 25 years, whereas excitonic PV lifetimes are much shorter. Perovskite, the most promising of the emerging technologies, faces reliability and stability issues as well. Perovskite's lab efficiency has increased nearly six times since its introduction in 2009 (Kojima et al., 2009;

NREL, 2016). Recently researchers were able to fabricate large, stable cells (University of New South Wales, 2016). Experts indicated that perovskite would not be ready for commercial production in the near future, but investors have shown intense interests in this technology (Snieckus, 2016b). Other emerging technologies have not made it past the lab stage, and there is little commercial interest for them in China.

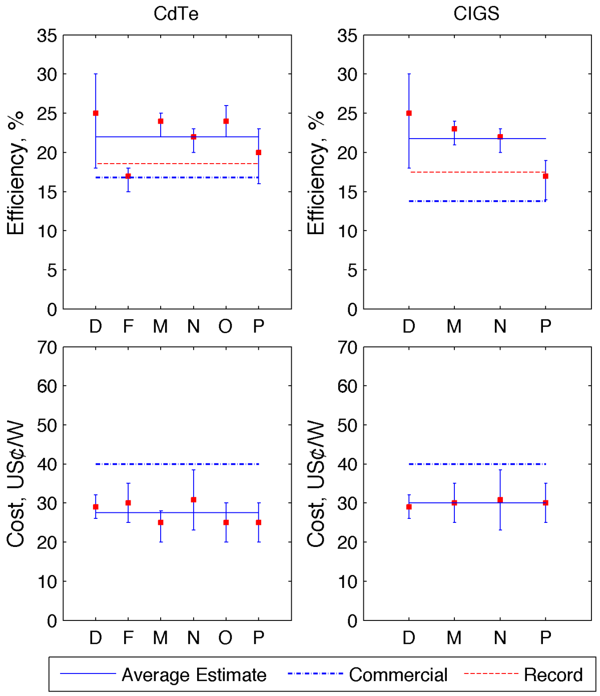

Figure 4.3: Expert judgments of efficiencies and costs in 2030 for CdTe and CIGS thin film technologies. Each expert responds with their best, upper, and lower estimates. CdTe modules will reach an average efficiency of 22%. First Solar CdTe panels hold a lab record efficiency of 18.6%, and their commercial panels have an efficiency of 17.1% (Green et al., 2016). Production cost for First Solar panels is $0.40/W ((Martin, 2016), compared to the experts' average estimate of $0.27/W. CI(G)S modules will reach an average efficiency of 23%. Current commercial efficiency is 13.8% (SolarFrontier, 2016), and record efficiency is 17.5% (Green et al., 2016). Production cost for CI(G)S modules will be $0.29/W. Solar Frontier, the largest CI(G)S incumbent, has a target production cost of $0.42/W by 2017 (C. Watanabe, 2015).

4.4 Discussion and conclusion

This paper details a number of technological and non-technological factors that affected the growth of China's PV industry in the past decade as well as factors that will influence its future development. If estimates provided by experts materialize, Chinese solar PV will continue following a cost reduction roadmap, closing in on coal as a cheap source of power. Among solar PV technologies, experts suggested that silicon PV would remain the dominant technology for large-scale electricity-generation applications.

That Chinese silicon PV makers did not require fundamental breakthroughs in order to slash costs and boost efficiency is remarkable. The standard Al-BSF design was invented decades ago, and physics principles behind photovoltaics were established much earlier. Advanced cell designs like PERT, IBC, and HIT predated China's entrance to the PV market. A prominent PV researcher remarked that Chinese PV makers "made small if any actual process cost reductions at Southwest Airlines margins" (Inman, 2013). Nonetheless, Chinese firms benefited from the technology's maturity and standardization and were able to push the industry to unprecedented production levels through economies of scale and learning.

Furthermore, China's leading production and installation status confers certain advantages. As long as a new innovation stays within the silicon paradigm, a firm has to rely on China's manufacturing infrastructure as a "platform for product development" (Nahm and Steinfeld, 2014). Equipment manufacturers need to design new "drop-in" machines that are compatible with existing production lines. In this sense, China has essentially become the test bed for new silicon PV technologies.

Behind these developments, policy has played a significant role. Solar PV would not have as sizeable a market without generous European FIT policies. It might not survive the aftermath of the global financial crisis and thrive without support policies in the U.S., Japan, and China. While these policies are not identical in their goals, they all have spurred substantial demand, creating market conditions in which solar PV can compete with fossil fuels. Solar PV's dependency on policy support will continue in the near future in China, and likely elsewhere in the world. It may be some years before solar PV can directly compete with coal on a pure cost basis – longer if taking integration costs into account.

In the short term, China solar PV's success may also be its largest obstacle. Attracted by burgeoning global and domestic demand, investors have poured money into capacity expansion. Local governments are eager to build the next local champion. Existing firms continue to scale up, hoping that economies of scale will justify their investment. These commitments leave large firms especially exposed to sudden market or policy shifts. As new capacity comes online, prices plunge and margins shrink. Instead of investing in long-term R&D, many firms are fixated on chasing short-term profits. What small firms cannot offer in quality, they make up in price. Price-conscious developers are willing to sacrifice quality for a better deal, especially in locations where land is not a constraint. Most remarkably, this pressure is almost entirely domestic. The industry is currently in the throes of another overcapacity episode: module prices in 2016 decreased by 30%. This is great news for PV customers around the world, but for central planners, it is neither efficient nor sustainable. Furthermore, episodic overcapacity of traditional silicon panels in recent years may have impeded the adoption of high-efficiency technologies.

The central government has taken heed of recent developments. In an effort to cull the industry, the National Energy Administration (NEA) has implemented the "Top Runner Program." The program grants development priority to projects that use modules of certain efficiency and reliability standards (NEA, 2015b). To cool the pace of solar development, the government has reduced the country's installed target to 110 GW from 150 GW (BJX, 2016). Feed-in-tariff levels for utility solar have been lowered by 24% to 31% (NDRC, 2016a). This adjustment was ostensibly designed to account for the falling module prices, but it will slow rampant development as well. At the same time, downstream problems have surfaced. China's wind industry has been continually troubled by curtailment (Lam et al., 2016), and its solar industry is facing similar problems. The national average curtailment for solar is 12.6% in 2015, and curtailment is much worse in the North Western provinces – more than half of Gansu's solar electricity was curtailed (CPIA, 2016b). Distributed solar PV can help to mitigate curtailment issues, but its development so far has fallen short of official targets (Zhang et al., 2015).

Finally, given the uncertain nature of the innovation process, China's heavy emphasis on one technology may cause it to miss out on potential breakthrough technologies. A diversified research and development portfolio enlarges the knowledge pool that serves as the basis for new technologies or new concepts. Even technologies that do not have big market potential can serve as catalysts for future developments. For instance, perovskite traces its origins to research in dye-sensitized solar cells (Kojima et al., 2009). In a diverse technology market, scientists and engineers can learn and draw inspiration from products outside their technical domain. Cross pollination of ideas can result in new breakthroughs. Thin film technologies improved their performance by building on surface passivating and antireflection principles used in crystalline silicon PV. At the heart of high-efficiency HIT cell's architecture is amorphous silicon, a thin film technology. Even if silicon PV is able to help countries to economically decarbonize their electricity systems like experts predicted, support for a diverse R&D portfolio can bring us to that future faster or in a more economically efficient manner.

5 Conclusion

This dissertation examines progress and challenges in China's renewable energy sector. Generous and sustained government support has propelled the growth of China's wind turbine manufacturing industry. Since the passage of the 2005 Renewable Energy Law, China has been aggressive in promoting wind energy, constructing wind projects at an unprecedented rate. The country has been successful at incubating a competitive domestic industry through technology transfer, technology absorption, and capacity building. In the beginning of the construction boom, foreign firms and joint-ventures rushed to ramp up their operations in China, but domestic producers caught up with striking speed and eventually gained most of the market share. Equipment prices fell, though it is unclear how much of the reduction could be attributed to cost and product innovation and how much to the imbalance of supply and demand. While Chinese firms managed to slash production costs to low levels, the industry's learning rate was relatively modest. At the same time, we find that international patenting activity among Chinese firms and inventors has been limited to date. Major Chinese wind turbine manufacturers have not patented many new technologies in major markets outside of China. Chinese international patents are less likely to be cited than their foreign counterparts, suggesting limited value to Chinese invention.

Solar PV followed a development path different from the wind power industry. China's solar PV industry grew as a response to burgeoning European demand. To balance contracting demand in the days after the financial crisis, the Chinese government implemented a host of policies to prop up the PV industry. Consistent with previous findings, we confirm that market formation policies – both domestic and international – economies of scale, agglomeration effects, learning-by-doing, human capital mobilization, and vertical integration were instrumental to the development of China's PV industry in the past decade (Yu et al., 2011; Goodrich et al., 2013; Luo et al., 2015; Gallagher, 2014; Zhang and Gallagher, 2016). PV module production costs fell dramatically from 2005-2015, and the industry follows the historical learning rate of about 22% (Chen et al., 2014). A number of technological breakthroughs allowed Chinese silicon PV makers to pare down production costs and raise efficiency. A leader in both production and installation, China has become a test bed for new silicon PV technologies as new equipment must be designed to be compatible with existing production lines. In the near future, experts expect silicon PV to remain the mainstream PV technology. Following the current rate of cost reduction, silicon PV can be an economically viable alternative to coal by 2030.

5.1 Challenges ahead and recent developments

In the short term, increasing reliance on the domestic market leaves Chinese renewable energy firms vulnerable to sudden market fluctuations and policy shifts. Unlike their foreign counterparts, sales from Chinese wind turbine producers lack geographic diversity. More than 40% of GE 2016 sales and almost all of Vestas sales were in markets outside their home countries (GlobalData, 2017). In contrast, virtually all of Goldwind's 2016 commissioned capacity was intended for the Chinese market. Chinese solar manufacturers traditionally export to markets around the world, but their focus has turned inward due to waning foreign demand and a booming domestic market. As a result, the industry lacks strategic tools to mitigate any turbulences in the local market.

In an attempt to address overcapacity and curtailment problems, the government has implemented a number of measures to cool the renewable energy sector's development pace. China has lowered its 2020 wind installation target from 250GW to 210GW. Approval for new wind projects has been suspended in Inner Mongolia, Jilin, Heilongjiang, Gansu, Ningxia, and Xinjiang – provinces that have been plagued with high wind curtailments (NEA, 2017a). Under new rules, grid companies are not to accept new grid connection requests for wind projects in these provinces. Feed-in-tariff levels have been adjusted downward several times and will be reduced to 0.40-0.57 yuan/kWh by 2018 (NDRC, 2016a). Together these policy changes resulted in the first market contraction since the 2011-2012 industry consolidation (GlobalData, 2017). Goldwind, the largest Chinese wind turbine maker, experienced negative growth rate in 2016, losing its global top spot from the year before.

The Chinese solar industry is facing similar challenges. FIT for solar was lowered to 0.8-0.98 yuan/kWh in June 2016. Shortfalls in renewable energy subsidy have widened, reaching as much as 60 billion yuan by the end of 2016 (Chen and Stanway, 2016). Further cuts in FIT are slated for this year. Also this year, growth in the Chinese PV market is expected to slow for the first time. At the same time, previously planned production capacity expansion is coming online, resulting in a massive glut in the market. In 2016 prices plunged by 30% (EnergyTrend, 2016). Margins have shrunk, and firms like Yingli Green Energy and Shunfeng International Clean Energy have posted huge losses (Publicover, 2017; Ryan, 2016)

The renewable energy industry's episodic overcapacity can be detrimental to its overall innovation activity. As cheap products inundate the market, firms are forced to compete on price.

Underperforming firms do not fold thanks to government support. Instead of pursuing long-term R&D projects, firms are forced to chase the bottom line in order to recoup investment costs and stay afloat. This problem is especially distinct in the solar PV industry. To unsophisticated customers, solar PV products remain by and large undifferentiated, and upfront savings can justify lower performance. As a result, the life cycle of low-quality and inefficient solar panels lengthens at the expense of the more technologically advanced panels.

Efforts to integrate renewable energy projects have proven both tenuous and inefficient. By the end of 2016, China has installed 148.6 GW of grid-connected wind capacity and 77.4 GW of solar capacity (CEC, 2017), more than any other country in the world. Turbines were quickly erected, but they were not connected to the grid. Widespread curtailments resulted in low capacity factors, diminishing the value of wind energy. We find that after accounting for the cost of unused and under-utilized capacity, the cost of wind energy in China in the mid-2000s was twice as high as projected. Consequently, the cost of carbon mitigation by replacing coal-generated electricity with wind energy has been four to six times higher than official estimates.

So far policy adjustments have failed to resolve integration problems, and China's struggle to turn its massive investment in new renewable power generating capacity into green energy that actually feeds the grid continues. Wind curtailment rate increased to 17.1% in 2016 from 15.4% one year earlier. Curtailment rate for solar was about 20% in the northwestern region, reaching as high as 32.1% and 32.4% in Gansu and Xinjiang, respectively (NEA, 2017a). Capacity factors remain low: the 2016 average capacity factor for solar was around 9.8%. That compares with 27.2% in the U.S. for the same year (EIA, 2017).

5.2 Future policy actions

Fundamental reforms are needed in order to accommodate China's large existing and incoming amount of renewable energy capacity. Electricity markets in many countries employ dynamic pricing, where electricity is dispatched based on merit order. In comparison, there is no system-wide optimized dispatch across different types of generators in China. Under current rules, priority dispatch should be given to electricity generated from renewable sources, but these rules are not enforced. Guaranteed generation for coal plants creates additional constraints for grid operators. A more flexible generation output planning system and a more flexible power market can integrate existing renewable sources into the grid more efficiently. For example, a new dispatch order can be based on the marginal cost of renewable sources. Prices can be adjusted more frequently to reflect real-time supply and demand.

