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Opportunity for Offshore Wind to Reduce Future Demand for Coal-fired Power Plants in China with Consequent Savings in Emissions of CO_2

Xi Lu, [†] **Michael B. McElroy,** [†,‡,*] **Xinyu Chen,** [§] **Chongqing Kang**[§]

†School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, United States

‡Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, United States

§ Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China

Contact Information:

Affiliation: School of Engineering and Applied Sciences and Department of Earth and Planetary Sciences, Harvard University
Address: 100C Peirce Hall, 29 Oxford St., MA 02138
Phone: 617-495-4359
Fax: 617-495-4551
Email: mbm@seas.harvard.edu

Supporting Information

Abstract

Although capacity credits for wind power have been embodied in power systems in the U.S. and Europe, the current planning framework for electricity in China continues to treat wind power as a non-dispatchable source with zero contribution to firm capacity. This study adopts a rigorous reliability model for the electric power system evaluating capacity credits that should be recognized for offshore wind resources supplying power demands for Jiangsu, China. Jiangsu is an economic hub located in the Yangtze River delta accounting for 10% of the total electricity consumed in China. Demand for electricity in Jiangsu is projected to increase from 331 TWh in 2009 to 800 TWh by 2030. Given a wind penetration level of 60% for the future additional Jiangsu power supply, wind resources distributed along the offshore region of five coastal provinces in China (Shandong, Jiangsu, Shanghai, Zhejiang and Fujian) should merit a capacity credit of 12.9%, the fraction of installed wind capacity that should be recognized to displace coal-fired systems without violating the reliability standard. In the high-coal-price scenario, with 60% wind penetration, reductions in CO_2 emissions relative to a business as usual reference could be as large as 200.2 million tons of CO_2 or 51.8% of the potential addition, with a cost for emissions avoided of $29.0 per ton.

Introduction

Driven by fast economic growth and the modernization progress over the past decades, demand for electricity in China increased rapidly from 1.32 PWh in 2000 to 4.69 PWh in 2011, at an average annual rate of over 12% [1, 2]. Coal-fired power systems provided the dominant source for electricity in China. In 2011, approximately 82.5% of China's electricity was generated using coal, with the balance supplied by hydro (14.0%), nuclear (1.9%), and wind (1.6%) [2]. As a result, emissions of CO_2 from China's electric power sector were approximately 4.1 billion tons in 2011, accounting for

45% of the total emissions from the country and 11.5% of total emissions for the world[3]. Demand for electricity in China is projected to increase by 150% by 2030 relative to 2010[4]. If coal-fired power generators continue to dominate China's electricity supply, they may be expected to contribute a significant source of global CO_2 emissions into the indefinite future.

The developed coastal regions (including nine provinces and two municipalities), where China's electric load center is concentrated, were responsible for 53.5% of China's total electricity consumption in 2011[2]. Power generation in coastal provinces of China, as is true for the country at large, is dominated by sources fueled by coal, with percentages ranging from 61% in Guangxi to as high as 99% in Shandong in 2011[5]. To meet the increasing demand for electricity in the coastal region, coal needs to be either transferred from inland provinces in the north and west of China, or imported from Australia and elsewhere[6], reflecting an increasing shortage of domestic coal resources. To harvest the rich onshore wind power, located in the North and West of China, requires significant expansion of the existing transmission grid system on a national scale[7]. As a renewable and convenient energy resource, offshore wind power, we shall argue, can provide an important alternative to coal for supply of electricity to coastal provinces of China with potential for significant savings in CO_2 emissions.

A number of recent studies indicated that China has abundant offshore wind resources for power generation[8-10]. Lu et al. (2009) using 100 m wind data derived from the NASA Goddard Earth Observing System Data Assimilation (GEOS-5) found that a network of 3.6-MW turbines deployed in ocean waters with depths <200 m within 50 nautical miles (92.6 km) of the closest coastline could supply potentially the total current demand for electricity in China[8]. In 2010, an assessment conducted jointly by the Chinese Wind Energy Association (CWEA) and Sun Yat-sen University concluded that the technical potential for offshore wind energy in China within 100 km from shore is about 11.6 PWh, more than twice the nationwide electricity demand[9]. Hong and Moller (2011) analyzing the costs of electricity generated from offshore wind in China suggested that offshore wind energy in China could contribute economically to 56%, 46% and 42% of the coastal region's total electricity demands by 2010, 2020 and 2030, respectively[10].

