



Opportunity for Offshore Wind to Reduce Future Demand for Coal-Fired Power Plants in China with Consequent Savings in Emissions of CO₂

Citation

Lu, Xi, Michael B. McElroy, Xinyu Chen, and Chongqing Kang. 2014. "Opportunity for Offshore Wind to Reduce Future Demand for Coal-Fired Power Plants in China with Consequent Savings in Emissions of CO₂." *Environ. Sci. Technol.* 48 (24) (December 16): 14764–14771. doi:10.1021/es503767x.

Published Version

doi:10.1021/es503767x

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:22560578>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Open Access Policy Articles, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP>

Share Your Story

The Harvard community has made this article openly available.
Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

Opportunity for Offshore Wind to Reduce Future Demand for Coal-fired Power Plants in China with Consequent Savings in Emissions of CO₂

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

1 **Abstract**

2 Although capacity credits for wind power have been embodied in power systems
3 in the U.S. and Europe, the current planning framework for electricity in China continues
4 to treat wind power as a non-dispatchable source with zero contribution to firm capacity.
5 This study adopts a rigorous reliability model for the electric power system evaluating
6 capacity credits that should be recognized for offshore wind resources supplying power
7 demands for Jiangsu, China. Jiangsu is an economic hub located in the Yangtze River
8 delta accounting for 10% of the total electricity consumed in China. Demand for
9 electricity in Jiangsu is projected to increase from 331 TWh in 2009 to 800 TWh by 2030.
10 Given a wind penetration level of 60% for the future additional Jiangsu power supply,
11 wind resources distributed along the offshore region of five coastal provinces in China
12 (Shandong, Jiangsu, Shanghai, Zhejiang and Fujian) should merit a capacity credit of
13 12.9%, the fraction of installed wind capacity that should be recognized to displace coal-
14 fired systems without violating the reliability standard. In the high-coal-price scenario,
15 with 60% wind penetration, reductions in CO₂ emissions relative to a business as usual
16 reference could be as large as 200.2 million tons of CO₂ or 51.8% of the potential
17 addition, with a cost for emissions avoided of \$29.0 per ton.

18 **Introduction**

19 Driven by fast economic growth and the modernization progress over the past
20 decades, demand for electricity in China increased rapidly from 1.32 PWh in 2000 to
21 4.69 PWh in 2011, at an average annual rate of over 12% [1, 2]. Coal-fired power
22 systems provided the dominant source for electricity in China. In 2011, approximately
23 82.5% of China's electricity was generated using coal, with the balance supplied by
24 hydro (14.0%), nuclear (1.9%), and wind (1.6%) [2]. As a result, emissions of CO₂ from
25 China's electric power sector were approximately 4.1 billion tons in 2011, accounting for

26 45% of the total emissions from the country and 11.5% of total emissions for the world[3].
27 Demand for electricity in China is projected to increase by 150% by 2030 relative to
28 2010[4]. If coal-fired power generators continue to dominate China's electricity supply,
29 they may be expected to contribute a significant source of global CO₂ emissions into the
30 indefinite future.

31 The developed coastal regions (including nine provinces and two municipalities),
32 where China's electric load center is concentrated, were responsible for 53.5% of
33 China's total electricity consumption in 2011[2]. Power generation in coastal provinces of
34 China, as is true for the country at large, is dominated by sources fueled by coal, with
35 percentages ranging from 61% in Guangxi to as high as 99% in Shandong in 2011[5].
36 To meet the increasing demand for electricity in the coastal region, coal needs to be
37 either transferred from inland provinces in the north and west of China, or imported from
38 Australia and elsewhere[6], reflecting an increasing shortage of domestic coal resources.
39 To harvest the rich onshore wind power, located in the North and West of China,
40 requires significant expansion of the existing transmission grid system on a national
41 scale[7]. As a renewable and convenient energy resource, offshore wind power, we
42 shall argue, can provide an important alternative to coal for supply of electricity to
43 coastal provinces of China with potential for significant savings in CO₂ emissions.

44 A number of recent studies indicated that China has abundant offshore wind
45 resources for power generation[8-10]. Lu et al. (2009) using 100 m wind data derived
46 from the NASA Goddard Earth Observing System Data Assimilation (GEOS-5) found
47 that a network of 3.6-MW turbines deployed in ocean waters with depths <200 m within
48 50 nautical miles (92.6 km) of the closest coastline could supply potentially the total
49 current demand for electricity in China[8]. In 2010, an assessment conducted jointly by
50 the Chinese Wind Energy Association (CWEA) and Sun Yat-sen University concluded

51 that the technical potential for offshore wind energy in China within 100 km from shore is
52 about 11.6 PWh, more than twice the nationwide electricity demand[9]. Hong and Moller
53 (2011) analyzing the costs of electricity generated from offshore wind in China
54 suggested that offshore wind energy in China could contribute economically to 56%,
55 46% and 42% of the coastal region's total electricity demands by 2010, 2020 and 2030,
56 respectively[10].