Current macroeconomic trends pose additional challenges as China pushes forward with its ambitious renewable energy development plans. The country's economic growth has slowed substantially in recent years, and electricity consumption has stagnated. Tepid growth in energy demand coupled with business-as-usual increase in supply have led to a sharp reduction in utilization rates across all energy sources. Unexpectedly low prices of fossil energy could make the green energy targets more expensive to attain at a time of weak industrial demand and economic uncertainty.

A nationwide cap-and-trade program could bring the divergent interests that have hindered China's progress into much better alignment. Under a well-organized nationwide cap-and-trade program, grid companies would have to pay more for electricity produced by carbon-intensive sources. A sufficiently high price set on carbon emissions can force a shift away from cheap coal. On the other hand, a carbon price will raise energy costs for downstream users, so the government needs to balance commitment to reduce carbon emissions against a slowing economy. Finding the right carbon price will be a delicate act. China plans to put in place a national cap-and-trade program this year using lessons learned from the seven pilot emission trading systems around the country. At the time of writing it is unclear whether China will meet its deadline and what the price level for carbon will be.

Despite its challenges, recent developments have confirmed China's status as a global renewable energy and climate leader. With President Donald Trump's recent Executive Order to roll back efforts to reduce greenhouse gas emissions, the U.S. has essentially abdicated its leadership in the fight against climate change. In response, China indicated that the country would follow through with its pledge to decarbonize its economy, intending to fill the leadership vacuum left by the U.S. This signals a complete role reversal: as recently as 2008 China was one of the main obstacles to a global climate treaty. At the same time, China's coal consumption has gone down in recent years (NBS, 2016), as has its annual carbon emissions (Global Carbon Project, 2017). China's transition to a low-carbon energy system has not been and will not be without obstacles, but these are encouraging signs.

5.3 Policy lessons for India

After China, India is the most important front in the fight against climate change. Home to 18% of the world's population, India currently consumes only 6% of the world's energy (IEA, 2015). Similar to China, India heavily depends on fossil fuels, which account for three quarters of India's energy consumption. Coal is responsible for 70% of electricity generation. At the same time, India is on pace to become the world's largest greenhouse gas emitter. Energy consumption has doubled since 2000 and is projected to soar in the next decades. As many as 240 million people still do not have access to electricity. At $1500, India's current GDP per capita is well below the world's average of more than $10,000[36] (The World Bank, 2017). Prime Minister Narendra Modi has repeatedly stressed the need for economic growth, preferably in the mold of China.

Many places in India have already reached dangerous levels of air pollution. India's air is becoming more toxic – the 2015 population-weight average PM2.5 concentration in India was 74 µg/m3, compared to 58 µg/m3 in China (Health Effects Institute, 2017). More than one million deaths in India can be attributable to PM2.5 in 2015, a number that is on the rise. Moreover, changes in climate patterns, retreating Himalayan glaciers, dwindling water resources, and rising sea levels will disrupt if not destroy the livelihoods of hundreds of millions of Indians throughout the country.

The Indian government has turned to renewable energy as a solution for the country's development quandary. By the end of 2016, India's wind installed capacity reached 28.7 GW, a remarkable feat given that the country virtually did not have any wind power a decade ago (GWEC, 2017). Likewise, India has installed 7 GW of solar capacity by 2015, compared to only 44 MW five years earlier (GlobalData, 2017). By 2022, the government plans to quadruple non-hydro renewable capacity to 175GW, most of which would come from wind and solar resources (IEA, 2015).

Although China's unique political and economic structures make the country's renewable energy development plans in the past decade ill-suited as a blueprint for developing countries around the world, China's experiences can still offer India a number of important policy insights. In order to meet the above target and fulfill its COP21 pledge to increase the share of renewable

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[36] http://data.worldbank.org/indicator/NY.GDP.PCAP.CD

energy to 40% of total electricity generation by 2030 (UNFCCC, 2015b), the Indian government needs to demonstrate firm and sustained financial commitment. Accomplishing these targets will require an unprecedented level of capital investment. Renewable energy investment in India reached a historic high of $12.8 billion in 2011 (McCrone, 2016), but it is a miniscule amount compared to the $2.5 trillion India needs (UNFCCC, 2015b). In contrast, China spent $102.9 billion on renewables in 2015, ten times more than India (McCrone, 2016). However, from an economic standpoint, the timing to develop renewables has never been better, with wind and solar equipment prices at historically low levels and continue to fall. At the same time, India can still exploit its low cost of labor to minimize soft costs, which have emerged as a significant fraction of total project cost in the U.S. and more recently in China.

Similar to China, grid infrastructure will be one of the main obstacles to India's efforts to integrate its renewable power plants. While China was able to deploy wind and solar at an unparalleled rate, the country took much longer to develop its grid infrastructure and make appropriate institutional changes to accommodate renewables, as evidenced by the country's persistent and severe grid connection and curtailment problems. India can learn from China's experience and take a comprehensive policy approach that assigns equal importance to generation, transmission, and distribution. India's Green Corridor and Desert Power India plans, which propose transmission lines that connect areas with abundant renewable energy to load centers, are good first steps. India's electricity sector is not bound by generation guarantee for coal plants, and its electricity market does not follow a rigid centrally planned dispatch program, affording the country more flexibility as more renewables are added to the grid. Nevertheless, India's electricity system is susceptible to frequent brownouts and blackouts; transmission and distribution systems are subject to high losses; its utilities are mired in financial problems owing partly to their high reliance on coal imports with high price volatility (NITI, 2015). Already solar curtailments have emerged in Tamil Nadu, a southern state, despite "must-run" rules that stipulate solar power must take priority in the dispatch sequence (Clover, 2016). Until India resolves these issues, massive renewable investment will induce waste. Indeed, with enough spending, India may be able to accomplish its 2022 goal to increase solar capacity to 100 GW and wind capacity to 60 GW, but power plants are only as useful as the amount of electricity they generate. In that sense, the electricity generation from renewable sources makes a more meaningful target than capacity installation.

Moving forward, the Indian government's multiple objectives for its clean energy programs may constitute its biggest challenge. In addition to addressing environmental concerns, broadening electricity access, and increasing energy security, renewable energy is supposed to help boost India's GDP output and provide stable manufacturing jobs, much like it did in China in the past decade. While some goals – such as environment and energy security – may complement each other, others may create tension. To support domestic manufacturers, the government required all solar projects to source domestic cells and modules, reminiscent of China's local content requirement for wind turbines[37]. Project developers protested this import substitution scheme, preferring to procure the latest, high-quality and cheaper equipment from foreign producers. While India's cell and module production capacity has achieved impressive growth rate – cell capacity at 1.5GW and module capacity at 5.8 GW by mid-2016[38] – they still make up a small fraction of the world's total supply. Colossal capital investments would be required in order for India to reach the China's PV production scale. Furthermore, few Indian firms can produce silicon PV equipment as efficiently and as cheaply as Chinese firms can. Indian cell and module makers have to compete with large, established, and integrated Chinese firms who benefit from being in the center of the world's largest solar PV cluster. The current global supply glut and shrinking margins make maintaining profitable operations challenging, especially for new entrants. Increasing level of automation within the solar sector detracts from the argument that solar manufacturing can bring more jobs – solar PV's labor intensity has dropped significantly in the past decade. With the right support policies and financial incentives, India may be able build a domestic solar industry that rivals China, but that is neither the most effective approach to deploy renewable energy nor the most efficient use of the country's limited resources.

Nevertheless, India can make inroads into the downstream segments of the solar sector, where jobs are most concentrated. According to one estimate, manufacturing accounts for only 14.7% of the sector's total employment (The Solar Foundation, 2016). The majority of the jobs are in the installation, sales and distribution segments of the solar sector. Additionally, relatively

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[37] The U.S. complained to the WTO that India's local content requirement (LCR) discriminated against solar importers. WTO ruled that India's LCRs violated WTO rules, and India is expected to rescind its LCR after it lost its appeal (Miles, 2016).

[38] http://mnre.gov.in/file-manager/UserFiles/information-sought-from-all-Solar-Cell-&-Module-manufacturers.pdf

low upfront investment costs and human capital render these segments more suitable to India's economic context.

Energy storage technology is an alternative technology space that India can consider. Given the current state of India's electricity infrastructure, distributed energy applications in the form of rooftop solar or micro-grids can provide millions of Indian citizens access to electricity. Off-grid installations have historically driven India's solar market, illustrating the real need and demand for distributed solutions. When coupled with energy storage systems, wind and solar can form a micro-grid that can provide low-cost and reliable electricity to remote communities, eliminating the need to construct expensive large power plants and related infrastructure. The nascent field of energy storage for grid-scale applications presents many opportunities with high payoffs. Countries around the world have invested in and experimented with different energy storage technologies, but so far no one technology or firm has emerged as a winner. Given India's energy context and its natural market for energy storage, this is a space that India can compete to be the global leader.

5.4 US-China trade implications

Even though solar installed capacity has surged in the U.S., it has not been a good decade for American solar producers. Many firms throughout the supply chain – from upstream polysilicon makers to downstream system installers – had to downsize or were forced to shutter their operations altogether (Wesoff, 2015). Early this year Oakland, California-based Sungevity filed for Chapter 11 bankruptcy after a decade in business and more than $850 millions of investments (Ferris, 2017). Not long after, high-efficiency cell maker Suniva followed suit, declaring bankruptcy. Like many of its predecessors, Suniva alleged that government-backed Chinese solar manufacturers flooded the U.S. market, calling the U.S. government to step up its protection for domestic producers (Lacey, 2017)[39].

This is not the first time that American solar firms have called upon the U.S. government to intervene on their behalf. In 2011 a group of American PV makers, led by SolarWorld, alleged to the U.S. International Trade Commission (USITC) and the U.S. Department of Commerce (USDOC) that Chinese PV producers received unfair government subsidies and dumped their

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[39] It is worth noting that Suniva's majority stakeholder is Shunfeng International Clean EnergyPV, a Hongkong-based energy conglomerate, who took over financially insolvent Suntech in 2014.

products in the U.S. After an investigation, the USITC and USDOC found that the U.S. solar industry was materially injured, and Chinese cell makers would be subject to antidumping and countervailing duties (DOC, 2012a; DOC, 2012b). In 2015 the USDOC imposed a second round of tariffs to close a sourcing loophole, expending the duties to include Chinese and Taiwanese solar wafers, cells, and modules (DOC, 2015). The effects of the first's ruling were immediate: stock prices of major Chinese PV producers nosedived, and their market shares shrank. In contrast, the second ruling did not have a noticeable effect on Chinese firms as they had already shifted their focus away from the U.S. market.

China's response to the first round of U.S. tariffs had a great impact on U.S. polysilicon producers. After an investigation into U.S. renewable energy program, China ruled that polysilicon produced in the U.S. would be subject to an effective anti-dumping and countervailing tariff rate of 57% (Ministry of Commerce, 2014). These punitive tariffs essentially prevented U.S. firms from selling polysilicon to the world's largest market. As a result, firms had to scale back their U.S. operations, and some even planned to construct new plants in China to bypass the tariffs[40]. Utilization rate of polysilicon production plants plummeted to 36% in Q1 2016, down from 91% when Chinese tariffs were first enacted (SEIA, 2016). This contraction is even more remarkable in light of the fast growing global market for polysilicon in the same period.

Many American solar makers were forced to exit the industry in the past decade due to increasing competitive pressure within the global industry, but cutthroat competition claimed hundreds of Chinese businesses as well. As many 20 percent of China's total cell makers (35 firms), and a third of Chinese module makers (208 firms) were closed or suspended by 2013 (ENF, 2013). Margins of the surviving firms have shrunk, and their financial prospects remain bleak. An Altman Z-score analysis by BNEF shows that major Chinese producers like Yingli, CSIQ, Jinko Solar, Trina, JA Solar are on the brink of bankruptcy (BNEF, 2017).

It is unclear to what extent U.S. tariffs have enhanced the competitiveness of *American* solar manufacturing firms. The two rounds of tariff failed to stem the tide of financial insolvency. Of the current module manufacturing capacity in the U.S., about half belongs to non-US companies (BNEF, 2017). Thin-film and small, boutique firms make up most of the U.S.

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[40] https://www.recsilicon.com/about-us/company-history

capacity, and they have been struggling to compete with Asian firms. In terms of sales, American solar firms are strikingly similar to Chinese wind turbine makers in that they lack geographic diversity and strongly depend on the home market. According to public filings, the overwhelming majority of First Solar's and SunPower's 2015 revenue comes from the U.S. These two firms do not have a presence in the Chinese market. In contrast, Chinese solar makers display a high degree of geographic diversity: annual reports show that domestic sales only account for 33%, 28%, and 12% of total 2015 revenue for JA Solar, Trina, and Canadian Solar, respectively.

High levels of interconnectedness and flexibility within the global solar PV industry make enforcing imposed tariffs even more difficult, turning it into a cat-and-mouse game. Even if all production facilities operated at full capacity, U.S. supply of solar cells and modules would still be far below demand. As a result, the U.S. has to import a substantial number of solar products, mostly from Southeast Asian countries. However, current tariffs do not cover solar products made in these countries. To boot, much of these products are manufactured in Chinese-owned plants.

On the other hand, tariffs on cells and modules have in essence raised the total cost of installation for U.S. consumers. As findings in Chapter 4 show, Chinese solar module price will continue to fall in the near future. With Chinese solar components becoming more standardized, the quality gap between Chinese and U.S. solar products narrows. At the same time, by lifting trade barriers and focusing on deployment of solar energy, the U.S. government can increase the number of U.S. jobs. After all, solar installation generates three and a half times more jobs relative to the manufacturing segment of the supply chain (The Solar Foundation, 2016). The solar industry is on the precipice of change due to increasing levels of automation, but it may be a while before machines can replace human solar installers.