The present study considers Jiangsu province as a case study exploring opportunities for offshore wind power as a source not only of clean electricity but also of firm capacity, providing an important opportunity to reduce requirements for additional coal-fired systems to meet projected demand for electricity in Jiangsu in 2030. Approximately 10% of the total electricity consumed nationally in China in 2009 was consumed in Jiangsu, an economic hub located in the Yangtze River Delta. In the same year, electric power systems in Jiangsu produced 298 TWh of electricity for 78.7 million consumers [11, 12]. Coal- fired systems contributed 74.4% of the total capacity for electricity generation (59.0 GW) in Jiangsu, with the balance supplied by natural gas (5.2%), nuclear power (2.9%), combined heat and power (CHP, 2.6%), and pumped hydro (1.6%). Jiangsu imports electricity from other inland provinces, especially during the peak summer demand period. In 2009, approximately 10% of the total electricity consumed in Jiangsu (about 32.7 TWh) was imported. Jiangsu was selected for this study for two reasons: first, we have access to electric load data for Jiangsu on an hourly basis, with detailed information on generating units in the existing power system. Second, Jiangsu is leading in exploiting offshore wind resources among other coastal provinces of China. In 2010, some 1.37 GW onshore wind turbines were installed in Jiangsu. Another 3.6 GW of offshore and 1 GW of onshore facilities are planned for deployment during the 12th Five-Year-Plan (FYP) (2011-2015). The official plan sets a target of 7

GW for offshore investments by 2020 with an even larger offshore target of 18 GW over the longer term[13, 14]. The case study for Jiangsu is expected to be of practical importance as an influence on how power system planning should be coordinated with development of offshore wind energy in Jiangsu and other coastal regions in China.

Reflecting the intrinsic variability of wind, real time demand for electricity is often poorly correlated with supply[8, 15-17]. Fluctuations in wind power outputs in China are compensated normally by other generation units (mainly coal-fired systems) deployed to balance the instantaneous demand for electricity[16]. The current planning framework for electric power systems in China continues to treat offshore wind sources as non-dispatchable power. The capacity credit (CC) of wind power, defined by the ratio of firm capacity contributed by wind to its total nameplate capacity, is assigned as zero. In contrast, many power grid regions in the US, such as the PJM Regional Transmission Organization (RTO), New York Independent System Operator (ISO) and New England ISO, have begun to assign CC values to wind facilities[18]. Failure to recognize the potential firm-capacity contribution from wind could lead to unnecessary construction of additional fossil-fuel generating plants in China. A recent study by Lu et al, analyzing the variations of hourly wind power from 12 offshore sites spread along the Chinese coastline, concluded that through an optimal combination of offshore wind facilities distributed over three coastal economic zones (Bohai Bay, the Yangtze River Delta, and the Pearl River Delta), the temporal variability of overall power outputs from offshore wind could be minimized so that as much as 28% of the total wind capacity could be deployed as base load power replacing the requirements on capacity for coal-fired systems[7]. Their analysis, however, did not consider the costs for integration of offshore wind power into the Chinese grid, nor did it consider the costs for resulting savings in CO_2 emissions.

The present analysis is intended to quantify the CC values that could be assigned to offshore wind based on a reliability model for the electric power system, together with the displacement of electricity generated from coal-fired system that could be realized by wind on an hourly basis. The potential electricity generation from offshore wind on an annual basis is assumed to vary from 0% to 60% in terms of its energy values relative to the additional system-wide load demand for Jiangsu between 2009 and 2030. The specific percentage value is referred to hereafter as the penetration level for wind power. Costs for integrating offshore wind power and associated costs for reductions of CO_2 will be quantified for each wind penetration level. As a step forward from the earlier studies[7, 17], this paper investigates also the implications for reductions in CO_2 emissions and associated costs for the future integration of geographically dispersed offshore wind resources into a specific coastal electric power system. The study considers the potential supply of electricity from offshore wind resources distributed over coastal regions for both the study province (Jiangsu/Shanghai) and for neighboring provinces (Shandong, Zhejiang and Fujian).

Data and Methods

The present analysis adopts a reliability model formulation for electric power system to evaluate the multifaceted implications pertaining to the future incorporation of offshore wind into Jiangsu's power system by 2030. Results will be compared with a business as usual (BAU) reference which assumes that all of the increase in demand for electricity between 2009 and 2030 will be met solely by new coal-fired systems with zero contribution from offshore wind. The electricity supply for the additional load in 2030 relative to 2009 in the alternative scenarios will involve a combination of coal-fired systems and offshore wind facilities, allowing the energy penetration levels for offshore wind to vary from 0 to 60%. The power system is required to maintain the same degree of reliability at each wind penetration level as with the BAU reference. We are interested particularly in understanding the capacity values (or capacity credits) that could result from offshore wind power, as well as how electricity generated using coal could be displaced by offshore sources. Building on this, the costs for integrating offshore wind power and associated costs for savings in CO_2 emissions will be quantified as a function of wind penetration level.

Wind data used for this analysis were derived for 2009 from the Goddard Earth Observing System Data Assimilation System (GEOS-5 DAS) by the U.S. National Aeronautics and Space Administration (NASA)[19]. The data include records of wind speeds on an hourly basis with a spatial resolution of 0.33 degree longitude by 0.25 degree latitude (approximately equivalent to 33 km × 25 km at mid-latitude). Wind speeds at 100 m elevation are extrapolated from winds at 50 m and 10 m using a vertical power law profile [7, 20]. The hourly power outputs from offshore wind were computed using the power curve appropriate for GE 3.6 MW wind turbines[21].