57 The present study considers Jiangsu province as a case study exploring
58 opportunities for offshore wind power as a source not only of clean electricity but also of
59 firm capacity, providing an important opportunity to reduce requirements for additional
60 coal-fired systems to meet projected demand for electricity in Jiangsu in 2030.
61 Approximately 10% of the total electricity consumed nationally in China in 2009 was
62 consumed in Jiangsu, an economic hub located in the Yangtze River Delta. In the same
63 year, electric power systems in Jiangsu produced 298 TWh of electricity for 78.7 million
64 consumers [11, 12]. Coal- fired systems contributed 74.4% of the total capacity for
65 electricity generation (59.0 GW) in Jiangsu, with the balance supplied by natural gas
66 (5.2%), nuclear power (2.9%), combined heat and power (CHP, 2.6%), and pumped
67 hydro (1.6%). Jiangsu imports electricity from other inland provinces, especially during
68 the peak summer demand period. In 2009, approximately 10% of the total electricity
69 consumed in Jiangsu (about 32.7 TWh) was imported. Jiangsu was selected for this
70 study for two reasons: first, we have access to electric load data for Jiangsu on an hourly
71 basis, with detailed information on generating units in the existing power system. Second,
72 Jiangsu is leading in exploiting offshore wind resources among other coastal provinces
73 of China. In 2010, some 1.37 GW onshore wind turbines were installed in Jiangsu.
74 Another 3.6 GW of offshore and 1 GW of onshore facilities are planned for deployment
75 during the 12th Five-Year-Plan (FYP) (2011-2015). The official plan sets a target of 7

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

80 Reflecting the intrinsic variability of wind, real time demand for electricity is often
81 poorly correlated with supply[8, 15-17]. Fluctuations in wind power outputs in China are
82 compensated normally by other generation units (mainly coal-fired systems) deployed to
83 balance the instantaneous demand for electricity[16]. The current planning framework for
84 electric power systems in China continues to treat offshore wind sources as non-
85 dispatchable power. The capacity credit (CC) of wind power, defined by the ratio of firm
86 capacity contributed by wind to its total nameplate capacity, is assigned as zero. In
87 contrast, many power grid regions in the US, such as the PJM Regional Transmission
88 Organization (RTO), New York Independent System Operator (ISO) and New England
89 ISO, have begun to assign CC values to wind facilities[18]. Failure to recognize the
90 potential firm-capacity contribution from wind could lead to unnecessary construction of
91 additional fossil-fuel generating plants in China. A recent study by Lu et al, analyzing the
92 variations of hourly wind power from 12 offshore sites spread along the Chinese
93 coastline, concluded that through an optimal combination of offshore wind facilities
94 distributed over three coastal economic zones (Bohai Bay, the Yangtze River Delta, and
95 the Pearl River Delta), the temporal variability of overall power outputs from offshore
96 wind could be minimized so that as much as 28% of the total wind capacity could be
97 deployed as base load power replacing the requirements on capacity for coal-fired
98 systems[7]. Their analysis, however, did not consider the costs for integration of offshore
99 wind power into the Chinese grid, nor did it consider the costs for resulting savings in
100 CO₂ emissions.

101 The present analysis is intended to quantify the CC values that could be
102 assigned to offshore wind based on a reliability model for the electric power system,
103 together with the displacement of electricity generated from coal-fired system that could
104 be realized by wind on an hourly basis. The potential electricity generation from offshore
105 wind on an annual basis is assumed to vary from 0% to 60% in terms of its energy
106 values relative to the additional system-wide load demand for Jiangsu between 2009
107 and 2030. The specific percentage value is referred to hereafter as the penetration level
108 for wind power. Costs for integrating offshore wind power and associated costs for
109 reductions of CO₂ will be quantified for each wind penetration level. As a step forward
110 from the earlier studies[7, 17], this paper investigates also the implications for reductions
111 in CO₂ emissions and associated costs for the future integration of geographically
112 dispersed offshore wind resources into a specific coastal electric power system. The
113 study considers the potential supply of electricity from offshore wind resources
114 distributed over coastal regions for both the study province (Jiangsu/Shanghai) and for
115 neighboring provinces (Shandong, Zhejiang and Fujian).