A. Supplemental information for Chapter 2

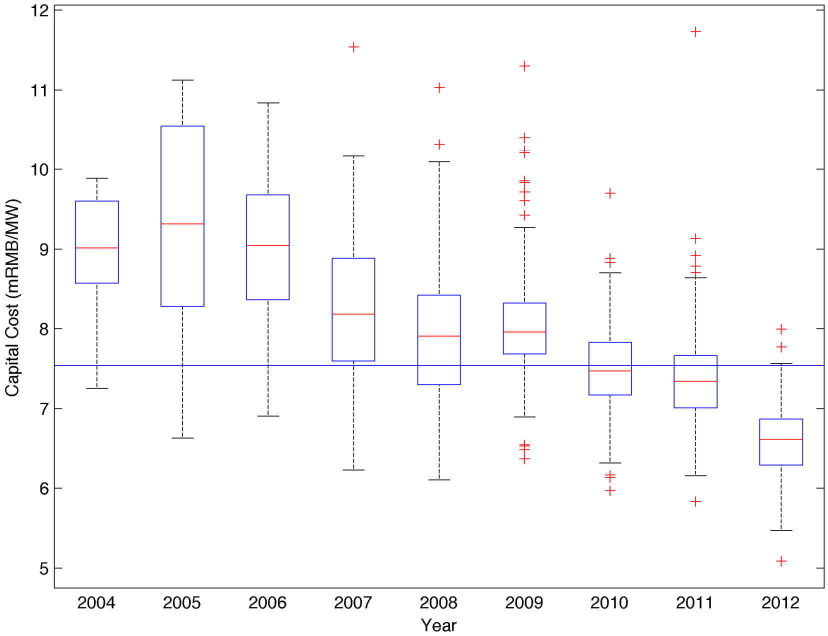

Figure A.1: Unit cost of wind turbines between 2004 and 2012. Plot constructed by the authors using data from UNEP (2015).

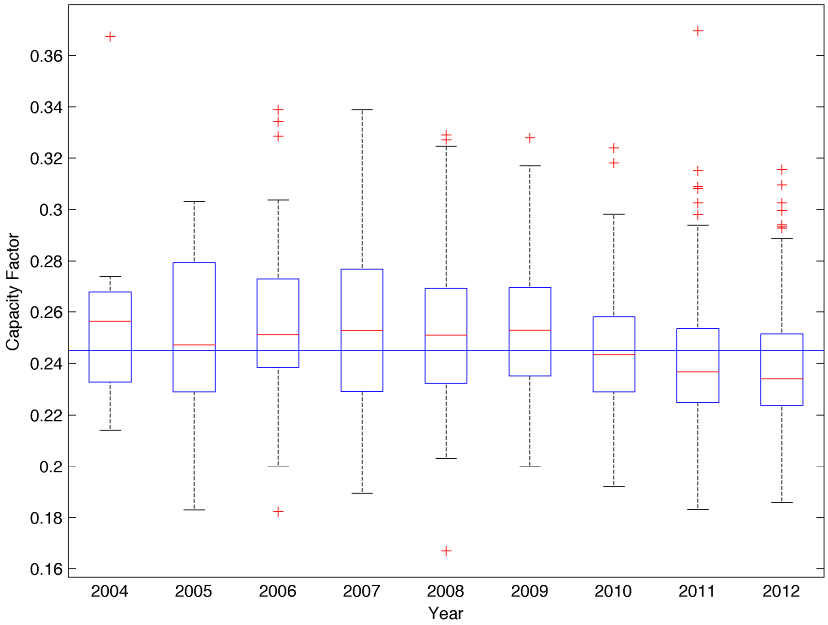

Figure A.2: Capacity factors of wind turbines between 2004 and 2012. Plot constructed by the authors using data from UNEP (2015).

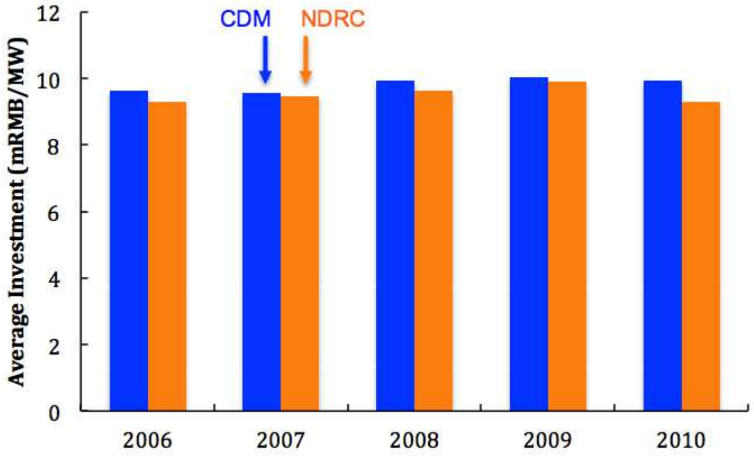

Figure A.3: Nominal average per unit investments using data from CDM and NDRC (million USD/MW). Plot produced by authors using date from UNEP (2015) and privately obtained NDRC data.

Table A.1: EPO citation statistics for inventors of different nationalities.

Nationality	N	Mean	SD	Min	Max
All	1342	2.29	3.04	0	24
CN	9	1.89	2.32	0	7
DE	485	2.5	3.13	0	24
JP	51	0.88	1.96	0	12
US	131	2.32	3.2	0	22
DK	267	2.89	3.08	0	19
ROW	399	1.8	2.85	0	19

Table A.2: USPTO citation statistics for inventors of different nationalities.

Nationality	N	Mean	SD	Min	Max
All	4859	6.07	8.13	0	92
CN	57	5.6	6.61	0	35
DE	617	7.18	7.66	0	651
JP	358	5.38	7.49	0	73
US	2349	5.94	8.73	0	92
DK	352	7.08	6.58	0	42
ROW	1126	5.68	7.68	0	66

Table A.3**:** Summary statistics for CDM-registered wind projects in China.

Year	No. of Projects	No. of Monitored Projects	Total Capacity (MW)	Actual Installed Capacity (MW)
2004	8	8	442	216
2005	14	13	601	487
2006	54	50	2822	1288
2007	124	107	6626	3311
2008	142	115	8595	6304
2009	182	125	11599	13653
2010	273	90	15406	18928
2011	393	40	19576	17631
2012	287	2	16069	13581
Total	1477	550	81736	75398

Table A.4**:** Summary statistics of key variables for CDM-registered wind projects in six Chinese regions.

Variable	No. of Projects	Mean	S.D.	Range
Project Capacity (MW)	1477	55.34	37.72	9 – 400.5
North	608	57.54	40.90	12 – 300.15
Northeast	301	51.02	30.53	9.35-400.5
East	88	52.23	40.84	10.92 – 201
Central	40	39.17	11.86	13.6 – 49.90
Northwest	310	61.75	44.14	9 –300
South	130	46.83	8.82	15 – 100.2
Capacity Factor (%)	1477	25	2	17 – 37
North	608	25	2	17 – 33
Northeast	301	24	2	18 – 37
East	88	24	3	19 – 33
Central	40	22	1	20 – 25
Northwest	310	24	3	18 – 37
South	130	23	3	18 – 29
Investment (mRMB/MW)	1477	7.54	0.9	5.08 – 11.73
North	608	7.73	0.9	5.08 – 11.30
Northeast	301	7.63	0.77	6.08 – 11.73
East	88	7.95	1.23	5.75 – 11.54
Central	40	7.69	1.00	6.16 – 10.09
Northwest	310	6.94	0.65	5.47 – 9.21
South	130	7.55	0.81	5.91 – 11.03

North includes Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia; *Northeast*: Liaoning, Jilin, Heilongjiang; *East:* Shanghai, Jiangsu, Zhejiang, Anhui, Fujian; *Central*: Jiangxi, Henan, Hubei, Hunan, Chongqing, Sichuan; *Northwest:* Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Tibet; *South:* Guangdong, Guangxi, Hainan, Guizhou, Yunnan

Table A.5: Learning rates for different time periods using LCOE and controls for the plant's load factor. 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.

Time Period	Cumulative Capacity Coefficient	Plant's Load Factor Coefficient	Learning Rate
2004-2005	-0.131	-0.510	8.7%
2004-2006	-0.036	-0.731***	2. 5%
2004-2007	-0.062***	-0.809***	4.2%
2004-2008	-0.052***	-0.718***	3.6%
2004-2009	-0.032***	-0.729***	2.2%
2004-2010	-0.043***	-0.699***	2.9%
2004-2011	-0.041***	-0.628***	2.8%
2004-2012	-0.060***	-0.607***	4.1%

B. Supplemental information for Chapter 3

B.1. CDM wind project investment data

Data quality is not of concern because the process and rules for a project to become CDM-registered and certified are lengthy and highly standardized. We compare CDM project investment data with a National Development Reform Commission (NDRC) dataset for 2006-2010 wind projects in China that we privately obtained. We find that the average per unit investments are similar for the two databases (see Figure A.3).

B.2. CDM summary statistics

Table B.1 and Table B.2 report summary statistics for the major variables of interest from the Clean Development Mechanism Database.

Table B.1: Summary statistics for CDM-registered wind projects in China.

Year	No. of Projects	No. of Monitored Projects	Total Capacity (MW)	Actual Installed Capacity (MW)
2004	8	8	442	216
2005	14	13	601	487
2006	54	50	2822	1288
2007	124	107	6626	3311
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2009	182	125	11599	13653
2010	273	90	15406	18928
2011	393	40	19576	17631
2012	287	2	16069	13581
Total	1477	550	81736	75398

Table B.2: Summary statistics of key variables for CDM-registered wind projects in six Chinese regions.

Variable	No. of Projects	Mean	S.D.	Range
Project Capacity (MW)	1477	55.34	37.72	9 – 400.5
North[41]	608	57.54	40.90	12 – 300.15
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South	130	46.83	8.82	15 – 100.2
Capacity Factor (%)	1477	25	2	17 – 37
North	608	25	2	17 – 33
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East	88	24	3	19 – 33
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Northwest	310	24	3	18 – 37
South	130	23	3	18 – 29
Investment (mil yuan/MW)	1477	7.54	0.9	5.08 – 11.73
North	608	7.73	0.9	5.08 – 11.30
Northeast	301	7.63	0.77	6.08 – 11.73
East	88	7.95	1.23	5.75 – 11.54
Central	40	7.69	1.00	6.16 – 10.09
Northwest	310	6.94	0.65	5.47 – 9.21
South	130	7.55	0.81	5.91 – 11.03

B.3. Midyear capacities

To account for the industry's high expansion rate, we also consider the yearly reported cumulative capacities by the averaged midyear capacities. The midyear capacity $C_m(t)$ is the average of the capacity at the end of that year C(t) and the capacity and the end of the previous year C(t-1). In symbol:

$$C_m(t) = \frac{C(t) + C(t-1)}{2}$$

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[41] *North* includes Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia; *Northeast*: Liaoning, Jilin, Heilongjiang; *East:* Shanghai, Jiangsu ,Zhejiang, Anhui, Fujian; *Central*: Jiangxi, Henan, Hubei, Hunan, Chongqing, Sichuan; *Northwest:* Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Tibet; *South:* Guangdong, Guangxi, Hainan, Guizhou, Yunnan

In addition to the utilization rate, three capacity factor estimations are reported in Table B.3. CDM *ex-ante* capacity factor is forecasted based on local wind resources, grid and equipment conditions. The *ex-post* capacity factor is calculated based on the reported wind installed capacity statistics at the end of the year. We also show the *ex-post* capacity factor computed using midyear capacity as shown above. Again, we use grid-connected cumulative capacities instead of cumulative installed capacity to calculate the capacity factors, though a high fraction of turbines were not connected to the grid.

As China's wind capacity accelerated, it failed to connect a substantial proportion of the wind farms. Grid-connection problems have abated in recent years, though the wind turbines are using decreasing less often. The utilization factor and capacity factors all exhibit downward trend.

Table B.3: Wind energy's cumulative capacity and capacity factor estimations. Cumulative installed capacity data are from CWEA (2015), LBNL (2014), CREIA (2015); connected capacity and utilization hour data are from CEC (2015); *ex-ante* capacity factor data are from UNEP (2015).

Year	Capacity (GW)			Utilization factor	Capacity Factor		
	Installed	Connected	Unconnected		*Ex-ante*	*Ex-post*	*Ex-post, Midyear*
2006	2.5	1.9	26%	0.22	0.26	0.16	0. 21
2007	5.9	4.2	28%	0.23	0.25	0.16	0.22
2008	12.2	8.4	31%	0.23	0.25	0.18	0.24
2009	25.8	17.6	32%	0.24	0.25	0.18	0.24
2010	44.7	29.6	34%	0.23	0.24	0.19	0.24
2011	62.4	47.0	25%	0.21	0.24	0.18	0.22
2012	75.9	62.4	18%	0.22	0.23	0.19	0.22
2013	92.0	75.5	18%	0.24	-	0.20	0.22
2014	114.6	95.8	16%	0.22	-	0.19	0.21
2015	145.1	129.3	11%	0.20	-	0.16	0.19

B.4. Success rate

The success rate is defined as the ratio of forecasted CERs to issued CERs and it tracks the performance of Chinese wind farms. CDM forecasts the number of carbon credits that a project will earn in its qualified period based on its design parameters. The actual number of issued credits depends on the actual amount of offset carbon, a number that is verified and reported in the project's subsequent monitoring reports. China wind projects' success rate between 2004 and 2012 averages out to about 87% (see Table B.4). Because not enough time has elapsed, the monitoring reports for projects in the last three years of our sample period are incomplete, covering less than a third of the total projects.

Table B.4: The average issuance success rate for China's wind projects from 2004-2012. Source: UNEP (2015).

Year	Issuance Success Rate	No. of Monitoring Projects	Percent of Total Projects
2004	86%	8	100%
2005	88%	13	93%
2006	87%	50	93%
2007	83%	107	86%
2008	87%	115	81%
2009	82%	125	69%
2010	80%	90	33%
2011	90%	40	10%
2012	100%	2	1%
Average	87%		

B.5. Curtailment and disconnection trends

Table B.5 shows the amount of curtailed electricity and the corresponding curtailment rates between 2011 and 2015 of various provinces. Although wind curtailment problems seemed to have improved by 2014, 2015 data show that they are far from being resolved, especially in the "Three North" provinces. Table B.6 shows the same provinces' cumulative installed capacity and corresponding disconnection rates in the same period. Once adjusted for the provinces' total capacity and electricity generation, there is no obvious relationship between curtailment and disconnection issues. The curtailment rates, are highest in the "Three North" region, but the rates of disconnected capacity are highest in the Central and Southern provinces.