Two different regions will be considered with respect to the potential electricity supply from offshore wind resources: Region 1, wind facilities located in the shallow sea regions of Jiangsu and Shanghai only; Region 2, an equal combination of sources from Jiangsu/Shanghai, Zhejiang, Shandong and Fujian. The latter case was selected to take advantage of the smoothing effect on the variation of offshore wind power that can be realized through a combination of power sources from geographically distributed offshore regions [7]. We focus attention on offshore wind resources within shallow, near-shore areas and intertidal zones (specifically, imposing constraints on both water depth, ≤ 30 m, and proximity to the closest shoreline, ≤ 80 km), where offshore wind has been identified as the top priority for exploitation in China. Locations for the offshore wind resources for the two cases considered are indicated in **Figure 1**.

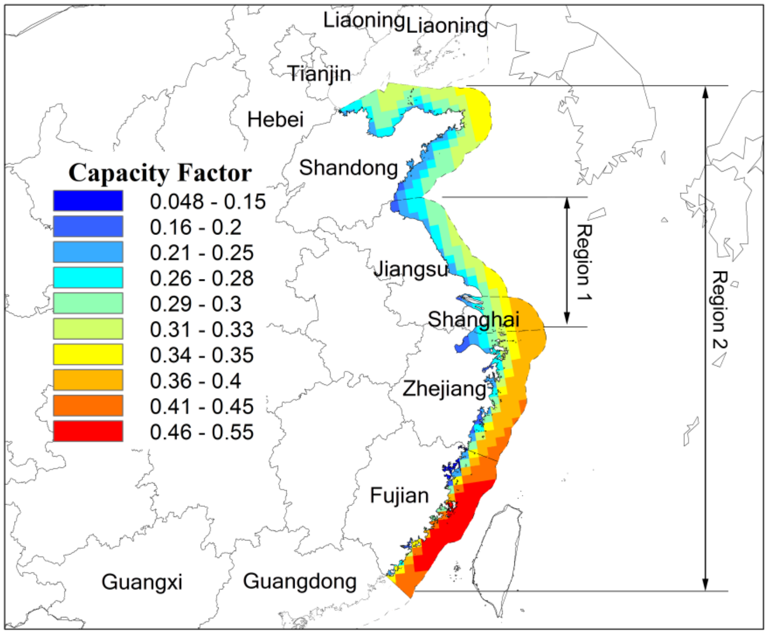

Figure 1. Wind resources for the two offshore regions discussed in the text. Distribution of annual average capacity factors (CFs) evaluated for deployment of a network of GE 3.6MW wind turbines within a distance of 80 km from the shoreline.

Future demand for electricity in Jiangsu province is projected to more than double by 2030 relative to 2009, increasing to 800 TWh in 2030 from 331 TWh in 2009, under the assumption of an annual growth rate of approximately 6.4% between 2009 and 2020, 2% between 2020 and 2030[4]. The variation of the load demand with time in 2030 is assumed to vary in a temporal fashion identical to the pattern that pertained in 2009. A comparison of hourly power outputs from offshore wind for the two cases described with the hourly additional electric load in 2030 relative 2009 is plotted in **Figure 2** for the first weeks of February, May, August and November respectively.

The present study adopts the Loss of Load Probability (LOLP) approach as a measure of the reliability of the Jiangsu power system. This is defined in terms of the number of hours that load is permitted to exceed the available generation capacity over the course of a year. The LOLP for a power system at a given penetration level of wind varies as a function of a number of variables including not only hourly loads and outputs of wind power, but also generation capacity, minimum power output, and the forced outage rate (FOR) for each generating unit in the system[18]. The detailed method for calculating LOLP is described in the Supporting Information (SI). The regulatory paradigm for the power system in China requires a maximum limit for LOLP of 12 hours per year [22]. This criterion for LOLP was adopted in the present study to evaluate the additional capacities of coal-fired systems that would be required in the BAU reference scenario and in all of the alternative scenarios.

To maintain the LOLP below its maximum allowable limit in a power system, the total installed capacity for power generation must exceed the maximum load by a specific margin since individual power generating units can experience mechanical or electrical failures requiring them to be taken out of service (the probability of this situation is measured by the FOR). Given the additional demand for electricity in 2030, the LOLP calculated for the electricity generating capacity for Jiangsu existing in 2009 would necessarily violate the reliability standard (i.e. 12 hours per year) where this system required satisfying demand anticipated for 2030. In the BAU reference, new coal-fired systems are needed to ensure that the power system should meet the LOLP standard in 2030. Each coal-fired unit is assumed to have a capacity of 600 MW with a FOR of 8.5% [23, 24]. Adding one new coal power plant will increase the capacity adequacy of the system, decreasing thus the value of LOLP. Continuing an iterative process with sequential addition of coal-fired units, the total capacities required for new coal-fired systems can be computed to define the point at which the LOLP of the system falls below the maximum limit.