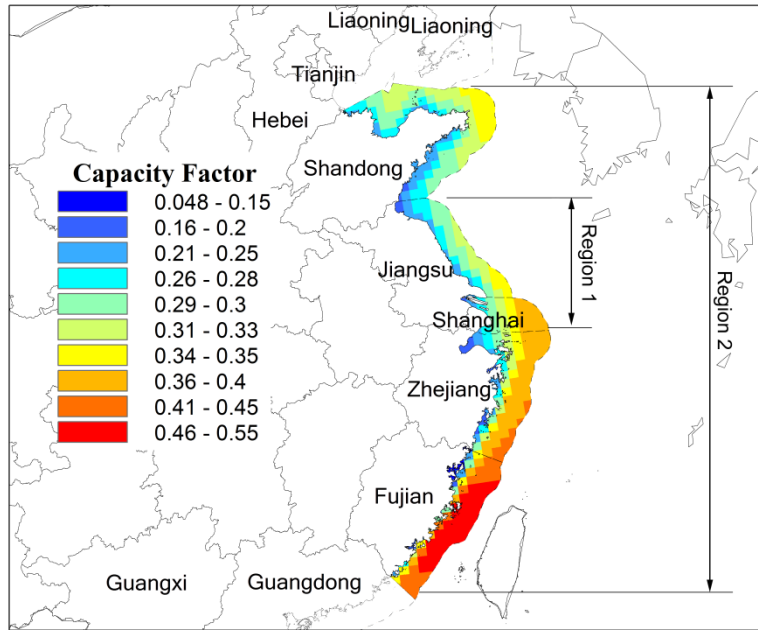
116 **Data and Methods**

117 The present analysis adopts a reliability model formulation for electric power
118 system to evaluate the multifaceted implications pertaining to the future incorporation of
119 offshore wind into Jiangsu's power system by 2030. Results will be compared with a
120 business as usual (BAU) reference which assumes that all of the increase in demand for
121 electricity between 2009 and 2030 will be met solely by new coal-fired systems with zero
122 contribution from offshore wind. The electricity supply for the additional load in 2030
123 relative to 2009 in the alternative scenarios will involve a combination of coal-fired
124 systems and offshore wind facilities, allowing the energy penetration levels for offshore
125 wind to vary from 0 to 60%. The power system is required to maintain the same degree
126 of reliability at each wind penetration level as with the BAU reference. We are interested

127 particularly in understanding the capacity values (or capacity credits) that could result
128 from offshore wind power, as well as how electricity generated using coal could be
129 displaced by offshore sources. Building on this, the costs for integrating offshore wind
130 power and associated costs for savings in CO₂ emissions will be quantified as a function
131 of wind penetration level.

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

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



151
 152 Figure 1. Wind resources for the two offshore regions discussed in the text. Distribution
 153 of annual average capacity factors (CFs) evaluated for deployment of a network of GE
 154 3.6MW wind turbines within a distance of 80 km from the shoreline.

155 Future demand for electricity in Jiangsu province is projected to more than
 156 double by 2030 relative to 2009, increasing to 800 TWh in 2030 from 331 TWh in 2009,
 157 under the assumption of an annual growth rate of approximately 6.4% between 2009
 158 and 2020, 2% between 2020 and 2030[4]. The variation of the load demand with time in
 159 2030 is assumed to vary in a temporal fashion identical to the pattern that pertained in
 160 2009. A comparison of hourly power outputs from offshore wind for the two cases
 161 described with the hourly additional electric load in 2030 relative 2009 is plotted in
 162 **Figure 2** for the first weeks of February, May, August and November respectively.

163 The present study adopts the Loss of Load Probability (LOLP) approach as a
 164 measure of the reliability of the Jiangsu power system. This is defined in terms of the
 165 number of hours that load is permitted to exceed the available generation capacity over
 166 the course of a year. The LOLP for a power system at a given penetration level of wind
 167 varies as a function of a number of variables including not only hourly loads and outputs
 168 of wind power, but also generation capacity, minimum power output, and the forced

169 outage rate (FOR) for each generating unit in the system[18]. The detailed method for
170 calculating LOLP is described in the Supporting Information (SI). The regulatory
171 paradigm for the power system in China requires a maximum limit for LOLP of 12 hours
172 per year [22]. This criterion for LOLP was adopted in the present study to evaluate the
173 additional capacities of coal-fired systems that would be required in the BAU reference
174 scenario and in all of the alternative scenarios.

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

190 The method for calculating the additional coal capacities required in the BAU
191 reference was applied also to the alternative scenarios reflecting different levels of
192 electricity derived from offshore wind. In this case, the expansion of the coal fired system
193 aims not at meeting additional load in the BAU reference but rather at meeting the net

194 additional load after deduction of the supply from offshore wind. The firm capacity
195 contributed from offshore wind power in each alternative scenario can be estimated
196 based on the corresponding savings in new coal capacities that would be required
197 otherwise in the BAU reference. The values of capacity credits (CC) assigned to offshore
198 wind facilities reflect the fractions of installed wind capacity by which the capacities for
199 coal-fired system can be displaced without compromising the LOLP constraint [25, 26].
200 The CC values of wind power can be expressed as follows:

$$201 \quad \text{Capacity Credit} = \frac{\text{Displacement of Thermal Capacities}}{\text{Total Wind Capacities}} \times 100\%,$$

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

217 Costs for future generation of electricity using coal-fired systems in Jiangsu
218 depend on a combination of capital investment, Operation and Maintenance (O&M)
219 costs, fuel consumption, and prices for coal. The economic parameters appropriate for
220 coal power plants for both current (Cost A) and future (Cost B) cost scenarios are
221 summarized in Table 1[27, 28]. We assume that the future capital costs and efficiency of
222 coal fired systems are the same in the Cost B scenario as with the Cost A option,
223 assuming that additional pollution control systems in the new power plants that will be
224 required to operate in a more restricted future environmental regulatory environment in
225 China will offset the potential decrease in capital costs and improvement in efficiency
226 resulting from progress reflected in the learning curve. An efficiency of 40% was
227 assumed for new coal-fired systems [29]. The present study is intended to investigate
228 carbon emissions associated with electricity production. CO₂ emission with per kWh of
229 electricity generation using coal was estimated then at 0.83 kg [29, 30]. Zero CO₂
230 emissions were assigned for wind-generated electricity. The average price of \$96.5 per
231 ton of standard coal (\$3.5/MMBTU) was selected for the Cost A scenario based on
232 prices that prevailed at all major coal exchange hubs in China in September 2012[31]
233 (nearly twice the concurrent price for coal in the US). The price for coal in China is
234 expected to increase by 45% in the Cost B scenario relative to Cost A [32], reflecting the
235 increasing future demand for coal and the higher costs for mining in suboptimal locations.

