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China's wind electricity and cost of carbon mitigation are more expensive than anticipated

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Supplementary material for this article is available [online](#)

Abstract

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 build up 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 (CCM), 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 CCM 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.

1. Background: renewable energy integration in China

In 2014 China's wind energy installed capacity outstripped that of the US by some 75%. However, China's wind turbines generated only 156 TWh of electricity in the same year, compared to 180 TWh in the US (see figure 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 32 GW of capacity.

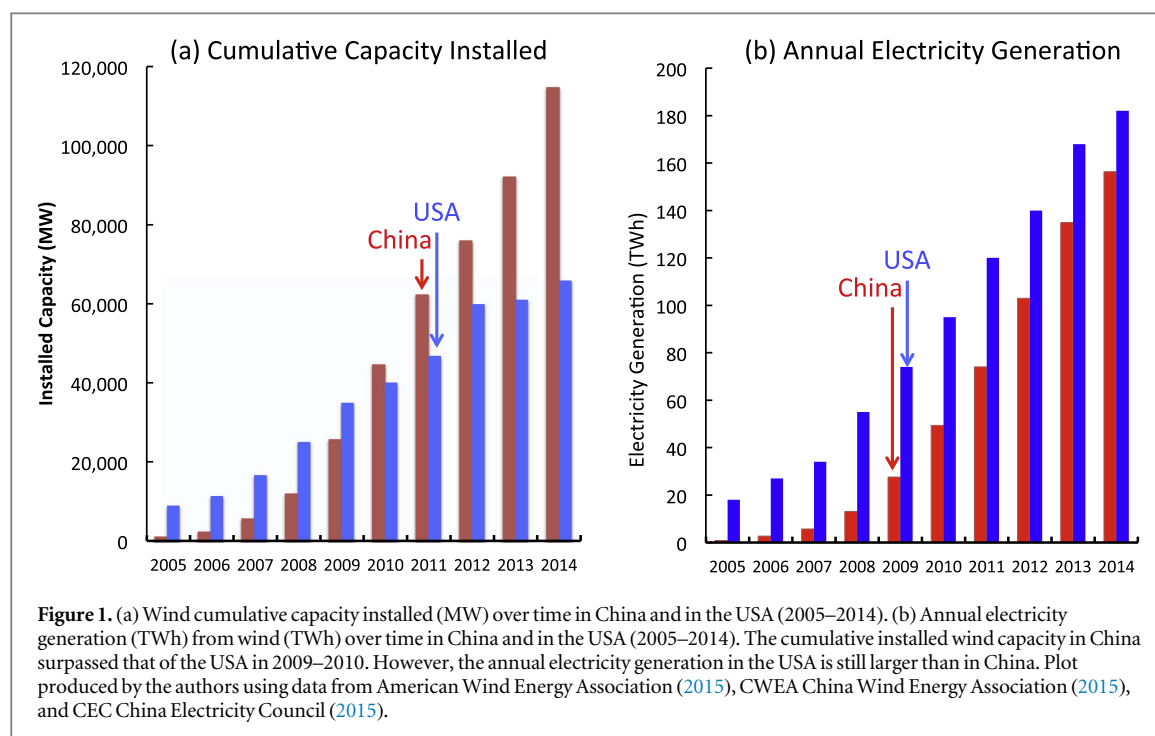
To address some of the country's serious environmental problems, China is undergoing a massive build up of renewable capacity, in particular wind. Furthermore, global progress in reducing emissions to avoid large negative consequences from climate change hinges on China's ability to transition to a low-carbon energy system. However, efforts to integrate the

country's wind power base 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, 2014, Pei *et al* 2015, Zhao *et al* 2016). The absence of inter-provincial 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 problems⁵.

Nevertheless, little has been reported on how the pervasive lack of grid connection and widespread

⁵ Please see IEA (2016), Lewis (2013), and Gallagher (2014) for a review of relevant renewable energy policies.



curtailment affect the industry's levelized cost of electricity (LCOE) and the cost of carbon mitigation (CCM). 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.