The method for calculating the additional coal capacities required in the BAU reference was applied also to the alternative scenarios reflecting different levels of electricity derived from offshore wind. In this case, the expansion of the coal fired system aims not at meeting additional load in the BAU reference but rather at meeting the net additional load after deduction of the supply from offshore wind. The firm capacity contributed from offshore wind power in each alternative scenario can be estimated based on the corresponding savings in new coal capacities that would be required otherwise in the BAU reference. The values of capacity credits (CC) assigned to offshore wind facilities reflect the fractions of installed wind capacity by which the capacities for coal-fired system can be displaced without compromising the LOLP constraint [25, 26]. The CC values of wind power can be expressed as follows:

$$\text{Capacity Credit} = \frac{\text{Displacement of Thermal Capacities}}{\text{Total Wind Capacities}} \times 100\%,$$

On occasions when the penetration level of offshore wind power is high, the power system may not have flexibility adequate to fully accommodate the potential source from wind. This results in an inevitable curtailment of wind power. In this study, we estimate the curtailments implied for hourly power output of offshore wind systems, considering not only the hourly load and wind power outputs, but also the minimum power outputs required for both existing and newly built coal-fired systems. Coal-fired units in China typically must be operated to maintain power outputs at a level greater than 50% of rated full capacity. Otherwise, plants would be forced to shut down during off-peak periods and to restart in peaking hours, an extremely costly and inefficient option. It takes hours for a coal power plant to fire up from a cold start and return to its normal operational condition. In this analysis, coal-fired systems are assumed to stay online during the night when load is low so that they can ramp up during daytime to meet load as it peaks. Winds tend to be strong during the night, and part of electricity supply from wind power must be curtailed for most cases under such circumstances. The detailed method for estimating curtailments of offshore wind power is described in the SI.

Costs for future generation of electricity using coal-fired systems in Jiangsu depend on a combination of capital investment, Operation and Maintenance (O&M) costs, fuel consumption, and prices for coal. The economic parameters appropriate for coal power plants for both current (Cost A) and future (Cost B) cost scenarios are summarized in Table 1[27, 28]. We assume that the future capital costs and efficiency of coal fired systems are the same in the Cost B scenario as with the Cost A option, assuming that additional pollution control systems in the new power plants that will be required to operate in a more restricted future environmental regulatory environment in China will offset the potential decrease in capital costs and improvement in efficiency resulting from progress reflected in the learning curve. An efficiency of 40% was assumed for new coal-fired systems [29]. The present study is intended to investigate carbon emissions associated with electricity production. CO_2 emission with per kWh of electricity generation using coal was estimated then at 0.83 kg [29, 30]. Zero CO_2 emissions were assigned for wind-generated electricity. The average price of $96.5 per ton of standard coal ($3.5/MMBTU) was selected for the Cost A scenario based on prices that prevailed at all major coal exchange hubs in China in September 2012[31] (nearly twice the concurrent price for coal in the US). The price for coal in China is expected to increase by 45% in the Cost B scenario relative to Cost A [32], reflecting the increasing future demand for coal and the higher costs for mining in suboptimal locations.

There are a number of factors impacting the costs for electricity generated from offshore wind, including the quality of wind resources, wind turbine costs, construction environments (such as distances from shorelines and depths of ocean water) and the cost for managing and maintaining operations, all of which are subject to uncertainty[10, 33]. In 2010, four offshore wind farms successfully completed the first concession bidding process for offshore demonstration projects in China, with a range of bidding prices from 9.7 c/kWh to 11.6 c/kWh in 2013 US dollars[13, 14]. Wind turbine costs are expected to decrease by 15% to 37% in real prices by 2030 reflecting improvements in technology [33]. O&M costs are expected to decrease also benefiting not only from lessons learned from offshore wind farms in China but also from experience in the rest of the world. The analysis assumes that capital costs are $2650/kW for the Cost A scenario, $2000/kW for the Cost B option, with annual O&M costs estimated at 1.5% of the upfront capital cost [34].

Table 1 Cost parameters for the future coal fired systems in Jiangsu Province and for the offshore wind facilities in both regions discussed in the text (in 2013 US dollars)

	Items	Cost A	Cost B
Coal-fired systems	Capital cost ($/kW)	650	650
	Variable O&M cost(c/kWh)	0.46	0.46
	Fixed O&M cost ($/kW)	32	32
	Fuel cost ($/MMBTU)	3.5	5
	Efficiency (%)	40%	40%
	Lifetime (years)	35	35
Offshore Wind Facilities	Capital Cost ($/kW)	2650	2000
	O&M cost ($/kW)	40	30
	Lifetime (years)	20	20