236 There are a number of factors impacting the costs for electricity generated from
237 offshore wind, including the quality of wind resources, wind turbine costs, construction
238 environments (such as distances from shorelines and depths of ocean water) and the
239 cost for managing and maintaining operations, all of which are subject to uncertainty[10,
240 33]. In 2010, four offshore wind farms successfully completed the first concession
241 bidding process for offshore demonstration projects in China, with a range of bidding

242 prices from 9.7 c/kWh to 11.6 c/kWh in 2013 US dollars[13, 14]. Wind turbine costs are
 243 expected to decrease by 15% to 37% in real prices by 2030 reflecting improvements in
 244 technology [33]. O&M costs are expected to decrease also benefiting not only from
 245 lessons learned from offshore wind farms in China but also from experience in the rest of
 246 the world. The analysis assumes that capital costs are \$2650/kW for the Cost A
 247 scenario, \$2000/kW for the Cost B option, with annual O&M costs estimated at 1.5% of
 248 the upfront capital cost [34].

249 **Table 1** Cost parameters for the future coal fired systems in Jiangsu Province and for
 250 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 |

251

252 **Results**

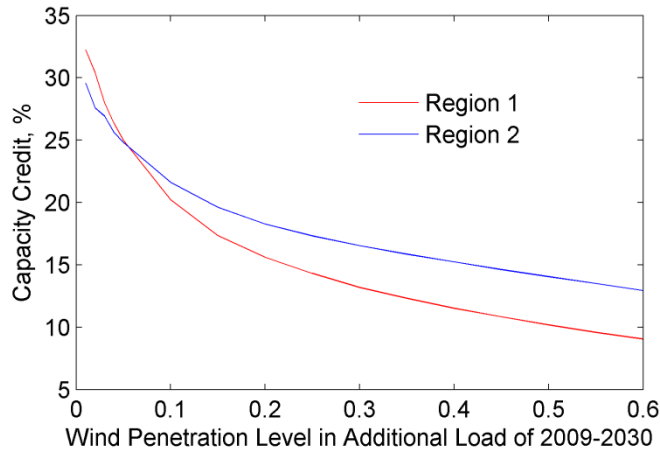
253 As illustrated in Figure 3, CCs were evaluated for potential offshore wind facilities
 254 in Regions 1 and 2 (defined in Section 2) as a function of penetration levels of wind
 255 power relative to the additional load demand projected for Jiangsu in 2030. When the
 256 contribution from wind power is as low as 1%, CC values for wind power amount to
 257 32.2% in Region 1, 29.6% in Region 2, approximately equal to the average realizable
 258 capacity factors (CFs) respectively of 31.1% and 34.3%. The values of CC in both cases

259 decrease with increasing penetration of wind, approaching constant values at large
260 penetrations. At a wind penetration level of 35%, the CC values are 12.3% and 15.9%
261 respectively for the potential offshore wind facilities envisaged in Regions 1 and 2. To
262 put this into context, new wind projects in the power grid overseen by the New York ISO
263 in the U.S. are assigned a summer CC of 10% and a winter CC of 30% [18].

264 The advantage for wind resources in Region 2 as compared to Region 1 in terms
265 of potential CC values is notable under circumstances where the wind penetration levels
266 are at or above 20%. At a penetration level of 60%, the CC values for wind power are
267 9.1% in Region 1, 12.9% in Region 2. This implies that for large wind penetrations,
268 approximately 12.9% of the total installed capacities for offshore wind facilities
269 envisaged in Region 2 can be used to displace coal-fired systems. Deploying the same
270 amount of wind, the offshore wind facilities in Region 2 would replace an additional
271 42.9% of coal-fired capacities as compared to that projected for Region 1. The additional
272 benefits projected at high wind levels for Region 2 relate to the fact that wind resources
273 in this case are harvested from a wide coastal region spreading from north to south
274 (Figure 1), influenced by distinct weather systems[7, 35]. As a result, low power outputs
275 from one offshore wind facility are statistically compensated by high outputs from others
276 within the same region, increasing the minimum production realizable at times of peak
277 load.

278 It is interesting to note that the CC values realized for wind resources in Region 1
279 are higher than for Region 2 at wind penetration levels of 5% or less. This arises from
280 the fact that the probability that hourly outputs of wind power in Region 1 are either high
281 or low tends to be greater as compared with the extremes observed for Region 2 (see
282 the SI). With a small fraction of wind power in the electric grid system, the often-
283 occurring low power outputs for wind systems in Region 1 can be compensated by non-

284 wind components of the power system, while the more frequent high power outputs
285 contribute to provide higher potential value for CC. The CC values for individual seasons
286 are presented in the SI.