2. Data and methods

2.1. 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 GHGs. 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)⁶, 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 Risoe Center 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), 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 date⁷, estimated utilization hours, estimated yearly and lifetime generation, estimated emission factors, etc. Tables S1 and S2 in the supplemental information (SI) 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 standardized⁸, 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

⁷ 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.

⁸ The CDM project database's investment data tracks closely with a similar database maintained by the NDRC. See SI for more details.

⁶ For more information see <https://cdm.unfccc.int/Projects/diagram.html>

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 LBNL Lawrence Berkeley National Laboratory (2014) and from the annual industry data published by CWEA China's Wind Energy Association (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 China Electricity Council 2015). The NEA and Chinese Renewable Energy Industries Association (CREIA) also keep track of grid-connected capacity, allowing us to compute unconnected capacity.

2.2. Methods

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 actual), the LCOE, and the CCM.

2.2.1. 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.

2.2.2. 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:

$$CF_t = \frac{GE_t}{C_t \cdot 8760}, \quad (1)$$

where t indexes the year; GE is the amount of electricity generated and delivered to the grid, C the installed capacity, 8760 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 National Energy Administration 2015).

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 do not provide a good proxy for the electricity produced since they do not take into account wind speeds and other factors (iii) *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*).

2.2.3. Levelized cost of electricity (LCOE)

We also estimate the LCOE for each of 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:

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

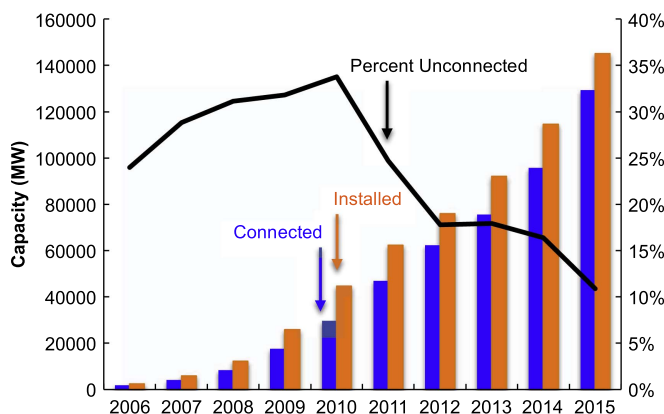


Figure 2. China's cumulative installed and connected capacity between 2006 and 2015 (left axis). The line tracks the percentage of China's wind base that is not connected to the grid (right axis). Figure produced by authors using data from CWEA China Wind Energy Association (2015), LBNL Lawrence Berkeley National Laboratory (2014) for installed capacity and from CEC China Electricity Council (2015) for connected capacity.

where j indexes the year, FC and VC indicate the project's fixed and variable investment costs, GE the total amount of generated electricity, and i 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. 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 comparison⁹. 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.

2.2.4. Cost of carbon mitigation

The CCM using wind electricity is the difference between the wind LCOE and baseline LCOE divided by the carbon emission factor EF, or:

$$CCM_t = \frac{LCOE_t^w - LCOE_t^b}{EF_t}, \quad (3)$$

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 Energy + Environmental Economics 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 Coal Web 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 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 ranges from 823 to 929 gCO₂ kWh⁻¹. All currency numbers are again deflated to 2004 prices.

3. Results

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 were 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 2). For comparison, grid connection issues are not common in the US, 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

⁹ We use a constant exchange rate of 1 Euro = 8 RMB throughout the paper.