Results

As illustrated in Figure 3, CCs were evaluated for potential offshore wind facilities in Regions 1 and 2 (defined in Section 2) as a function of penetration levels of wind power relative to the additional load demand projected for Jiangsu in 2030. When the contribution from wind power is as low as 1%, CC values for wind power amount to 32.2% in Region 1, 29.6% in Region 2, approximately equal to the average realizable capacity factors (CFs) respectively of 31.1% and 34.3%. The values of CC in both cases decrease with increasing penetration of wind, approaching constant values at large penetrations. At a wind penetration level of 35%, the CC values are 12.3% and 15.9% respectively for the potential offshore wind facilities envisaged in Regions 1 and 2. To put this into context, new wind projects in the power grid overseen by the New York ISO in the U.S. are assigned a summer CC of 10% and a winter CC of 30% [18].

The advantage for wind resources in Region 2 as compared to Region 1 in terms of potential CC values is notable under circumstances where the wind penetration levels are at or above 20%. At a penetration level of 60%, the CC values for wind power are 9.1% in Region 1, 12.9% in Region 2. This implies that for large wind penetrations, approximately 12.9% of the total installed capacities for offshore wind facilities envisaged in Region 2 can be used to displace coal-fired systems. Deploying the same amount of wind, the offshore wind facilities in Region 2 would replace an additional 42.9% of coal-fired capacities as compared to that projected for Region 1. The additional benefits projected at high wind levels for Region 2 relate to the fact that wind resources in this case are harvested from a wide coastal region spreading from north to south (Figure 1), influenced by distinct weather systems[7, 35]. As a result, low power outputs from one offshore wind facility are statistically compensated by high outputs from others within the same region, increasing the minimum production realizable at times of peak load.

It is interesting to note that the CC values realized for wind resources in Region 1 are higher than for Region 2 at wind penetration levels of 5% or less. This arises from the fact that the probability that hourly outputs of wind power in Region 1 are either high or low tends to be greater as compared with the extremes observed for Region 2 (see the SI). With a small fraction of wind power in the electric grid system, the often-occurring low power outputs for wind systems in Region 1 can be compensated by non-wind components of the power system, while the more frequent high power outputs contribute to provide higher potential value for CC. The CC values for individual seasons are presented in the SI.

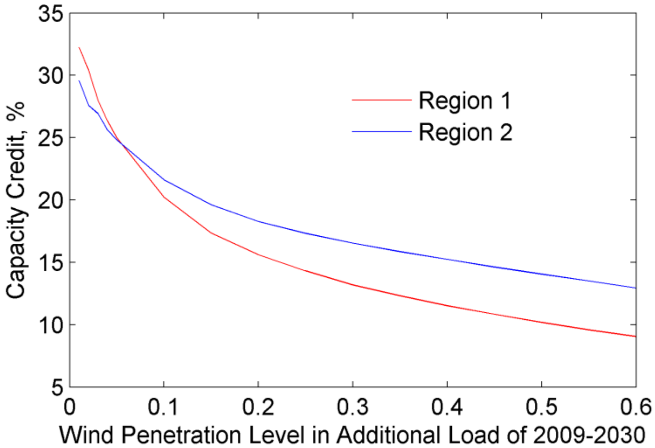

Figure 3. Capacity credits of offshore wind power as a function of its penetration level to additional load of Jiangsu power system in 2030 relative to 2009 for two regions discussed in the text

Figure 4 displays the different electricity mixes projected to meet the additional load demand for Jiangsu in 2030. In the BAU reference, the additional load (470 TWh) in 2030 would be met by coal-fired systems, implying an increase in annual CO_2 emissions of 419 million tons. At a wind penetration level of 60%, offshore wind power from Regions 1 and 2 could supply respectively 45.3% and 51.7% of the additional load. The corresponding savings in emissions of CO_2 are 175.2 million tons for Region 1 and 200.2 million tons for Region 2, accounting respectively for 32.7% and 37.6% of total CO_2 emissions from the entire energy economy of Jiangsu in 2009[30].

Curtailments of wind power were estimated for different wind penetration levels. When the contribution from wind is low, the non-wind components of the power system required to cope with variations in demand for electricity are capable of compensating for slightly greater variations in the residual demand for electricity or net load (defined as the instantaneous system load minus wind power). Under these circumstances, the amount of electricity generated from coal that displaced by offshore wind exhibits a linear relationship as a function of wind penetration levels [36] (Figure 4). With additional wind, the non-wind components of the power system experience increasingly frequent suboptimal operation requiring steeper ramping up or down. Curtailments begin to occur when the wind penetration level reaches a critical value, the curtailment point. As illustrated in Figure 4, the curtailment point is reached at a wind penetration level of 10% for the offshore wind facilities envisaged in Region 1, shifting to the a penetration level of 15% for Region 2.