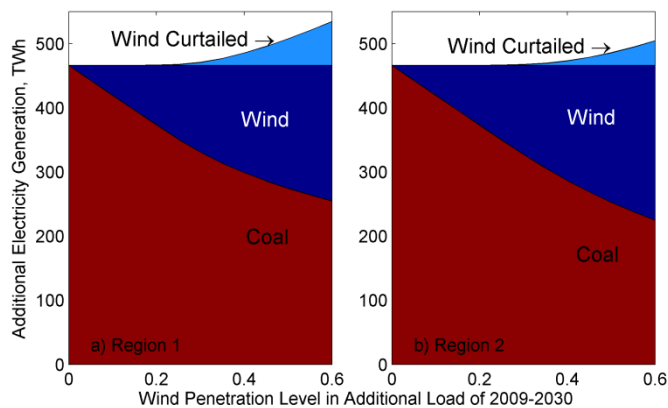
287 **Figure 3.** Capacity credits of offshore wind power as a function of its penetration level to
288 additional load of Jiangsu power system in 2030 relative to 2009 for two regions
289 discussed in the text
290

291 Figure 4 displays the different electricity mixes projected to meet the additional load
292 demand for Jiangsu in 2030. In the BAU reference, the additional load (470 TWh) in
293 2030 would be met by coal-fired systems, implying an increase in annual CO₂ emissions
294 of 419 million tons. At a wind penetration level of 60%, offshore wind power from
295 Regions 1 and 2 could supply respectively 45.3% and 51.7% of the additional load. The
296 corresponding savings in emissions of CO₂ are 175.2 million tons for Region 1 and 200.2
297 million tons for Region 2, accounting respectively for 32.7% and 37.6% of total CO₂
298 emissions from the entire energy economy of Jiangsu in 2009[30].

299 Curtailments of wind power were estimated for different wind penetration levels.
300 When the contribution from wind is low, the non-wind components of the power system
301 required to cope with variations in demand for electricity are capable of compensating for
302 slightly greater variations in the residual demand for electricity or net load (defined as the
303 instantaneous system load minus wind power). Under these circumstances, the amount

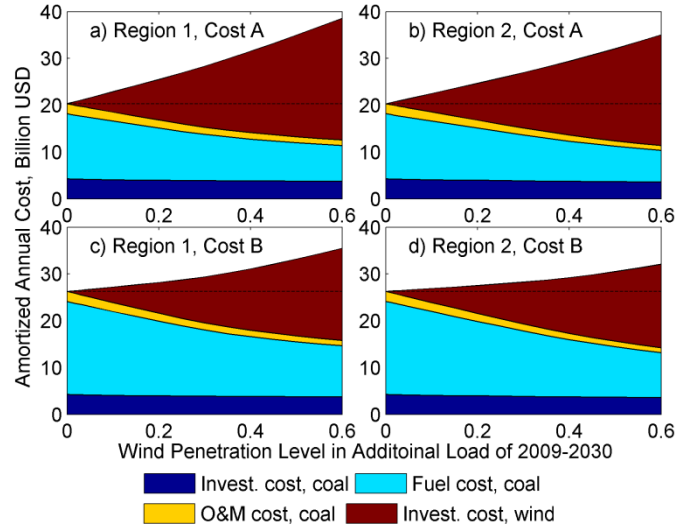
304 of electricity generated from coal that displaced by offshore wind exhibits a linear
305 relationship as a function of wind penetration levels [36] (Figure 4). With additional wind,
306 the non-wind components of the power system experience increasingly frequent
307 suboptimal operation requiring steeper ramping up or down. Curtailments begin to occur
308 when the wind penetration level reaches a critical value, the curtailment point. As
309 illustrated in Figure 4, the curtailment point is reached at a wind penetration level of 10%
310 for the offshore wind facilities envisaged in Region 1, shifting to the a penetration level of
311 15% for Region 2.

312 In the curtailment regime, the reductions in electricity produced using coal vary as a
313 sub-linear function of wind penetration levels. At high penetrations, there are notable
314 advantages for the dispersed offshore wind power available in Region 2 as compared
315 with Region 1. For example, at a wind penetration level of 60%, as much as 68.6 TWh
316 electricity produced from wind would be curtailed in Region 1, approximately 78.4%
317 higher than curtailment estimated for Region 2. The difference is attributed primarily to
318 the fact that wind resources are influenced by distinct weather systems in different
319 locations in Region 2, canceling out to a significant extent variability from individual
320 sources [7]. The resulting overall power output is smoother on an hourly basis in Region
321 2 as compared to Region 1 (see Figure 1). At a wind penetration of 60%, the percentage
322 of curtailment evaluated for Region 2 is approximately 13.7%, significantly lower than the
323 value estimated for Region 1, 24.5%. To put this in context, the curtailment ratio was
324 close to 16% for existing onshore wind farms in China in 2011, resulting in a financial
325 loss of as much as one billion US dollars [37], while wind-generated electricity accounted
326 of 5.2% of the incremental load between 2007 and 2011.