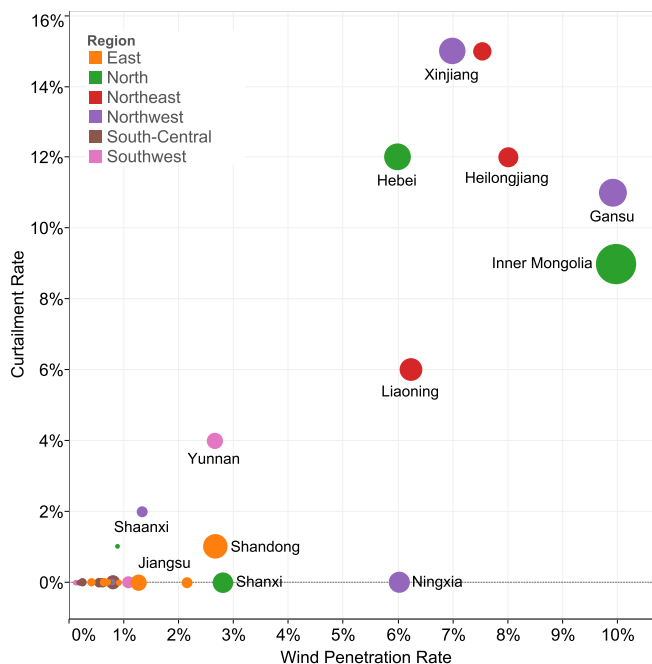


Figure 3. 2014 wind curtailment rates in various provinces (circle areas are proportional to the installed capacity). Provinces with high wind penetration rates tend to have high curtailment rates as well. Plot produced by authors using data from CWEA China Wind Energy Association (2015) for wind installed capacity, NEA National Energy Administration (2015) for electricity generated by wind, and NBS National Bureau of Statistics (2014) for total electricity generation.

experienced some of the worst power loss accidents. On 24th February 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).

3.2. Curtailment

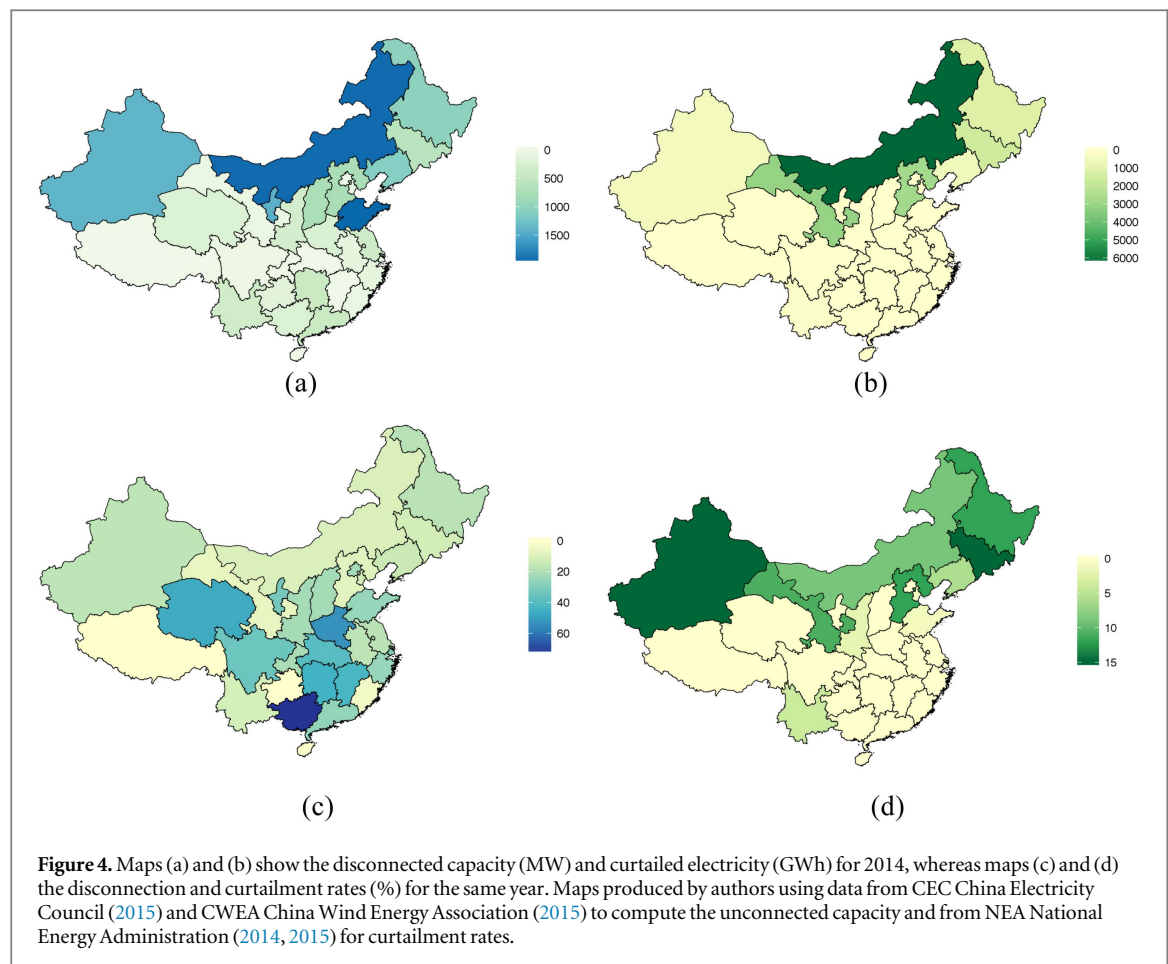
China's installed wind has seen large curtailment rates, in particular in the North and Northeastern regions (see figure 3). According to NEA, the 2013 curtailment rate was greater than 15% in Hebei and Inner Mongolia and around 20% in Jilin and Gansu (NEA National Energy Administration 2014). (In table S5, we show the curtailment for various provinces between 2011 and 2015 in the supplemental information.) Curtailment issues initially occurred in the 'Three North' regions¹⁰, 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⁻¹ (€6.38 cents kWh⁻¹) (NEA National Energy Administration 2015). In fact, with the exception of Inner Mongolia, curtailment rates actually worsened for all concerned provinces between 2011 and 2015.