Table B.5: 2011-2015 curtailed electricity (GWh) and corresponding curtailment rates in parentheses by province. Sources: NEA (2014, 2015a, 2016a), CREIA (2012, 2013), SERC (2013).

Province	2011	2012	2013	2014	2015
Inner Mongolia	6958 (32)	11335+ (30)	6389 (20)	3568 (9)	9100 (18)
Gansu	2680 (27)	3024 (24)	3102 (21)	1384 (11)	8200 (39)
Xinjiang	101 (3)	215 (4)	431 (5)	2334 (15)	7100 (32)
Jilin	696 (15)	2032 (32)	1572 (22)	1002 (15)	2700 (32)
Hebei	361 (4)	1765 (12)	2800 (17)	2036 (12)	1900 (10)
Heilongjiang	744 (14)	1050 (17)	1151 (15)	953 (12)	1900 (21)
Liaoning	656 (9)	1129 (13)	528 (5)	639 (6)	1200 (10)
Ningxia	- -	47 (1)	43 (1)	- -	1300 (13)
Yunnan	- -	170 (6)	169 (4)	259 (4)	300 (3)
Shanxi	- -	16 (1)	- -	- -	300 (2)
Shandong	- -	- -	- -	99 (1)	- -
Shaanxi	- -	- -	37 (3)	43 (2)	- -
Tianjin	1 (1)	- -	9 (2)	6 (1)	- -
Total	12300 (16)	20822 (17)	16231 (11)	13338 (8)	33900 (15)

+: includes East and West Inner Mongolia

Table B.6: 2011-2015 cumulative installed wind capacity (MW) and corresponding disconnection rates in parentheses by province. Sources: NEA (2014, 2015a, 2016a), LBNL (2014), CWEA (2015).

Province	2011	2012	2013	2014	2015
Inner Mongolia	17594	18624	20270	22351	23201
	(18)	(10)	(10)	(10)	(9)
Gansu	5409	6479	7096	10726	11280
	( )[+]	(2)	(1)	(6)	(0)
Xinjiang	2316	3306	6452	9668	11212
	(28)	(21)	(22)	(17)	(25)
Jilin	3563	3997	4380	4652	4888
	(18)	(17)	(14)	(12)	(15)
Hebei	6970	7979	8500	9872	10313
	(28)	(11)	(9)	(8)	(10)
Heilongjiang	3446	4264	4887	5527	5566
	(24)	(25)	(21)	(18)	(17)
Liaoning	5249	6118	6758	7111	7215
	(23)	(23)	(16)	(14)	(13)
Ningxia	2886	3566	4450	6144	6568
	(53)	(22)	(32)	(32)	(17)
Yunnan	932	1964	2484	3641	4823
	(27)	(19)	(14)	(11)	(17)
Shanxi	1881	2907	4216	5806	6585
	(45)	(22)	(18)	(22)	(21)
Shandong	4562	5691	6981	8263	8914
	(40)	(31)	(28)	(25)	(25)
Shaanxi	498	710	1293	1666	1933
	(51)	(29)	(23)	(22)	(28)
Tianjin	244	278	305	323	323
	(49)	(18)	(25)	(12)	(12)
Country	62353	75323	91412	114608	124709
	(24)	(17)	(8%	(8)	(15)

[+] Reported installed capacity is slightly larger than reported connected capacity.

The 2013 energy production profiles of provinces most affected by wind curtailments are shown in Table B.7. There is no straightforward relationship between a province's hydropower penetration rate and its wind curtailment rate. High curtailment rates in Inner Mongolia and Hebei could attributed to these provinces' lack of hydropower, though these provinces may be more hamstrung by their commitment to provide winter heating (Pei et al., 2015). However, in 2013 hydropower plants generated proportionally more electricity than wind turbines in provinces like Yunnan (76%), Gansu (28%), Jilin (15%), and Xinjiang (12%), and yet these regions are still prone to have high wind curtailments.

Table B.7: Provinces with some of the highest wind curtailment rates power capacity in 2013 and their corresponding hydro penetration rates. Data from NEA (2014), NBS (2014).

Province	Wind Generation (TWh)	Curtailed Amount (TWh)	% Curtailed	Penetration Rate (%)	
				Wind	Hydro
Jilin	5.6	1.6	21.8	7.3	15.2
Gansu	11.9	3.1	20.7	9.9	27.7
Inner Mongolia	35.6	6.4	17.9	10.1	0.6
Hebei	14.1	2.8	16.6	5.6	0.4
Heilongjiang	6.7	1.2	14.6	8.0	3.6
Xinjiang	7.8	0.4	5.2	4.7	12.4
Liaoning	10.0	0.5	5.0	6.4	3.9
Ningxia	5.8	0.04	0.73	5.2	1.7
Yunnan	4.4	0.2	3.7	2.0	75.9

B.6. LCOE and CCM sensitivity analysis

While accurate, it may be the case that CDM total project investment data may not reflect the true costs of the projects because some State-Owned Enterprises (SOEs) may be willing to sell products below cost to undercut their competitors and gain market share. If this is the case, the total investment costs are actually higher in reality. We explore how different level of price distortions may affect the levelized cost of electricity (LCOE) and and cost of carbon mitigation (CCM).

Comparing to those in the US, the total investment costs of Chinese wind projects are from 23% to 36% lower (Wiser and Bolinger, 2013). In our sensitivity analyses, for each assumption about the capacity factor, we will consider three scenarios where Chinese total investment costs are 10%, 20%, and 30% higher than reported. Results are reported in Table B.6. The LCOE is more sensitive to the capital investments and the capacity factors. For the 30% scenario, the lowest LCOE is 0.51 yuan/kWh, which occurred in 2012 using CDM *ex-ante* capacity factor, 0.12 yuan/kWh or 24% higher than the corresponding baseline case.

We perform similar analyses for the cost of carbon mitigation. For simplicity, we only report results from a 30% investment increase scenario in Table B.10. We consider different assumptions about the capacity factors and the composition of China's coal fleet. Again, we observe a steady decrease in CCM across different assumptions. There was a spike in cost in 2009 due to high coal prices. In 2012 the lowest CCM is 136 yuan/ tCO_2, which is found assuming *ex-ante* capacity factor and all subcritical plants. This is over 100 yuan/ tCO_2 or 74% higher than the corresponding baseline case. Again assuming China's coal fleet is made up only of sub critical plants, the highest CCM is 260 yuan/ tCO_2, which is found using *ex-post* capacity factor, around 146 yuan/tCO_2 or 56% higher than the corresponding baseline case.

Table B.8: Sensitivity Analysis for LCOE (yuan/kWh) where the capital investments are 10%, 20%, and 30% higher than reported. Currency is in 2004 value.

Year	CDM *ex-ante*			UF			Midyear *ex-post*			Endyear *ex-post*		
	10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%
2004	0.53	0.58	0.62	-	-	-	-	-	-	-	-	-
2005	0.52	0.57	0.61	-	-	-	-	-	-	-	-	-
2006	0.54	0.58	0.63	0.62	0.68	0.74	0.65	0.71	0.76	0.83	0.90	0.98
2007	0.49	0.54	0.58	0.54	0.59	0.64	0.58	0.63	0.68	0.80	0.87	0.95
2008	0.48	0.52	0.56	0.51	0.56	0.61	0.51	0.55	0.60	0.67	0.73	0.79
2009	0.50	0.55	0.60	0.52	0.56	0.61	0.51	0.55	0.60	0.68	0.74	0.80
2010	0.48	0.52	0.57	0.49	0.54	0.58	0.48	0.52	0.57	0.60	0.66	0.71
2011	0.44	0.48	0.52	0.49	0.54	0.58	0.48	0.52	0.56	0.58	0.64	0.69
2012	0.43	0.47	0.51	0.46	0.50	0.54	0.47	0.51	0.55	0.53	0.58	0.63

Table B.9: Sensitivity Analysis for LCOE (yuan/kWh) where the O&M costs are 10%, 20%, and 30% of the reported capital investments. Currency is in 2004 value.

Year	LCOE		
	10%	20%	30%
2004	0.44	0.48	0.52
2005	0.43	0.47	0.51
2006	0.45	0.49	0.53
2007	0.41	0.45	0.48
2008	0.40	0.43	0.47
2009	0.42	0.46	0.50
2010	0.40	0.44	0.47
2011	0.37	0.40	0.43
2012	0.36	0.39	0.42

Table B.10: Sensitivity analysis for CCM (yuan/ tCO_2) for 30% increase in investment costs under different assumptions about capacity factors and the composition of China's coal fleet.

Year	CDM *ex-ante*		UF		Midyear *ex-post*		Endyear *ex-post*	
	Sub	Super	Sub	Super	Sub	Super	Sub	Super
2004	258	283	-	-	-	-	-	-
2005	227	251	-	-	-	-	-	-
2006	274	299	366	390	391	416	580	605
2007	225	248	276	299	316	339	549	572
2008	128	158	170	199	161	191	336	366
2009	210	232	224	247	211	234	405	427
2010	150	186	164	200	151	187	290	326
2011	110	135	163	188	147	172	262	287
2012	136	159	164	187	175	198	237	260

B.7. Overcapacity in energy supply

China's economy has slowed down in recent years, though the 2015 GDP growth rate clocks a still impressive rate of 6.9%. Electricity consumption growth rate, which historically closely tracks GDP growth rate, fell precipitously last year to 0.5% (See Figure B.1). At the same time, new electric power plants are being constructed. In 2015, around 75GW of thermal capacity, or around 50% of the total new capacity, was added to the national electric system, a growth rate of 8% (Figure B.3). Meanwhile, existing plants had to scale back their operations to make space for the new power plants. Utilization factors in 2015 dropped across all energy technologies (Figure B.2). Historically, utilization factors of nuclear and hydropower are relatively stable. Thermal power's utilization factor is subject to the most significant cutback, from 67% in 2005 to 49% in 2015.

Current macroeconomic trends present some of the most daunting challenges as China pushes forward with its ambitious renewable energy development plans. China's economy has slowed substantially in recent years, and the electricity consumption growth rate has suddenly come to a virtual halt. China's GDP growth rate in 2014 is 7.3%, but electricity consumption rate only increased by 4%. In 2015 China's economy grew 6.9%, but the electricity consumption rate increased merely half a percentage point (See Figure B.1). Widespread commentary, including that voiced by China's own top officials, points to a "new normal," in which energy-intensive manufacturing will grow much more slowly in the future than it has in the past. Growth will increasingly rely on the much less energy-and-resource-intensive service sector. In contrast to this significant and potentially permanent slowdown in energy demand, the country's energy supply has continued to expand at a rapid pace. Last year, hydropower capacity grew by 6%, thermal capacity (mostly coal) 8%, and wind a stunning 36%. Greenpeace East Asia estimates that in 2015 China permitted 210 new and proposed coal-fired power plants, equivalent to about $100 billion in investment (Wong, 2016).

The dramatic slowdown of energy demand coupled with a business-as-usual increase in supply has led to sharp reduction in utilization rates across all energy sources. Thermal power, which makes up a substantial portion of China's energy portfolio, was most affected. The national average utilization rate for thermal power sharply decreased from 67% in 2005 to 49% in 2015. This steep fall in utilization rate reflects a large mismatch between the country's growing electricity supply, including both thermal and renewable, and the weaker-than-expected rise in electricity demand.

To illustrate the severity of China's overcapacity problem, we performed a first order estimate of the amount of electricity China can produce using its thermal power fleet alone. If China were to put all 990GW of its 2015 thermal capacity to use at a 64% utilization rate (2006 actual utilization rate), it could generate as much as 5552 TWh, more than the 5550 TWh of demand in the same year. In reality, thermal power generated only 4100TWh last year, or about 73% of the country's total.

A coal plant's construction schedule may last several years, and many of the coal plants currently under construction were planned when the Chinese economy had rosier prospects, so we expect the overcapacity problems to persist in the near future[42]. Already the government announced plans for lay off 1.8 million workers in the SOE-dominated coal and steel industries (Wong, 2016). Further reductions in utilization of thermal power may be politically untenable, and renewables will have to share in the brunt of the country's overcapacity problems. In fact, wind energy's utilization rate last year was under 20%, an all-time low (Figure B.2). Some provinces failed break the 1200-hour utilization mark, approximately half of the average CDM's projected numbers, suggesting that these turbines were heavily under-utilized.

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[42] While there is evidence that CDM had a positive effect on wind energy deployment in China (Liu, 2014), it is not the cause for this overcapacity. China's wind market did not show any signs of slowing down after the European carbon market imploded in 2012. Even though the number of CDM-registered wind projects fell precipitously, newly wind capacity actually accelerated after 2012.

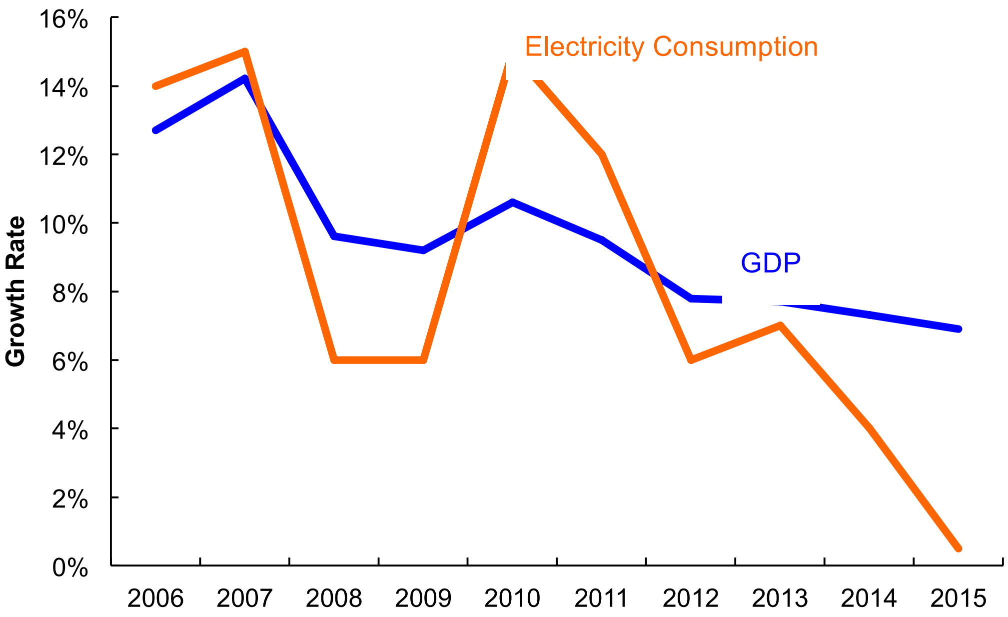

Figure B.1: GDP and electricity consumption growth rates from 2006 to 2015. Plot produced by authors using data from World Bank (2015) for GDP growth rate, Magnier (2016) for 2015 GDP growth rate, and CEC (2015) for electricity consumption growth rate.