327
 328 **Figure 4.** Mix of electricity supply for additional load in Jiangsu province between 2009
 329 and 2030 for wind penetration levels varying from 0% to 60%: a) for wind resources in
 330 Region 1 and b) for Region 2.

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



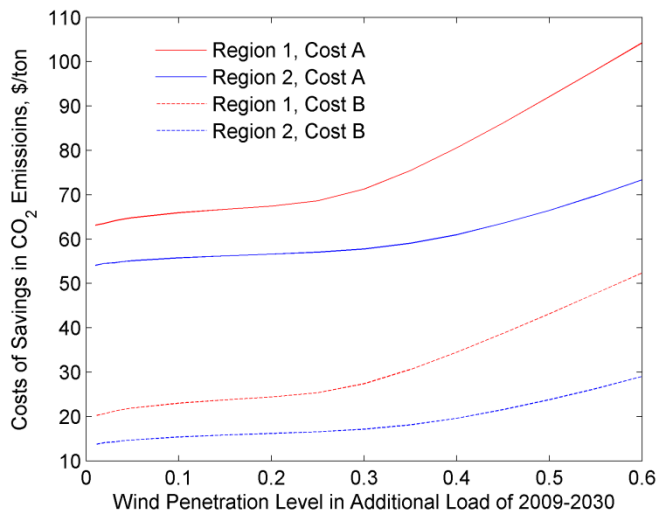
348
 349
 350
 351
 352

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.

353
 354
 355
 356
 357
 358
 359
 360
 361
 362
 363
 364
 365
 366

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.

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



378 **Figure 6.** Reduction costs for CO₂ emissions associated with additional electricity
 379 supply in 2030 of Jiangsu province as a function of penetration levels of offshore
 380 wind power
 381

382 Costs for reduction of CO₂ emissions associated with integrating offshore wind
 383 power into the additional 2030 load for Jiangsu are illustrated in Figure 6. There are
 384 clear transition zones in the trends of costs for reductions of CO₂ emissions: at a wind
 385 penetration level of 25% for Region 1, at 35% for Region 2. The costs for CO₂ avoided

386 tapping wind resources for the two regions tend to increase slowly in advance of these
387 transition zones, exhibiting rapid subsequent growth. At low penetrations of wind, most
388 of the electricity generated from offshore resources is readily accommodated by the
389 power system. At the same time, the firm capacities provided by these wind systems
390 serve to decrease requirements for investments in new coal systems. The slow growth
391 trends for abatement costs of CO₂ before the transition zones reflect the decreasing
392 values of CC attributed to the offshore wind facilities as increasing supplies of wind
393 power are accommodated. For wind penetration levels beyond the transition zones, a
394 significant portion of offshore wind power must be curtailed, and is thus unavailable to
395 displace electricity from coal and to contribute to reductions in the emissions of CO₂.
396 The marginal reduction costs for emissions of CO₂ attributed to the curtailment of wind
397 power are summarized in the SI.

398 For the same wind regions, the reduction costs are significantly higher in the Cost A
399 scenario as compared to Cost B. Taking wind resources from Region 2 as an example,
400 the costs for savings in CO₂ emissions in the Cost B scenario vary from \$13.7 per ton to
401 \$29.0 per ton as wind penetration levels increase from 1% to 60%, while the costs in the
402 Cost A scenario increase from \$20.2 per ton to \$52.4 per ton over the same range of
403 wind penetrations. The wide difference in costs for avoided CO₂ between the two
404 scenarios reflects mainly the differences in investment costs assumed for offshore wind
405 facilities, together with the different prices assumed for coal.

406 Under the same cost scenario, a number of factors associated with the offshore
407 wind resources contribute to the differences in costs for avoided CO₂ between the two
408 regions, namely the CF and CC values, and the curtailment ratios for wind power. The
409 gap in reduction costs for CO₂ between Region 1 and Region 2 is relatively narrow in
410 advance of the transition zones, diverging subsequently. In the Cost B scenario, the

411 costs for reduction of CO₂ emissions resulting from exploitation of wind resources in
412 Region 2 are lower than for Region 1 by \$6.5 per ton at a wind penetration level of 5%,
413 \$10.3 per ton at 30%, and up to \$23.4 per ton at 60%. The cost-effectiveness for saving
414 CO₂ emissions in Region 2 is particularly prominent at wind penetration levels beyond
415 the transition zones, reflecting primarily the relatively smaller curtailment and higher CC
416 values realized by tapping wind resources in Region 2 as compared with the less
417 favorable resources available in Region 1.

418 Should the wind power contemplated in Region 2 be deployed in the Cost B
419 scenario, with 30% wind penetration, reductions in CO₂ relative to the BAU reference
420 could be as large as 115.0 million tons of CO₂ or 29.6% at a cost for abatement of as low
421 as \$17.1 per ton. Even greater reductions, 200.3 million tons of CO₂ or 51.8%, could be
422 realized at a wind penetration level of 60% but at a higher cost, \$29.0 per ton. The
423 results suggest that interlinked offshore wind facilities from five Jiangsu-centered coastal
424 provinces in China could provide a means to abate CO₂ emissions that would be
425 significantly more cost-effective as compared for example with options for carbon
426 capture and sequestrations (CCS), costs for which could range as high as \$260 per
427 ton[38].