In the curtailment regime, the reductions in electricity produced using coal vary as a sub-linear function of wind penetration levels. At high penetrations, there are notable advantages for the dispersed offshore wind power available in Region 2 as compared with Region 1. For example, at a wind penetration level of 60%, as much as 68.6 TWh electricity produced from wind would be curtailed in Region 1, approximately 78.4% higher than curtailment estimated for Region 2. The difference is attributed primarily to the fact that wind resources are influenced by distinct weather systems in different locations in Region 2, canceling out to a significant extent variability from individual sources [7]. The resulting overall power output is smoother on an hourly basis in Region 2 as compared to Region 1 (see Figure 1). At a wind penetration of 60%, the percentage of curtailment evaluated for Region 2 is approximately 13.7%, significantly lower than the value estimated for Region 1, 24.5%. To put this in context, the curtailment ratio was close to 16% for existing onshore wind farms in China in 2011, resulting in a financial loss of as much as one billion US dollars [37], while wind-generated electricity accounted of 5.2% of the incremental load between 2007 and 2011.

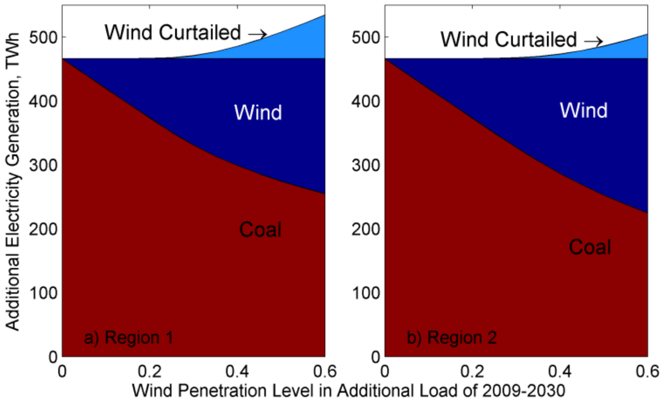

Figure 4. Mix of electricity supply for additional load in Jiangsu province between 2009 and 2030 for wind penetration levels varying from 0% to 60%: a) for wind resources in Region 1 and b) for Region 2.

The breakdown of costs associated with increased electricity generation for the different penetration levels of offshore wind power is illustrated in Figure 5. Costs for upfront investment in both coal-fired systems and offshore wind power facilities were amortized for each year discounted to present values over their lifetimes, assuming a discount rate of 7%[34]. The overall costs for the non-wind BAU references are $20.3 billion and $26.3 billion for the Cost A and Cost B scenarios respectively, the difference reflecting the higher prices for coal assumed in the latter case. With increasing penetrations of electricity from offshore wind, greater contributions of power from coal were replaced by wind. The amortized annual fuel costs for coal-fired systems decline accordingly. There is also a slight downward trend in the upfront investment costs for coal-fired systems reflecting the greater firm capacity, a product of CC values and the corresponding total wind capacities contributed by the offshore wind installations. These savings are more than offset by the costs for upfront investment and O&M needed to develop the offshore wind facilities, resulting in a net increase in overall costs for both regions. The slopes for the Cost A scenario are steeper than for the corresponding cases with the Cost B option reflecting the lower investment costs for offshore wind systems assumed in the latter case.

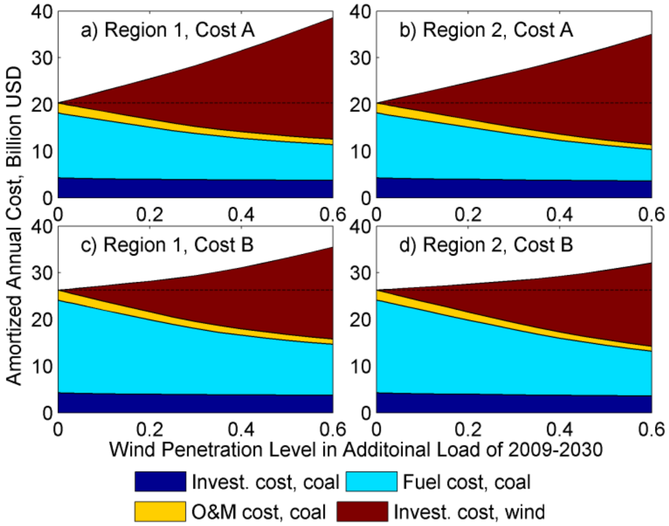

Figure 5. Costs of electricity to meet the additional load of Jiangsu from 2009 to 2030 for penetration levels of wind power from 0% to 60%: a) for Region 1, Cost A scenario; b) for Region 2, Cost A scenario; c) for Region 1, Cost B scenario and d) for Region 2, Cost B scenario.