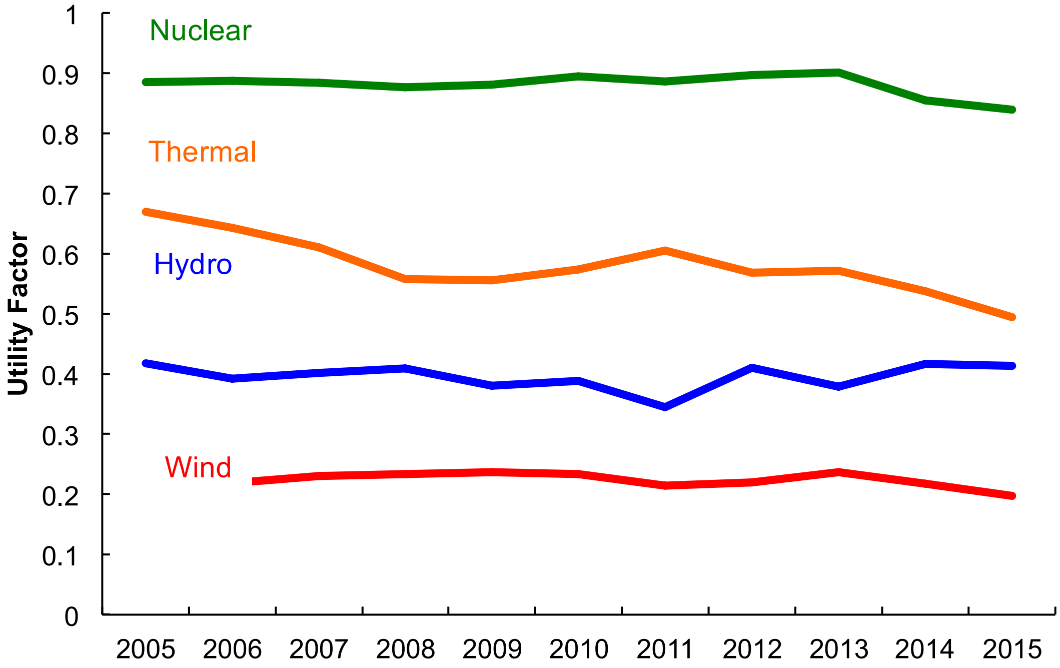

Figure B.2: Utilization factors for different technologies in China between 2005 and 2016. Plot produced by authors using data from CEC (2015)**.**

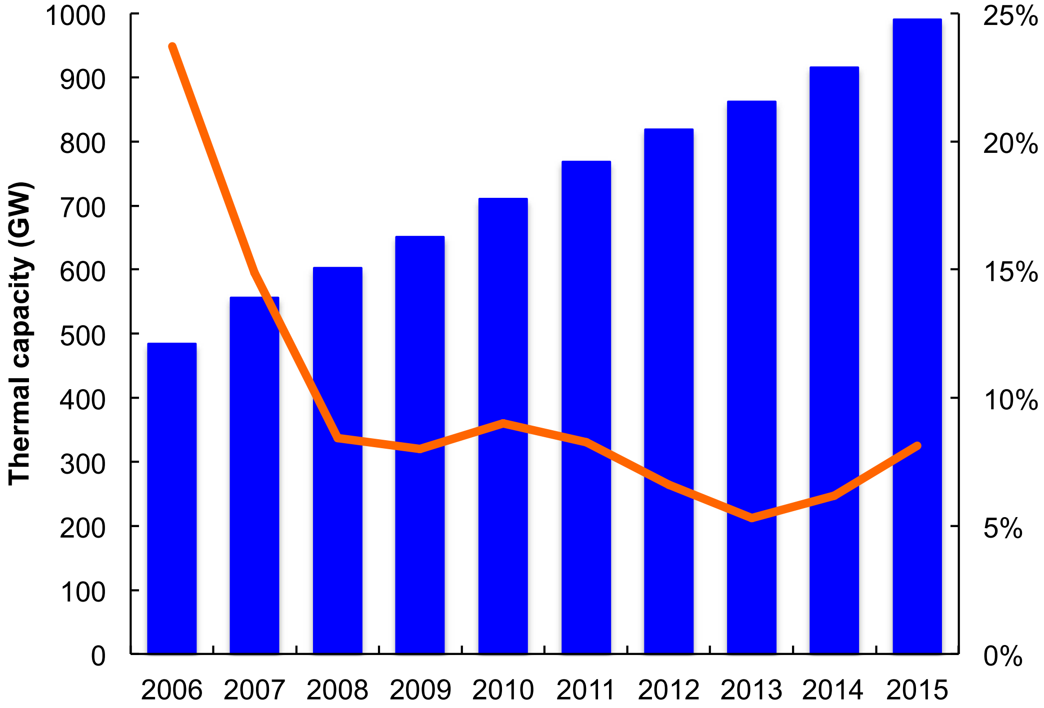

Figure B.3: Thermal power's cumulative capacity and its growth rate from 2006 to 2015. Plot produced by authors using data from CEC (2015).

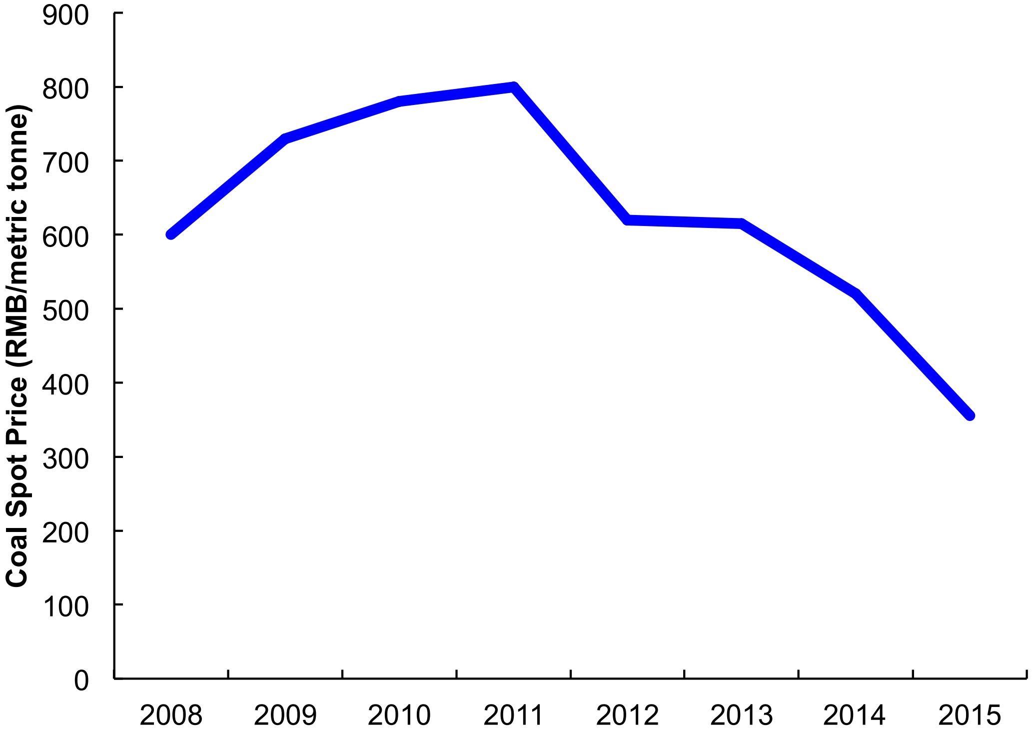

Figure B.4: Spot price of China thermal coal FOB Qinhuangdao (5500 kcal/kg). Source: Bloomberg (2016a)

C. Supplemental information for Chapter 4

C.1. Alternative methods to estimate cost

Learning rate, or experience curve estimation, is an alternative method that can be used to gauge how costs of energy supply technology change over time (Arrow, 1962; Maycock and Wakefield, 1975; Grübler et al., 1999; Swanson, 2006; Zheng and Kammen, 2014; Rubin et al., 2015). Accumulation of production experience in manufacturing can lead to an increase in productivity and a decrease in cost. By linking to unit cost of solar PV technology to its cumulative production or installed capacity, we can determine the “learning rate” parameter, which tracks the reduction in cost for each doubling of cumulative production or capacity. The learning rate, which is derived from historically observed cost reductions, can also be used to project the technology’s future trends and progress. One can further measure cost reduction as a function of cumulative production, or “learning-by-doing”, or as a function of total research expenditure, or “learning-by-searching.”

The learning rate for solar PV is around 23%, though results vary, owing to differences in data availability, study periods, econometric methods, etc. (Ferioli et al., 2009; Rubin et al., 2015). Furthermore, past learning rates are not necessarily good predictors of future trends because they often focus on costs and discount uncertainties in technological progress, thus overlooking or oversimplifying many related factors (Nemet, 2006). Recently, Farmer and Lafond (2016) build on this literature and propose using geometric random walk with drift method to model technological progress. Instead of using the usual stationary regression, the authors put themselves in the past, dynamically predicting what the values would be in the following time periods.

Bottom-up engineering-economics assessment approach has been used for cost estimations of solar PV(Nemet, 2006; Goodrich et al, 2013; Zheng et al., 2016). This approach examines major material and components as well as industrial processes that are involved in manufacturing solar PV products. These valuable efforts provide modelers excellent insights into trends that may influence the overall costs of certain technologies, though they may place an undue emphasis on incremental advances and not enough on the probability of different outcomes (Wiser et al., 2016).

Expert elicitation is another tool that can be used to characterize the state of knowledge of different technologies and their future progress. Expert elicitation involves a process of seeking judgments from experts about an uncertain quantity in their domain of expertise, often in the form of subjective probability distributions (Morgan, 2014). When performed properly, it can be a useful tool that complements learning rate analysis and engineering-economic assessments. This study relies on experts to quantify future cost reductions and to identify sources of these reductions, thus providing a nuanced view of how potential improvements can be achieved as well as uncertainties that underlie these estimates.

C.2. Study Descriptions

Whenever possible, interviews were conducted face-to-face, usually in the experts' office, where they had access to relevant reference material. Prior to the formal elicitation, we explained to experts the goals, scope, and overview of the study. We assured participants of their anonymity and reminded them of some common biases associated with this type of study and strategies to minimize the effects of these biases.

Experts were asked to judge their own levels of expertise with respect to the 17 PV technologies, with 1 indicating basic knowledge, 2 good knowledge, 3 expert knowledge, and 4 top expert knowledge. In the interest of time, we proceeded with technologies that participants indicated that they had expert or top knowledge (3 or 4). These are the results that we reported. We observed that Chinese experts tended to be more modest than their non-Chinese counterparts in self-identifying their expertise level. Several experts considered out loud selecting one level lower than their initial inclinations. Whenever this happened, we encouraged experts to rank their expertise as honestly as possible and reassured them of the anonymous nature of the study.

The survey was roughly divided into two parts: silicon technologies and non-silicon technologies. In the first part of the study, experts were asked to rank the importance of polysilicon material, ingot/wafer, cell, and module progress in bringing down module's overall production cost. They also ranked the contribution of module, inverters, balance of plant (BOS), and others to the decline of system cost[43]. Experts then identified specific technological and non-technological factors that influenced the decline in module and system costs and evaluated technical barriers to the large-scale commercial success of Silicon PV technology. Finally,

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[43] BOS costs include costs of all non-photoactive parts, excluding inverters. Others refer to all other costs, including engineering, procurement, and construction management costs.

experts estimated what they thought module efficiency and cost would be by 2030 for different silicon PV technologies under current levels of R&D. The tasks for non-silicon technologies were similar, but participants did not have to formally assess historical progress. To ensure internal consistency, experts were asked to assign the probability that system cost of any representative technology within the previously evaluated major technology category would be below 4 yuan RMB per Watt and above 6 yuan RMB per Watt by 2030. Whenever we spotted inconsistencies, we would bring them up, and experts had the option to make adjustments. We finished the interview with open-ended questions.

Table C.1: Demographics of participating experts

Description		No.
No. of experts		16
	Non-Chinese nationals	3
No. of organizations represented		13
Current formal affiliation*		
	Academia	3
	Industry	7
	Institution	8
Years spent in the solar industry		
	Average	18.2
	Median	15
	SD	9.5
Outside of China		
	Average	8.1
	Median	3
	SD	10.4
No. of experts who have experience in the following areas†		
	Research	16
	Development	16
	Product Optimization	9
	Cost Optimization	9
Age		
	Average	53.7
	Median	52
	SD	16.6
No. of female experts		2

*: Some have more than one formal affiliation

†: Experts could select multiple areas of experience

C.3. Study development

The study was inspired by some of our initial questions concerning the rise of China's solar PV industry:

-What technological advancements helped China's solar PV industry to bring down production costs?
-How sustainable are these advancements?
-What are the future costs and efficiencies for solar PV modules produced by Chinese firms?