428 It should be pointed out that the existing paradigm for planning the future power
429 system in China assigns zero CC value to wind facilities, which leads to high estimates
430 of costs for abatement of CO₂ emissions using offshore wind power. If the potential for
431 firm capacities contributed by offshore wind facilities is discounted, for example for
432 Region 2 in the Cost B scenario, the costs for avoided CO₂ using offshore wind would be
433 raised by \$5.24 per ton at a penetration level 5% decreasing to \$3.17 per ton at a
434 penetration level of 60% (see the SI).

435 **Discussion**

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

445 Benefits of combining offshore wind resources from an extended offshore region
446 were investigated by comparing the results for Regions 1 and 2 with respect to both the
447 CC values potentially available and implied curtailments of wind-generated electricity.
448 Results for Region 2 suggest higher CC values and lower curtailment ratios especially
449 for high wind penetrations in comparison with Region 1, leading to an enhanced
450 capability of offshore wind facilities for Region 2 reducing requirements for both new
451 capacities and fuel demand for coal-fired systems. The lowest costs for reductions in
452 CO₂ emissions were identified for Region 2 under the Cost B scenario. They range from
453 as low as \$13.7 per ton of CO₂ at a wind penetration level of 1% to \$29.0 per ton of CO₂
454 at a penetration level of 60%.

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

460 2, it will be necessary to strengthen the connection between those two. Despite high
461 capital costs, investments to upgrade the backbone transmission network will be needed
462 eventually to accommodate anticipated future growth in demand for electricity whether this
463 power is supplied by offshore wind or by other possible sources (nuclear for example). China's
464 2011-2015 12th Five-Year Plan proposes construction of a super grid system using ultra
465 high voltage alternating current (AC) lines integrating the North China, Central China,
466 and Eastern China regional grids[33, 39]. The strategy for offshore developments will
467 involve most likely linking the offshore wind facilities individually to local on-shore
468 transmission systems taking advantage of the anticipated increase in the
469 interconnectivity of the land-based regional grid systems.

470 The price of coal was assumed to increase by 45% in 2030 under the Cost B
471 scenario relatively to the Cost A situation, contributing to an important difference in costs
472 between these scenarios in terms of avoided CO₂ emissions for both Regions 1 and 2.
473 China switched from the condition as a net exporter to a net importer of coal in 2009[6].
474 To an increasing extent, future supplies of coal are expected to depend on imports,
475 driving up prices. According to the annual statistical report by BP [40], the ratio of
476 reserves to production for China's coal is approximately 33 years. If production of coal in
477 China were to grow at an annual rate of 3.5% as projected by BP for the 2010-2020 time
478 periods [40], the analysis would suggest that China could run out of domestic supplies of
479 coal by as early as 2032. Offshore wind resources – domestically available in close
480 proximity to the developed coastal regions – provide not only an economically viable
481 means to reduce consumption of coal with consequent reduction in emissions of CO₂,
482 they can make an important contribution also to the challenge China faces in terms of its
483 national energy security.

484 Acknowledgements

485 We thank Gang Wu, Haikun Wang, Yu Deng, Hui Xu, and Gang He for help. The
486 research was supported by the National Foundation, NSF-AGS-1019134, and by the
487 China Three Gorges Corporation grant, A17835, to Harvard University. Xinyu Chen and
488 Chongqing Kang were also supported by Chinese National High-Tech Research and
489 Development Program (863 Scheme), 2011AA 05A101. We thank the anonymous
490 reviewers for helpful comments and suggestions.

491 Supporting Information Available

492 Full description of the methodology to estimate the LOLP, the requirements on
493 reserves, and curtailment of wind power, as well as the results for capacity credits of
494 wind power on a seasonal basis, the generation duration curve of wind power, reduction
495 of CO₂ emissions due to the capacity credit of wind power, and the additional reduction
496 costs for emissions of CO₂ caused by wind curtailments. This information is available
497 free of charge via the Internet at <http://pubs.acs.org/> .