In both cost scenarios, wind resources in Region 2 are superior to those in Region 1 in terms of costs for the additional electricity supply, especially under high penetration levels. Taking the Cost B scenario as an example, the total costs for Region 2 are $3.2 billion lower than the costs for Region 1 at a wind penetration level of 60%. A number of factors are responsible for the cost differences between Region 1 and Region 2. The average CFs for potential offshore wind facilities are estimated at 31.1% for Region 1 and 34.3% for Region 2, resulting in lower requirements for the capacities of total wind installations in Region 2 compared to Region 1. For a wind penetration level of 60%, the required capacities for wind power are 103.3 GW and 93.8 GW respectively for Regions 1 and 2. Additionally, greater savings in capacities and fuel consumption for the coal-fired systems relative to the BAU reference are realized by tapping wind resources in Region 2 as compared to Region 1, reflecting the higher firm wind capacities and lower curtailments of wind-generated electricity realized in the former case as compared to latter.

At wind penetration levels of 10% or lower, wind-power installations for Region 1 provide more firm capacity as compared with Region 2. The total wind capacity required for Region 1 is higher than for Region 2 at the same penetration level. Combined with the relatively high CC values with the wind resources in Region 1 at low penetration levels (see Figure 3), these factors contribute to greater displacement of coal systems in Region 1. When penetrations for wind power reach 10% or higher, the advantage of greater CC values realized by wind power in Region 2 more than offsets the impact of the larger wind capacities available in Region 1, resulting in enhanced savings in coal-fired power capacities in the former case. As a consequence, in both the Cost A and Cost B scenarios, there is a flipping point at wind penetration level of 10% for the relative overall costs for coal-fired systems between Region 1 and Region 2.

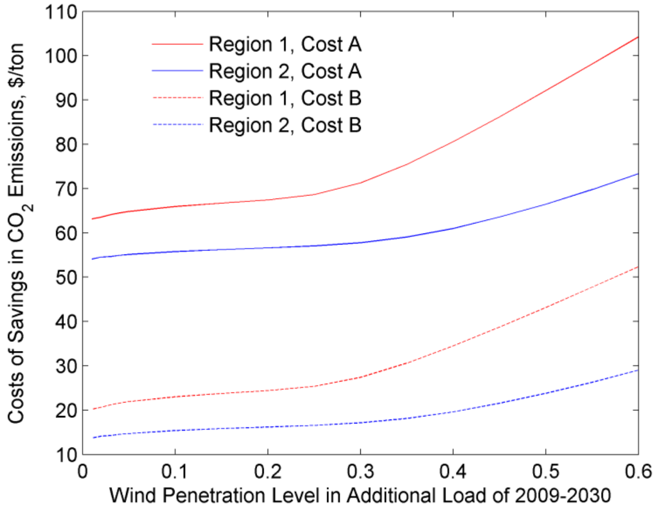

Figure 6. Reduction costs for CO_2 emissions associated with additional electricity supply in 2030 of Jiangsu province as a function of penetration levels of offshore wind power

Costs for reduction of CO_2 emissions associated with integrating offshore wind power into the additional 2030 load for Jiangsu are illustrated in Figure 6. There are clear transition zones in the trends of costs for reductions of CO_2 emissions: at a wind penetration level of 25% for Region 1, at 35% for Region 2. The costs for CO_2 avoided tapping wind resources for the two regions tend to increase slowly in advance of these transition zones, exhibiting rapid subsequent growth. At low penetrations of wind, most of the electricity generated from offshore resources is readily accommodated by the power system. At the same time, the firm capacities provided by these wind systems serve to decrease requirements for investments in new coal systems. The slow growth trends for abatement costs of CO_2 before the transition zones reflect the decreasing values of CC attributed to the offshore wind facilities as increasing supplies of wind power are accommodated. For wind penetration levels beyond the transition zones, a significant portion of offshore wind power must be curtailed, and is thus unavailable to displace electricity from coal and to contribute to reductions in the emissions of CO_2. The marginal reduction costs for emissions of CO_2 attributed to the curtailment of wind power are summarized in the SI.

For the same wind regions, the reduction costs are significantly higher in the Cost A scenario as compared to Cost B. Taking wind resources from Region 2 as an example, the costs for savings in CO_2 emissions in the Cost B scenario vary from $13.7 per ton to $29.0 per ton as wind penetration levels increase from 1% to 60%, while the costs in the Cost A scenario increase from $20.2 per ton to $52.4 per ton over the same range of wind penetrations. The wide difference in costs for avoided CO_2 between the two scenarios reflects mainly the differences in investment costs assumed for offshore wind facilities, together with the different prices assumed for coal.

Under the same cost scenario, a number of factors associated with the offshore wind resources contribute to the differences in costs for avoided CO_2 between the two regions, namely the CF and CC values, and the curtailment ratios for wind power. The gap in reduction costs for CO_2 between Region 1 and Region 2 is relatively narrow in advance of the transition zones, diverging subsequently. In the Cost B scenario, the costs for reduction of CO_2 emissions resulting from exploitation of wind resources in Region 2 are lower than for Region 1 by \$6.5 per ton at a wind penetration level of 5%, \$10.3 per ton at 30%, and up to \$23.4 per ton at 60%. The cost-effectiveness for saving CO_2 emissions in Region 2 is particularly prominent at wind penetration levels beyond the transition zones, reflecting primarily the relatively smaller curtailment and higher CC values realized by tapping wind resources in Region 2 as compared with the less favorable resources available in Region 1.