After several rounds of discussion and iteration, the authors developed the protocol in English. We consulted instruments used in previous studies (Curtright et al., 2008; Bosetti et al., 2012; Abdulla et al., 2013). The protocol's content, language, and formatting were revised based on feedback from one non-expert, two behavioral social science researchers, and one expert. The first author then translated the protocol to Chinese, which was again revised to resolve any linguistic or cultural problems using suggestions from one Chinese linguist and one Chinese expert during the pilot study. Due to experts' demanding schedules, we limited the protocol to two hours. We made one modification to the protocol after the first two interviews, where we omitted tasks on past production costs due to time constraints. In reality, interviews lasted between one to three hours. One interview was completed over two sessions due to the expert's inability to commit to a time block that was longer than one hour. We reminded the expert of associated heuristics and biases prior to the start of the second session. Interviews were conducted and translated manually by the first author.

C.4. Addressing biases

There remains no clear-cut formula for how to robustly assess and adjust for the type of subjectivity and biases associated with elicitation procedures. The effects of these biases and how to minimize them are discussed thoroughly by Morgan and Henrion in their pioneer work (Morgan et al., 1992). In this study, we adopted a number of suggested strategies to mitigate these biases, which are reflected in our procedure. For example, we asked experts to establish an upper bound and a lower bound for the parameter in question before giving a best estimate. We asked experts to provide justifications for their estimates and consider scenarios in which their estimates could change. Second, we performed consistency check, asking experts to assign the probability of a system cost being lower or higher than a certain value, which was immediately verified against previous estimated values. Whenever applicable, we pointed out any inconsistency that arose and allowed experts to adjust their estimates.

C.5. **In-house production costs versus blended costs**

Production costs usually refer to manufacturing and processing costs. They take into account depreciation but exclude selling, general, and administrative expenses (SG&A). Costs reported by thin-film solar PV makers are usually considered in-house production costs. For silicon solar PV technology, some makers report in-house production costs while others report blended costs. The main difference is that the latter includes additional expenses that go into outsourced products made by "contract manufacturers." As more silicon solar PV makers integrate their production chain, the gap between in-house production costs and blended costs will narrow. For the purpose of this study, we asked experts to provide in-house production costs.

C.6. **Technology Advancements**

a. Polysilicon

Most polysilicon producers use the Siemens process, which was initially developed for solid-state electronics applications and later gained interests and support from the U.S. government during the 1970s oil crises (Breneman and Julsrud, 2016). The Siemens process is mature with limited space for improvement, and Chinese firms can purchase Western equipment and tools to set up their plants. Daqo New Energy Corp is one of the few exceptions who, in partnership with Chinese academic and research institutions and under the auspices of the Chinese government, opted to develop their own technology through trial and error. Some Chinese firms struggled to operate their plants efficiently in the beginning. For instance, two experts suggested that mismanagement of LDK Solar's polysilicon operation led to the company's eventual demise. After all, Western incumbents had spent decades perfecting this technology for the semiconductor industry. Incumbents do seek legal protection for their technologies through patents, but many techniques are closely held as trade secrets[44].

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[44] Interview #34

Nevertheless, Chinese firms have made some progress to date, gradually improving polysilicon quality. For solar PV applications, polysilicon must be refined to 9N purity (99.9999999% pure), meaning that for every billion atoms, there can only be 1 non-silicon atom. For electronics application, the silicon must be ultra-pure, requiring 11N purity (Fu et al., 2015). While much of the domestically produced material still does not meet high quality standards for the electronics industry, it can be used for PV applications. Chinese polysilicon producers were able to curb their electricity consumption through technological upgrade. For instance, hydrochloronation technology upgrades allowed manufacturing plants to lower the operation temperature and electricity consumption[45]. Chinese firms also reduce their electricity consumption by placing more seed rods in the furnace.

Compared to the Siemens process, fluidized bed reactor (FBR) is a less energy-intensive and continuous process, yielding higher production. According to one estimate, FBR uses only 10% to 20% of the energy used by the Siemens method (Roselund, 2015). This is an attractive proposition considering currently electricity makes up 30-40% of polysilicon production costs (BNEF, 2016a).

Chinese producers, usually in partnerships with Western firms, are eager to adopt and expand FBR production, hoping to at least halve production costs. Chinese firms can secure high capital investments, whereas their Western counterparts bring the technological know-how. However, these projects have run into various technical problems, most pressing of which is material impurity. The continuous generation of raw granular silicon has to be interrupted often as granules are contaminated by the furnace’s wall material. FBR at the moment accounts for only 5% of the global production (21,800 tonnes), falling far short of the 10% that industry experts previously expected (BNEF, 2016b; ITRPV, 2016).

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[45] Interview #2

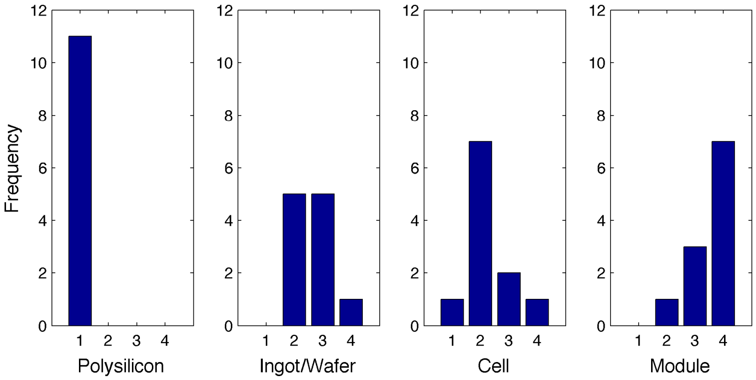

Figure C.1: Order of importance of different components to decrease of silicon PV module cost between 2005 and 2015, with 1 being most important. Experts B, O, and P emphasize that polysilicon was especially important during the 2008-2015 period.

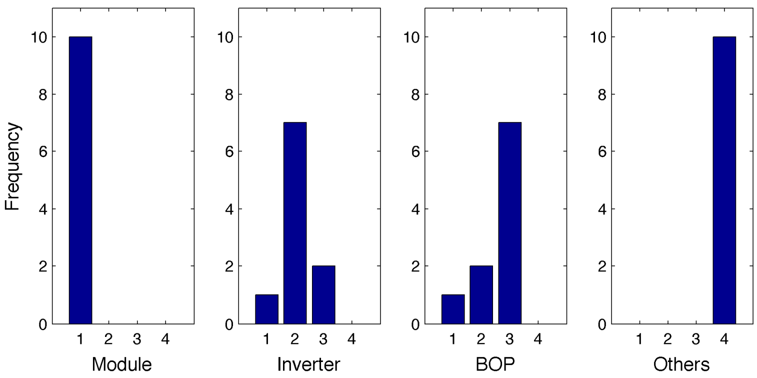

Figure C.2: Order of importance of module, inverters, balance of plant (BOP), and other factors to decrease of silicon PV system cost between 2005 and 2015, with 1 being most important. Others refers to all other costs, including engineering, procurement, and construction management (EPCM) costs.

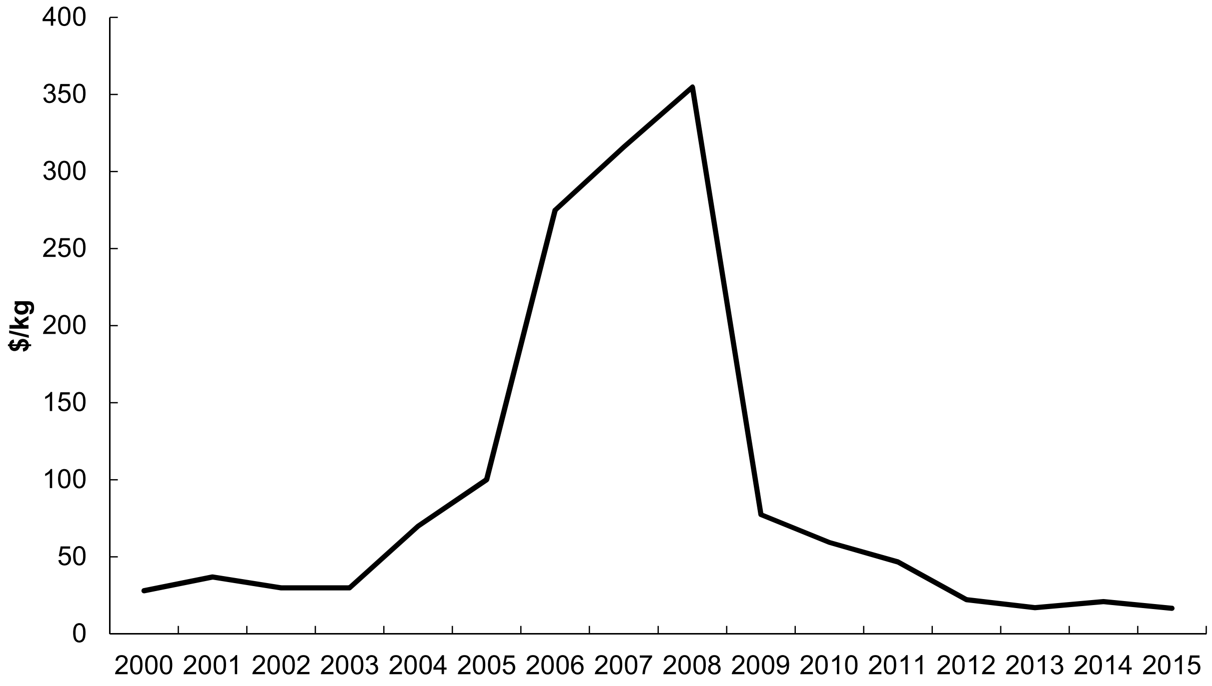

Figure C.3: Polysilicon spot prices from 2000 to 2015. Prices peaked in 2008 at over $350/kg. Prices dropped to around $16/kg in 2015. Sources: Bloomberg (2016b).

b. Ingot/Wafer

Traditionally, mc-Si is grown through a directional solidification process, a relatively inexpensive and straightforward method, though resulting mc-Si cells have lower efficiencies compared to monocrystalline cells due to defects such as grain boundaries and dislocations (Rodriguez et al., 2011). Chinese manufacturers were able to control the distribution of grain sizes and to bring down the level of dislocation density through a seed-assisted growth method, where commercial raw mc-Si seeds are placed at the bottom of the crucible, acting as starting points (Zhu et al., 2014). This technique yields mc-Si with fewer defects and can lead to an efficiency gain of 0.5% for a standard cell. In this method, seeded mc-Si feedstock at the bottom of the crucible – sites of nucleation – must not be completely melted, though partial melting renders this bottom layer of the ingot block unsuitable for further processing. To address this problem, researchers at GCL-Poly line the crucible bottom wall with quartz powder, which guides the nucleation process and allows complete melting of polysilicon, thus increasing yield (Zhang et al., 2016).

Multi-wire slurry sawing, where an abrasive silicon-carbide is squeezed between a steel wire and silicon ingots, has been the main technique employed by the solar photovoltaic industry to slice large silicon ingots into thin wafers. However, there are a number of issues associated with this technique: high steel wire breakage rates, high kerf loss (sawdust generated from the slicing process), and industrial waste (non water-soluble cutting fluid, slurry, and disposable wires).

Diamond wires, an alternative wafer slicing technology, can address a number of issues inherent to multi-wire slurry sawing. Research has shown that diamond wire, or wire coated with abrasive diamond grits by resin bonding, can saw wafers at a higher speed than slurry sawing, and result in thinner damage zones (N. Watanabe et al., 2010). Because diamond wire is thinner than steel wire, there is less kerf loss. According to Canadian Solar, diamond wire can slice a kilogram of silicon into 60 wafers, compared to steel wire's 51, delivering substantially more efficient production and effectively decreasing the module cost by 2.6 cents/W (Xing, 2016). Furthermore, diamond wire can reduce the wafer's thickness to around 60 microns (Yu et al., 2012), compared to the current industry's average of 180 microns, although breakage may be of concern for thinner wafers (ITRPV, 2016).

Large mono-Si wafer makers have adopted diamond wire sawing in their new production lines, and some are retrofitting their slurry sawing equipment with diamond wire in existing factories (BNEF, 2016a). For instance, Xi'an LONGi Silicon Materials Corp., the largest single crystal manufacturer in the world, already switched all of its slicing equipment to diamond wires already. One study estimates that diamond wire sawing will take an increasingly large share of both mono- and multi-Si wafer production in the next several years (ITRPV, 2016).

Adoption of diamond wire sawing for multi-Si wafers has been slow due to a number of challenges related to multi-Si's crystalline properties. Traditionally, wafers are textured to create pyramidal structures that can capture more light by inducing multiple light reflections. The chemical texturing process requires a rough surface, but when sliced with diamond wire, the surface of multi-Si wafer is too smooth for the standard texturing process. The cutting mechanism in multi-wire slurry sawing results in a rough surface for multi-Si wafers due to rotating free silicon carbide particles found in the slurry. In contrast, the surface of a wafer cut by a diamond wire has smooth areas, individual fractures, parallel grooves due to sawing direction, and many cracks (Cao et al., 2015). In order to achieve the same texturing effect, these multi-Si wafers must undergo additional etching. Additional processing costs cancel or even outweigh the potential savings, thus there is little market for multi-Si wafers sliced by diamond wires (BNEF, 2016a).

Black silicon, which refers to silicon surfaces covered by a layer of nanostructures, can provide an effective solution to the aforementioned smooth surface problem. Through multiple interactions of light and the textured surface, the needle-like nanostructures enhance the absorption of light. When the nanostructure is sufficiently small (<100 nm), the surface acts as an effective medium with a continuous change of refractive index, thus significantly reducing reflection (Liu et al., 2014). Currently, there are three main methods to fabricate black silicon: reactive ion etching (RIE, or sometimes called dry etching) (Jansen et al., 1995), metal-assisted chemical etching (MACE, or wet etching) (Huang et al., 2010), and laser etching (Her et al., 1998)[46]. Thus far, MACE appears to be the most promising technique due to its simplicity, low capital cost, and ability to control various parameters of the nanostructures[47].