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

¹⁰ China's 'Three Norths' refers to Hebei, Beijing, Tianjin, Shanxi, Shandong, West Inner Mongolia (North); Heilongjiang, Jilin, Liaoning, East Inner Mongolia (Northeast); Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang (Northwest).



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. Relationship between unconnected capacity and curtailed electricity

Figures 4(a) and (b) 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 (figures 4(c) and (d)). 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

Table 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.

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

Sources: CWEA China Wind Energy Association (2015), UNEP Risoe Center (2015), CREIA China Renewable Energy Industries Association (2012), SERC State Electricity Regulatory Commission (2013), CEC China Electricity Council (2015).

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 curtailment problems persist (tables S5 and S6). As curtailment worsens, the central government turned the focus to other provinces (NEA National Energy Administration 2016a), and these provinces have some of the highest disconnection rates in recent year. In 2015 42% of wind turbines in Guangxi were not connected, compared Qinghai's 47%, Sichuan's 37%, and Hunan's 37%.

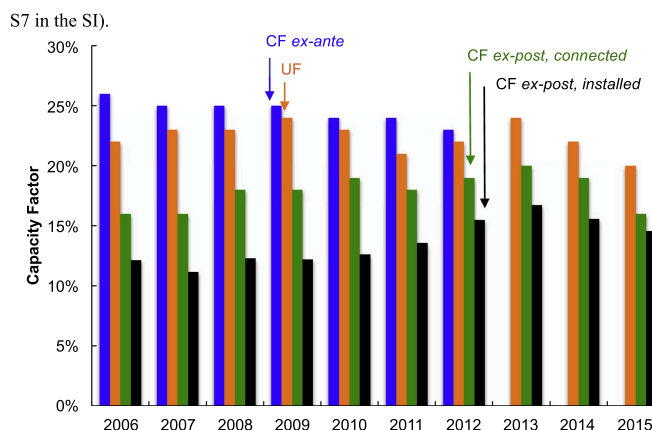


Figure 5. Wind farm's utilization factor (UF) and *ex-ante* and *ex-post* capacity factors (CF) in China. The *ex-post* capacity factors are consistently smaller than the *ex-ante* capacity factors. The difference between CF *ex-ante* and UF is due to unanticipated time that wind turbines stand idle; the difference between UF and CF *ex-post, connected* is primarily due to 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 Risoe Center (2015) and CEC China Electricity Council (2015). The CDM data are only available up to 2012.

We also show in table 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 20.8 TWh of the shortfall in the same year, or 42% of the discrepancy between expected and actual amount of generation.

3.4. Capacity factors

In figure 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 Energy Information Administration 2015a, 2015b), 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 S3 in the SI).