Should the wind power contemplated in Region 2 be deployed in the Cost B scenario, with 30% wind penetration, reductions in CO_2 relative to the BAU reference could be as large as 115.0 million tons of CO_2 or 29.6% at a cost for abatement of as low as \$17.1 per ton. Even greater reductions, 200.3 million tons of CO_2 or 51.8%, could be realized at a wind penetration level of 60% but at a higher cost, \$29.0 per ton. The results suggest that interlinked offshore wind facilities from five Jiangsu-centered coastal provinces in China could provide a means to abate CO_2 emissions that would be significantly more cost-effective as compared for example with options for carbon capture and sequestrations (CCS), costs for which could range as high as \$260 per ton[38].

It should be pointed out that the existing paradigm for planning the future power system in China assigns zero CC value to wind facilities, which leads to high estimates of costs for abatement of CO_2 emissions using offshore wind power. If the potential for firm capacities contributed by offshore wind facilities is discounted, for example for Region 2 in the Cost B scenario, the costs for avoided CO_2 using offshore wind would be raised by \$5.24 per ton at a penetration level 5% decreasing to \$3.17 per ton at a penetration level of 60% (see the SI).

Discussion

The present analysis adopted a rigorous LOLP-based approach to evaluate the capacity credits that could be realized by recognizing the potential value of offshore wind resources in China. The methodology considered hourly wind power outputs potentially available in two different offshore regions, with detailed information on both existing and new power generating units, and hourly load data for the future electric power system for Jiangsu. The results demonstrate that offshore wind power could provide significant firm capacities that could be used to reduce the need for new coal-fired systems. With wind penetrations as large as 60%, firm capacities for wind power could be as high as 9.3 GW for Region 1, 12.6 GW for Region 2.

Benefits of combining offshore wind resources from an extended offshore region were investigated by comparing the results for Regions 1 and 2 with respect to both the CC values potentially available and implied curtailments of wind-generated electricity. Results for Region 2 suggest higher CC values and lower curtailment ratios especially for high wind penetrations in comparison with Region 1, leading to an enhanced capability of offshore wind facilities for Region 2 reducing requirements for both new capacities and fuel demand for coal-fired systems. The lowest costs for reductions in CO_2 emissions were identified for Region 2 under the Cost B scenario. They range from as low as \$13.7 per ton of CO_2 at a wind penetration level of 1% to \$29.0 per ton of CO_2 at a penetration level of 60%.

The offshore wind resources envisaged for Region 2 were distributed along the coastline feeding into two weakly connected power grid regions: the North China Power Grid including Shandong, and the East China grid covering the other provinces (Jiangsu, Zhejiang and Fujian) and the municipality (Shanghai) in Region 2. To realize the advantage of high CC values and low curtailment of wind power contemplated in Region

2, it will be necessary to strengthen the connection between those two. Despite high capital costs, investments to upgrade the backbone transmission network will be needed eventually to accommodate anticipated future growth in demand for electricity whether this power is supplied by offshore wind or by other possible sources (nuclear for example). China's 2011-2015 12th Five-Year Plan proposes construction of a super grid system using ultra high voltage alternating current (AC) lines integrating the North China, Central China, and Eastern China regional grids[33, 39]. The strategy for offshore developments will involve most likely linking the offshore wind facilities individually to local on-shore transmission systems taking advantage of the anticipated increase in the interconnectivity of the land-based regional grid systems.

The price of coal was assumed to increase by 45% in 2030 under the Cost B scenario relatively to the Cost A situation, contributing to an important difference in costs between these scenarios in terms of avoided CO_2 emissions for both Regions 1 and 2. China switched from the condition as a net exporter to a net importer of coal in 2009[6]. To an increasing extent, future supplies of coal are expected to depend on imports, driving up prices. According to the annual statistical report by BP [40], the ratio of reserves to production for China's coal is approximately 33 years. If production of coal in China were to grow at an annual rate of 3.5% as projected by BP for the 2010-2020 time periods [40], the analysis would suggest that China could run out of domestic supplies of coal by as early as 2032. Offshore wind resources – domestically available in close proximity to the developed coastal regions – provide not only an economically viable means to reduce consumption of coal with consequent reduction in emissions of CO_2, they can make an important contribution also to the challenge China faces in terms of its national energy security.

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Supporting Information Available

Full description of the methodology to estimate the LOLP, the requirements on reserves, and curtailment of wind power, as well as the results for capacity credits of wind power on a seasonal basis, the generation duration curve of wind power, reduction of CO_2 emissions due to the capacity credit of wind power, and the additional reduction costs for emissions of CO_2 caused by wind curtailments. This information is available free of charge via the Internet at http://pubs.acs.org/ .

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