Due to potential improvements in efficiency and cost reduction, a number of manufacturers in recent years have pursued black silicon technology for large-scale production, including Canadian Solar, Jinko Solar, and Risen. Combined diamond wire sawing and black silicon can raise the multi-Si cell efficiency to 19%, or 0.45% higher than conventional cells (Xing, 2016). Canadian Solar kick started their black silicon R&D program in 2012 and began mass production in 2015. By the end of 2016, Canadian Solar planned to produce a total of 1 GW of black silicon cells, a number that would increase to 3GW by the following year.

c. Cell

While domestic suppliers have not been able to manufacture silver paste, Chinese cell makers have benefited from progress made by international suppliers. A mixture of inorganic and organic material, silver paste is one of the most important and expensive components of a solar cell. When deposited onto wafers (usually by screen-printing), silver paste acts as an electrical

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[46] To remove material deposited on wafers, RIE uses chemically reactive plasma, which is generated under low pressure (vacuum) by an electromagnetic field. High-energy ions from the plasma attach to the wafer surface and react with it. Laser etching method irradiates silicon with femtosecond laser pulses in the presence of a gas containing sulfur hexafluoride and other dopants. In the MACE method, a layer of noble metal such as aluminum covers the silicon substrate in a solution that contains fluoric acid, nitric acid, and water. The metal will catalyze the etching process, resulting in columnar structures.

[47] The production process may also bypass the expensive plasma-enhanced chemical vapor deposition (PECVD) process used to deposit silicon nitride.

contact in the form of a finger or a busbar. Silver printing is a complicated technology with high technical requirements: not only must the paste have high conductivity and high reliability, it also must have good printability, meaning that it must be fired through the antireflective layer to make as low as possible contact with the absorber layer without shunting the p/n junction (Glunz et al., 2012). Poor contact quality can result in lower efficiency.

Chinese cell makers have been aggressive in adding more busbars to their solar cells, which can be a challenging engineering problem. Designed to collect current from contact fingers and to connect to external leads via soldering, busbars must have good electrical and mechanical contact. An additional busbar delivers more power, increasing the overall efficiency, but it must be designed to minimize grid shading, which occurs when the active cell area is covered. For this reason, busbars must be thin and tall with strong adhesion. They also must be accurately aligned when soldered to external leads.

New solar cell designs can further increase cell efficiency. The simplest and most attractive silicon cell technology upgrade is called PERC, which stands for passivated emitter rear cell. PERC and related designs passivated emitter rear locally-diffused (PERL) or passivated emitter rear totally-diffused (PERT) were invented by researchers at University of New South Wales, Australia (Blakers et al., 1989; Zhao et al., 1990, 2001). A dielectric passivation layer on the rear side of a PERC cell allows the cell to capture more light and minimize recombination. This adjustment substantially boosts cell efficiency while requiring only two additional processing steps, obviating the need to upgrade the entire production line. Other prominent technologies including interdigitated back contact (IBC), in which contacts are brought the rear side (no shading loss), and heterojunction with intrinsic thin layer (HIT/HJT), where two passivating layers of amorphous silicon sandwich an n-type silicon core (Taguchi et al., 2000). N-type silicon is preferred for these high-efficiency cells because of the material's quality, resistance to light-induced degradation, and lower sensitivity to metallic impurities.

d. Module

The most expensive component in the module manufacturing process, the backsheet is also technically demanding. Acting as a skin, the backsheet protects cells from mechanical degradation and minimizes moisture penetration as well as damages from high temperature and ultraviolet radiation. Backsheets must also have good mechanical strength, adhesion, electrical isolation at system voltage levels. Dupont produces the industry's mainstream backsheet called

TPT, or a tedlar-polyethylene terephthalate (PET)-tedlar[48]. (Tedlar is the DuPont's brand name for polyvinyl fluoride, or PVF.) However, in recent years, a number of Chinese companies have explored inexpensive alternatives, the most prominent of which is Jolywood (Suzhou) Sunwatt. Jolywood's backsheet design sandwiches PET between two fluoride coatings and costs half as much as foreign brands (Jolywood, 2016). Thanks to this new product, Jolywood has experienced rapid growth: between 2011 and 2015, the company's revenue from backsheet sales has increased five times, and Jolywood quickly gains industry-wide recognition (Osiris, 2016).

Similar to industry trends that we illustrated above, decrease in related commodity prices as well as more efficient use of material further drove down module production costs. For instance, price of EVA resin, a material used to make EVA encapsulants, has decreased in recent years. Similarly, drop in aluminum commodity prices in the past decade also helped decrease the cost of aluminum frame.

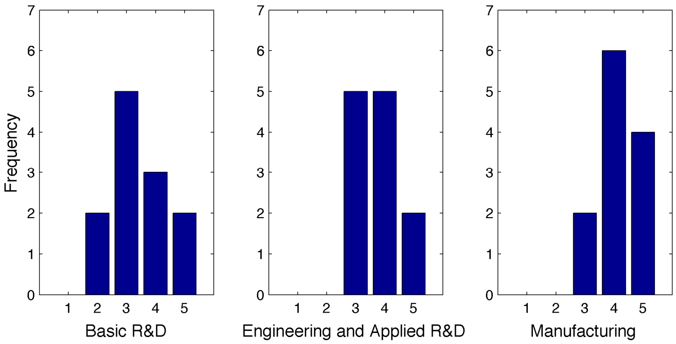

Figure C.4: Rankings of maturity levels of silicon photovoltaic technologies in three major R&D areas.

e. Equipment

The indigenization of capital equipment was one of the most important factors in driving down PV module costs. Early Chinese PV entrants purchased turnkey production lines from Western equipment makers, who in turn trained local employees to operate the machines (la Tour et al., 2011; Zhang and Gallagher, 2016). This arrangement created at least three openings for local equipment makers. First, equipment was sold as-is, with each machine a technical black box. Should a piece of equipment fail, the provider could take months to acknowledge and

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[48] http://www.dupont.com/products-and-services/solar-photovoltaic-materials/photovoltaic-backsheet-films/products/tedlar-film-based-backsheets.html

address the issue, time that PV makers could not afford. Second, the rush of PV investment due to burgeoning European demand in the 2000s created a backlog of orders for incumbent equipment makers. Third, foreign equipment was expensive.

Chinese PV makers, especially smaller ones, were more willing to purchase domestic equipment. Though Chinese makers were able to reverse-engineer[49] Western equipment and sell theirs at a lower price, there were many quality issues. Through an interactive process of iteration and learning, often alongside with customers, equipment makers were able to iron out technical kinks and fine tune their designs.

Investment costs for setting up a production line have dropped significantly. For example, an expert from a leading Chinese equipment maker estimated that a 25 MW production line in the mid 2000s costed 100-300 million yuan RMB to set up, but currently a production line of the same capacity costs about 25 million yuan RMB for main equipment and another 15 million yuan RMB for auxiliary equipment. One representative of a major PV producer said that 90% of the company's equipment was domestic, which they purchased for 70% of the price quoted by foreign brands[50].

Automation also helped reduce labor costs. For instance, five years ago running a 500MW module manufacturing plant required around 2000 employees, but only 400 people are needed now to run the same plant (Zheng, 2016) . Similarly, after emerging from its bankruptcy as a subsidiary of Shunfeng-PV, Suntech reduced its work force from 10,000 in 2011 to 3000 in 2016 while maintaining the same level of production capacity[51].

C.7. Estimation Results

Median estimates show that Low Concentrator Photovoltaic (LCPV) system will reach an average efficiency of 26% by 2030. Industry leader SunPower produces solar cells for LCPV application with 20% efficiency (SunPower, 2012). According to experts, LCPV system cost will reach around $1.22/W. Experts A and I believed that the estimated cost was the minimum viable cost for LCPV system. Expert O declined to provide efficiency and cost estimates, stating that CPV did not have any future prospects. Many demonstration projects exist around the world, though there are scant details on their operations and project costs. Of the projects with available

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[49] 反造，though several interview subjects directly referred to this process as copycat, or 山寨
[50] Interview #8
[51] Interviews #27, #28

investment cost data, LCPV system cost can be as low as $1.24/Watt (GlobalData, 2017). In contrast, experts estimated that HCPV system cost would reach $1.51/Watt. IHS, an industry analysis company, forecasted that system cost could reach $2.58/W in 2015 (Sharma 2015). Fraunhofer Institute reports that current installation costs for CPV plants ranged between €1.4/W to €2.2/W and will decline to between €0.7 and €1.1/W by 2030 (Philipps et al., 2015).

Median estimates show that DSSC will reach an efficiency of 15% by 2030. The current record for a 26-cell submodule is 8.8% (Green et al, 2016). Molecular and polymeric organic PV (OPV) efficiencies will reach 13% and 14.3%, respectively. The current highest OPV efficiency is 9.7% for an 8-cell minimodule (Green et al., 2016). There is no commercial production for any of the excitonic PV technologies. Experts stated that in the future DSSC and OPV would have special applications, such as outdoors portable electricity generators, but they would not replace silicon PV for large-scale electricity generation.

Of the emerging PV technologies, experts judged that perovskite had the most potential. Perovskite's lab efficiency has increased nearly six times fold since its introduction in 2009 (Kojima et al., 2009; NREL, 2016), and recently researchers were able to fabricate large stable cells (University of New South Wales, 2016). Experts estimated that perovskite module would reach a record of 24%, and the current record efficiency is 19.7% (small-scale cell). Experts indicated that perovskite would not be ready for commercial production in the near future, but investors have shown intense interests in this technology (Snieckus, 2016b). Other emerging technologies have not made it past the lab stage, and there is little commercial interest for them in China.

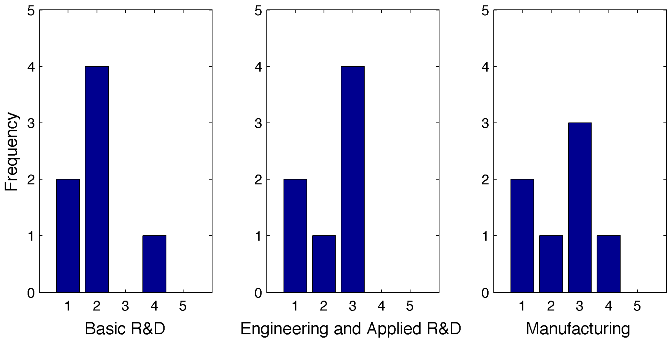

Figure C.5: Rankings of maturity levels of thin film PV technologies in three major R&D areas.

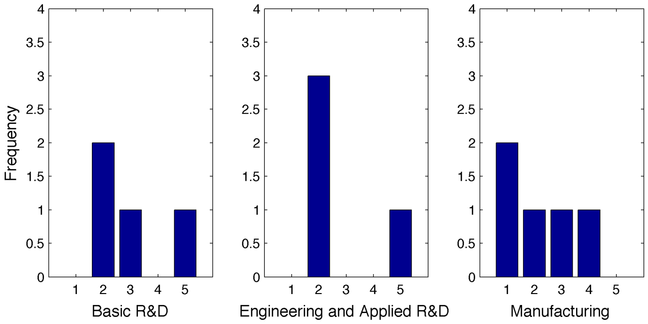

Figure C.6: Rankings of maturity levels of concentrating photovoltaic technologies in three major R&D areas.

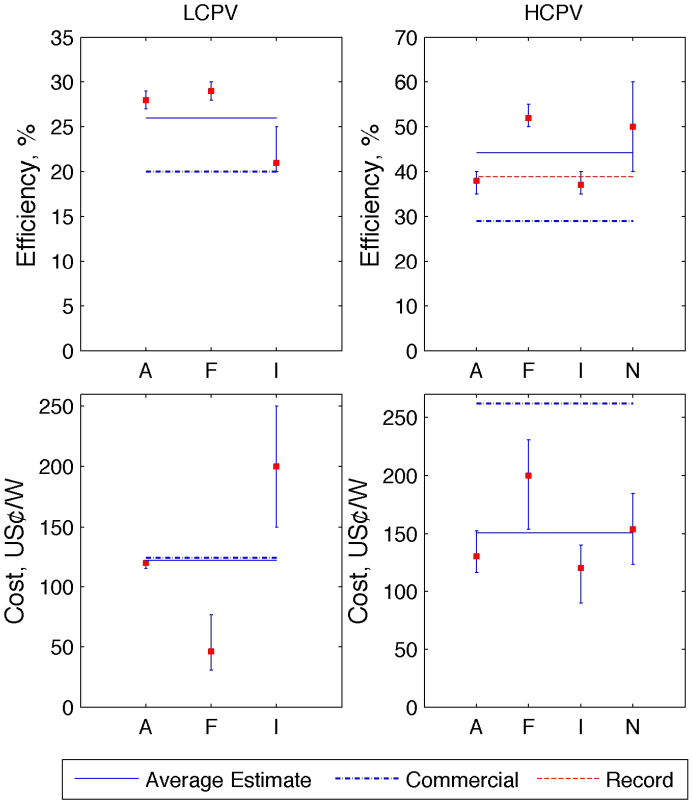

Figure C.7: Expert judgments of efficiencies and costs for CPV system by 2030. Each expert responds with their best, upper, and lower estimates. LCPV commercial efficiency is from SunPower's C7 *module* efficiency (SunPower, 2012); commercial cost is from SunPower Wuchuan project's average capital expenditure (GlobalData, 2017). HCPV system's commercial efficiency is 29%, lab record *module* efficiency is 38.9 % (Fraunhofer, 2016), compared to experts' estimated system efficiency of 44%. HCPV system *price* is $2.62/W (IHS, 2013).

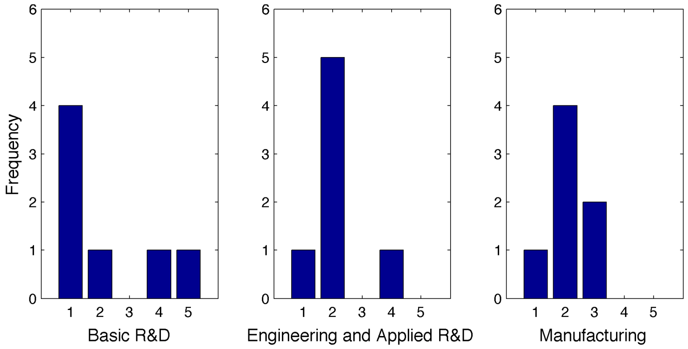

Figure C.8: Rankings of maturity levels of organic photovoltaic technologies in three major R&D areas.