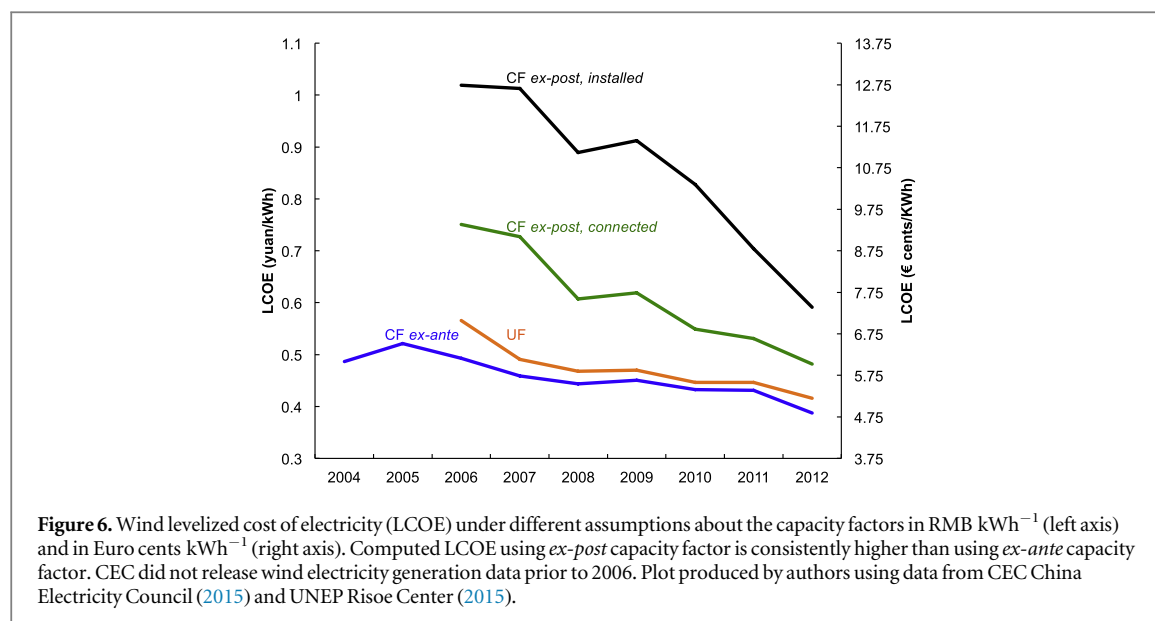
We could alternatively use the CDM project's success rate—ratio of forecasted CERs to issued CERs—to gauge the performance of Chinese wind farms. CDM forecasts the number of carbon credits that a project will earn in its qualified period based on its design parameters, and the number of issued credits 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 S4 in the SI).

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 mitigate wind curtailment problems completely. 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 S7 in the SI).

3.5. Levelized cost of electricity

China's wind capital equipment unit costs fell 26% between 2004 and 2012, from 8.9 m yuan MW^{-1} to 6.6 m yuan MW^{-1} (or €1.1 m–€0.83 m MW^{-1}), and are among the lowest in the world. For comparison, the 2012 US average project cost per unit capacity was approximately \$1.7 m MW^{-1} (Wiser and Bolinger 2013), or 10.71 m yuan MW^{-1} at 6.3 yuan to a dollar exchange rate¹¹. Similarly, the average LCOE during this period

¹¹ The CDM initial investment costs include turbine cost and other related expenses, such as grid connection, civil works, and other miscellaneous items. Wiser and Bolinger's (2013) reported project costs 'reflect turbine purchase and installation, balance of plant, and any substation and/or interconnection expenses' (page 34).



decreased significantly, owing to a sharp reduction in investment costs and a slight increase in capacity factor.

In figure 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⁻¹ in 2006 (or €6.13 cents kWh⁻¹), which decreased to 0.39 yuan kWh⁻¹ (or €4.88 cents kWh⁻¹) 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 *ex-ante* estimate, at around 1.02 yuan kWh⁻¹. As grid connection problems improved, the corresponding LCOE decreased at a fast rate, though at 0.59 yuan kWh⁻¹ (€7.4 cents kWh⁻¹), 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.