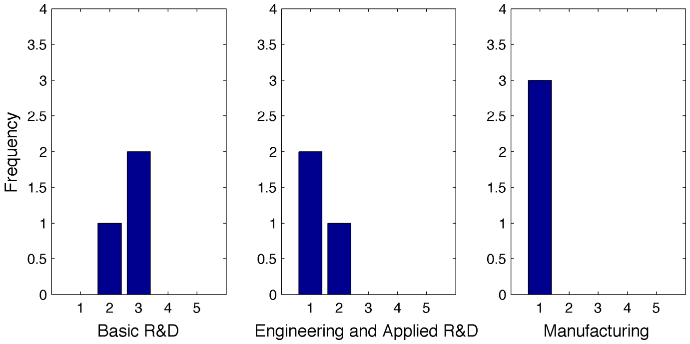

Figure C.9: Rankings of maturity levels of emerging photovoltaic technologies in three major R&D areas.

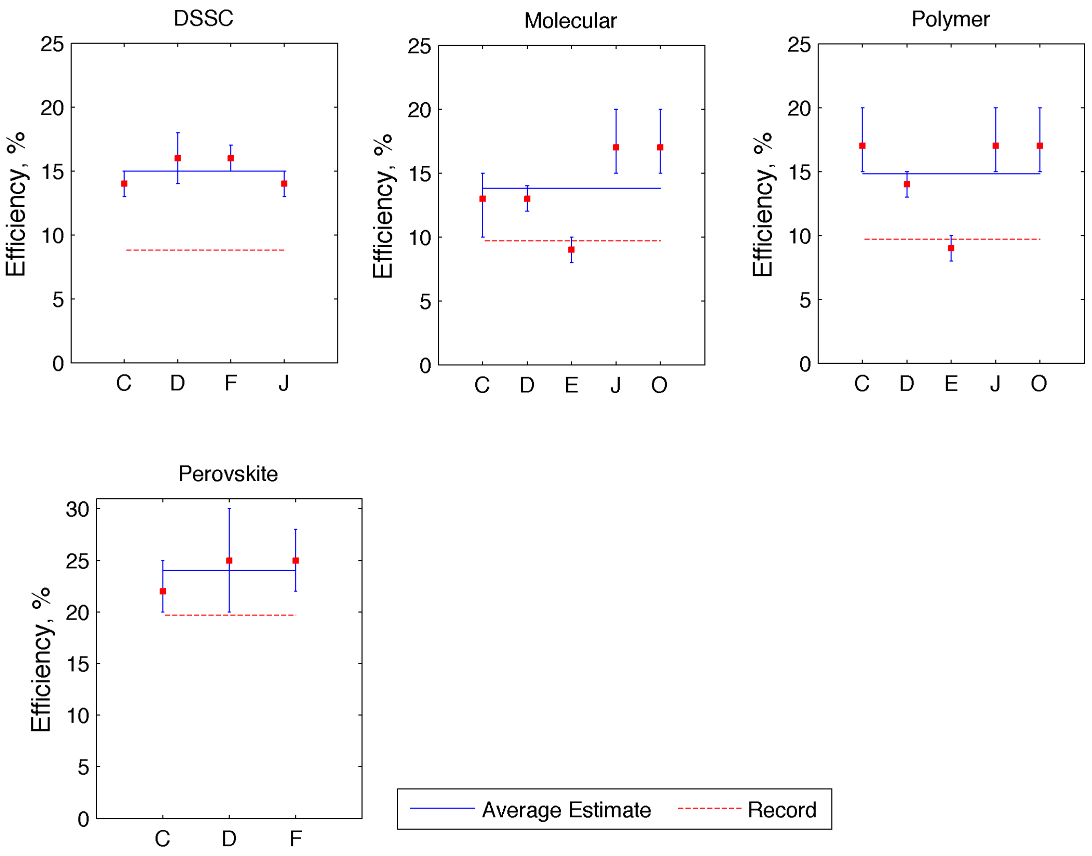

Figure C.10: Expert judgments of expected efficiencies in 2030 for organic photovoltaic and perovskite modules. Each expert responds with their best, upper, and lower estimates. Record efficiencies from Green et al. (2016). Perovskite record efficiency is for cells.

Table C.2: Probabilistic distribution of silicon PV system cost by 2030

Expert	<4RMB/W (%)	>6RMB/W (%)
A	100	0
B	100	0
D	95-100	0-5
F	95-100	0-5
G	50-60	0
H	20-40	0
I	30	0
K	90-100	0-5
L	80-90	10-20
O	40	25

C.8. **Calculating LCOE for solar**

Assumptions
System size: 1kW
Capacity Factor: 20%
Interest Rate: 10%
Investment Period (Years): 25 (length of typical warranty)
Annual O&M: 0.5% of Capital
Exchange rate: 1USD = 6.5 yuan RMB

Current LCOE for other energy technologies in China

Table C.3: Levelized cost of electricity for different technologies in China ($/kWh). Sources: Zindler (2015), Salvatore (2013), WNA (2016b)

Technology	BNEF	World Energy Council	World Nuclear Association
Coal	0.44	0.35-0.39	
Wind (onshore)	0.77	0.49-0.93	
Solar	1.09	0.79-1.45	
Natural Gas	1.13	–	
Biomass	–	0.34-0.83	
Nuclear	–	–	0.49-0.64†

†: at 10% discount rate

Table C.4: Estimated levelized costs of electricity under two scenarios presented in the survey.

	Scenario presented in this study	
	6 RMB/W System	4 RMB/W System
Module Cost ($)	–	–
BOS ($/W)	–	–
Capital ($/W)	0.92	0.62
Annual O&M (0.5% of capital)	0.00	0.00
Total O&M ($)	0.04	0.03
Total Capital ($)	0.96	0.64
Total Electricity (kWh)	15902.97	15902.97
LCOE ($/kWh)	**0.061**	**0.040**

Table C.5: Estimated levelized costs of electricity using experts' module estimations. Balance of system cost is assumed to account for 55% of system cost (BNEF 2013 estimation from BNEF, 2014b).

	BNEF 2013 BOS (55% of system cost)					
	Mono-Si Module	Mono System	Multi-Si Module	Multi System	Novel Si	Novel System
Module Cost ($)	0.27	–	0.24	–	0.304	–
BOS ($/W)	0.33	–	0.28	–	0.37	–
Capital ($/W)	0.60	0.702	0.52	0.668	0.67	0.742
Annual O&M (0.5% capital, $)	0.00	0.00	0.00	0.00	0.00	0.00
Total O&M ($)	0.03	0.03	0.02	0.03	0.03	0.03
Total Capital ($)	0.63	0.73	0.54	0.70	0.70	0.78
Total Electricity (kWh)	15902.97	15902.97	15902.97	15902.97	15902.97	15902.97
LCOE ($/kWh)	**0.039**	**0.046**	**0.034**	**0.044**	**0.044**	**0.049**

Table C.6: Estimated levelized costs of electricity using experts' module estimations. Balance of system cost is assumed to account for 59% of system cost (BNEF 2020 projection from BNEF, 2014b).

	BNEF 2020 Projected BOS (59% of system cost)					
	Mono-Si Module	Mono System	Multi-Si Module	Multi System	Novel Si	Novel System
Module Cost	0.27	–	0.24	–	0.304	–
BOS %	0.40	–	0.35	–	0.45	–
Capital ($/W)	0.67	0.702	0.59	0.668	0.75	0.742
Annual O&M (0.5% capital, $)	0.00	0.00	0.00	0.00	0.00	0.00
Total O&M ($)	0.03	0.03	0.03	0.03	0.03	0.03
Total Capital ($)	0.70	0.73	0.62	0.70	0.78	0.78
Total Electricity (kWh)	15902.97	15902.97	15902.97	15902.97	15902.97	15902.97
LCOE ($/kWh)	**0.044**	**0.046**	**0.039**	**0.044**	**0.049**	**0.049**

C.9 Responses to open-ended questions

A) What are some of the significant solar technological and process innovations in China in the past decade?

-Black Silicon
-Thin silver pasting

-equipment indigenization

-there are not many; all are using old technologies/concepts

-thinner wafers; thinner silver electrodes; higher efficiency, though many are not that significant

-scale up of new cell architecture with different processes; selective emitters at mass production level

-higher efficiency

- pull multiple ingots
-continuous add silicon material
-production efficiency increased, so lower costs
-kerf loss (diamond wire)

-Domestic CdTe technology

-crystal-seeded growth

B) Experts previously did not expect crystalline Silicon PV prices to fall as much as they did. Looking back, what could be some of factors that experts may have overlooked?

-"People do not really understand the detailed operation of this industry and did not taking into consideration the contribution by China."
-The cost structure for crystalline Si is different.
"People may be familiar with electronics industry, but PV industry has a wider scope than just crystalline Si. Although the core component is crystalline Si, but it's not the biggest part in terms of cost."

-Price of polysilicon
-Scale of Chinese production

-The domestic manufacturing and installation of equipment
-The rush of private investment
-Dramatic drop of prices of polysilicon

-Polysilicon prices

-Break up of polysilicon monopoly and partially the rate of technological improvement

-"They did not consider the manufacturing in China. Chinese and German investors would invest massively in manufacturing and lower the costs that fast. If the manufacturing had stayed in Germany, the price would have stayed at 4-5 dollars/W."

-Polysilicon prices; technological improvements

-Polysilicon supply increased; China broke up and decreased the monopolistic profits

-Technological improvements: thinner wafer, thinner silver electrode, higher efficiency

-Wrong judgment on the scale of polysilicon material expansion
-Rapid improvement in efficiency thanks to technological improvements (equipment as well as other manufacturing processes)
-Economies of scale

C) Between 2008 and 2012, the Chinese solar industry went through a period of consolidation and witnessed a number of high profile bankruptcies. What were some of the underlying problems that the industry faced during this period?

-Drop in demand
-Lack of support policies

-Trade barriers

-Collapse of demand

-Financial mismanagement

-Lots of fluctuation in policy and market
-Large firms are more exposed because of the large investments that are required
-Risky investments (both upstream and downstream)

D) To what extent did tariffs imposed by the U.S. and the E.U. affect the Chinese solar PV industry?

-Hurts because of less demand

-Reduced demand abroad, but caused CN government to step in and open domestic market
-Hurts in the beginning, though currently little effect because US and EU markets are not as large anymore

-Smaller market for Chinese firms

-Uncertain market due to policy uncertainties

-Discriminate Chinese firms; but eventually no big differences thanks to domestic market

E) Why did some of the more advanced technologies fail to take hold?

-"Without any other possibilities, I think crystalline Si can serve its function, which is to provide clean energy with low LCOE, comparable, or even lower than other fuel sources. But I still think since other opportunities are there already, they are worth exploring."
-"I cannot think of a factor that will stop crystalline PV from its continuous cost reductions. There could be some factors, such as the price spike of silver. Even that happens, there are other

alternatives such as copper plating… There might be some temporary negative factors, but I can't think of any that is a sustainable obstacle."
-Standardization: the electronic industry had been using SI for decades, so that paved the way pretty well.
-"Some electronics engineers think that making a solar cell is so easy compared to more complicated structures (Si-based components), so that is kind of boring."

-Easy to switch from ICE to PV

-Material characteristics (crystalline structure; band gap characteristics, absorption index) – crystalline versus thin film; CdTe versus CIGS
-Though a lot of technologies borrow from one another
-Complicated products (like HIT) are more expensive because of the additional processing steps

-"A lot of the Si-PV technologies come from ICE, and people already figured this out really well for ICE, so it's easy to transition from ICE to PV. SO if there are problems, you can see if the ICE industry has had to face similar problems in the past and how they solved it. For thin film, they had to start from the beginning."

-Fairly mature technology with similarities from semiconductor industry

-Standardization

-Division of labor
-Trade secret
-Equipment lock in (amorphous silicon)

F) What are the greatest challenges facing the Chinese solar PV industry right now?

-Oversupply

-China lacks innovative technologies like 1366; all "walking on the same old roads"; there are not big breakthroughs
-PERC PERL MWT HWT HIT HJT are all old technologies

-How to promote healthy growth in far away places?
-"A lot of our studies do not have a purpose. With the exception of perovskite, new types of solar cells do not exist…Existing technologies have a lot of technological and research bottlenecks, and I think going forward it will be very difficult."
-"There is no long-term scientific research support, which is more difficult. Because a country's research policy, if you don't have new ideas, applying for project funding is difficult, and because of that a lot of the old projects cannot continue. The Government's support is very important… stable support may be better."

-The size of demand

-For large firms, how to make their products stand out in a commodity market

-Financial: the manufacturing companies don’t generate enough gross margins to grow. “The market is growing fast than it is sustainable for a company, so the industry needs constant ejection of capital. So the fact of the situation is that some of the companies are with a lot of debt — financial sustainability its number one.”
-Resistance of utility to distributed grid. “The utility/ the energy landscape/global landscape for the energy market of the world is changing rapidly from a centralized production controlled market by utilities to a more individual generation and the utility is resisting to that change, so they are doing everything to prevent the development of PV.”

-Not enough diversification in terms of product; all about optimization,
-Still depending subsidies
-Changes in policies in China and around the world

-Running into technological bottleneck; monolithic technology
-Polysilicon material cannot be cheaper
-Too many government agencies involved; directions are not centralized
-Capital: Not enough RD on the upstream; too focused on chasing profits downstream; investments are short term (both government and private investments)
-Unhealthy competition; sell below margins, price wars

-Demand: both domestic and foreign

-China still mainly focuses on production. Research is outdated, even for mono and multi-crystalline research, the basic concepts were discovered before with no big developments, no revolutionary developments.

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