3.6. Cost of carbon mitigation

China also made significant inroads in driving down the CCM using wind energy. Using CDM *ex-ante* estimates for capacity factors, we find that mitigation costs range from 151 yuan/tCO₂ in 2004 to 33 yuan/tCO₂ in 2012 (or €18.9–€4.1/tCO₂) for the baseline case (assuming all subcritical plants). Again, results are sensitive to capacity factor assumptions (see figure 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/tCO₂ in 2012 to 618 yuan/tCO₂ in 2006 (or around €25.8–€77.3/tCO₂). 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

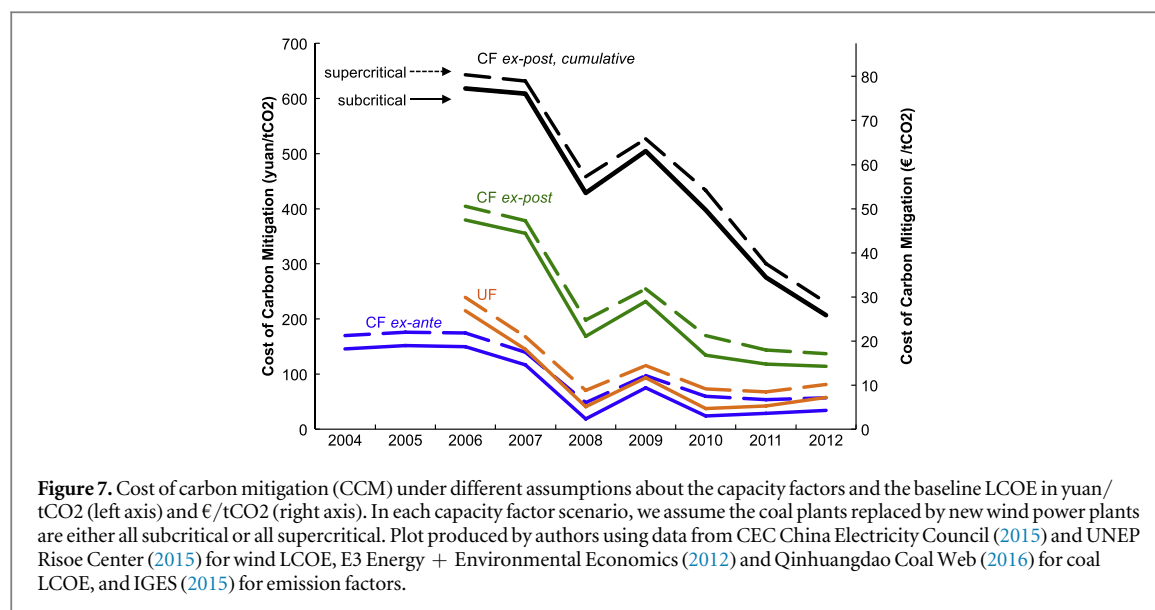
the sharp decrease that followed. We expect the CCM in recent years to be much higher given the recent precipitous drop in coal prices (figure S5). Likewise, the recent lower capacity factors are likely to push up the corresponding CCM.

4. Discussion and conclusions

In this paper we illustrate the scale of connection and curtailment problems of China's wind energy industry across provinces, their affect on China's wind capacity factor, LCOE produced by wind, and the associated CCM. 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 SI (table S6). 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⁻¹, which occurred in 2012 using CDM *ex-ante* capacity factor, 0.12 yuan kWh⁻¹ or 24% higher than the corresponding baseline case. Using the *ex-post* capacity results in a 0.63 yuan kWh⁻¹ LCOE for the same year, 0.24 yuan kWh⁻¹ or 24% 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⁻¹ (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 China Electricity Council 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 CO₂ 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 CO₂ 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 tons of CO₂ would have been avoided—roughly the same amount of CO₂ Connecticut produces (EIA Energy Information Administration 2015a, 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 CO₂. 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 (please see the SI for more information). 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 S2 in the SI). 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 S4 in the SI), 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 S3 in the SI).

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 World Nuclear Association 2016). 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 National Energy Administration 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 (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, Office of the Press Secretary 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 National Energy Administration 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, Office of the Press Secretary 2015). While challenging, such a trading system can significantly reduce China's carbon emissions and boost its utilization of renewable energy if successfully implemented.

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