498 References

- 499 1. Ma, J.; Zhang, W.; Luo, L.; Xu, Y.; Xie, H.; Xu, X.; Li, Q.; Zheng, J.; Sheng, L.,
500 *China Energy Statistical Yearbook 2012*. China Statistics Press: Beijing, 2012; p 1057.
- 501 2. SERC *China Power Regulation Annual Report 2011*; State Electricity Regulatory
502 Commission: Beijing, May, 2012; p 111.
- 503 3. Boden, T. A.; Andres, R. J.; Marland, G. *Preliminary 2011 and 2012 Global &*
504 *National Estimates*; Carbon Dioxide Information Analysis Center: Oak Ridge, Tennessee
505 2013; p 4.
- 506 4. National Power Planning Research Center, China's Mid-term and Long-term
507 Development Plan for Supply and Demand for Electricity. *China Energy News* February
508 2013, 2013, p 4.
- 509 5. Ma, J.; Zhang, W.; Luo, L.; Xu, Y.; Xie, H.; Xu, X.; Li, Q.; Zheng, J.; Sheng, L.,
510 *China Energy Statistical Yearbook 2011*. China Statistics Press: Beijing, 2011; p 1057.
- 511 6. Morse, R. K.; He, G. *The World's Greatest Coal Arbitrage: China's Coal Import*
512 *Behavior and Implications for the Global Coal Market*; Working Paper #94; Freeman
513 Spogli Institute for International Studies: Stanford, CA, August 2010, 2010; p 25.
- 514 7. Lu, X.; McElroy, M. B.; Nielsen, C. P.; Chen, X.; Huang, J., Optimal integration of
515 offshore wind power for a steadier, environmentally friendlier, supply of electricity in
516 China. *Energy Policy* **2013**, *62*, (2013), 131-138.
- 517 8. Lu, X.; McElroy, M. B.; Kiviluoma, J., Global potential for wind-generated
518 electricity. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, (27), 10933-10938.
- 519 9. Xiao, Z.; Zhu, R.; Song, L.; Cheng, X.; He, X.; Jiang, Y.; Lin, S.; Liu, Y.; Shen, Y.;
520 Tao, S.; Wang, X.; Wang, Y.; Xu, J.; Yuan, C.; Zhang, D.; Zhang, X.; Zhang, Y.; Zhao, D.;
521 Zhou, R.; Zhu, J., *Assessment of Wind Resources in China 2009*. 1 ed.; China
522 Meteorological Press: Beijing, China, 2010; p 141.

- 523 10. Hong, L. X.; Moller, B., Offshore wind energy potential in China: Under technical,
524 spatial and economic constraints. *Energy* **2011**, *36*, (7), 4482-4491.
- 525 11. NBS, *Tabulation on the 2010 Population Census of People's Republic of China*.
526 China Statistics Press: Beijing, 2012.
- 527 12. Electric Power Statistical Year Book Editorial Board, *Electric Power Statistical*
528 *Year Book 2011*. China Electric Power Press: Beijing, 2012; p 818.
- 529 13. Li, J.; Cai, F.; Qiao, L.; Xie, H.; Gao, H.; Yang, X.; Tang, W.; Wang, W.; Li, X.,
530 *China Wind Energy Outlook 2012*. Chinese Renewable Energy Industry Association:
531 Beijing, China, 2013.
- 532 14. Li, J.; Shi, P.; Gao, H. *China Wind Power Outlook 2010*; 978-7-5443-2968-2;
533 Chinese Renewable Energy Industries Association: Beijing, 2011; p 108.
- 534 15. Lu, X.; McElroy, M. B.; Sluzas, N. A., Costs for Integrating Wind into the Future
535 ERCOT System with Related Costs for Savings in CO₂ Emissions. *Environ. Sci. Technol.*
536 **2011**, *45*, (7), 3160-3166.
- 537 16. Yu, D. Y.; Liang, J.; Han, X. S.; Zhao, J. G., Profiling the regional wind power
538 fluctuation in China. *Energy Policy* **2011**, *39*, (1), 299-306.
- 539 17. Kempton, W.; Pimenta, F. M.; Veron, D. E.; Colle, B. A., Electric power from
540 offshore wind via synoptic-scale interconnection. *Proc. Natl. Acad. Sci. USA* **2010**, *107*,
541 (16), 7240-7245.
- 542 18. Milligan, M.; Porter, K. *Determining the Capacity Value of Wind: An Updated*
543 *Survey of Methods and Implementation*; U.S. National Renewable Energy Laboratory:
544 Golden, CO, June, 2008; p 30.
- 545 19. Rienecker, M. M.; Suarez, M. J.; Todling, R.; Bacmeister, J.; Takacs, L.; Liu, H.-
546 C.; Gu, W.; Sienkiewicz, M.; Koster, R. D.; Gelaro, R.; Stajner, I.; Nielsen., J. E. *The*
547 *GEOS-5 Data Assimilation System-Documentation of Versions 5.0.1, 5.1.0, and 5.2.0.*;
548 NASA: Washington, DC, December 2008, 2007; p 118.
- 549 20. Archer, C. L.; Jacobson, M. Z., Evaluation of global wind power. *J. Geophys. Res.*
550 **2005**, *110*, (D12), D12110.
- 551 21. GE 3.6 MW Wind Turbine Technical Specifications.
552 http://www.gepower.com/prod_serv/products/wind_turbines/en/36mw/36mw_specs.htm
553 (August 5),
- 554 22. Wang, X.; Wang, X.; Bie, C.; Mao, Y., The Reliability Index Study on Generation
555 System in China *Electric Power* **1999**, *32*, (2), 24-28.
- 556 23. Archer, C. L.; Jacobson, M. Z., Supplying Baseload Power and Reducing
557 Transmission Requirements by Interconnecting Wind Farms. *J. Appl. Meteor. Climatol.*
558 **2007**, *46*, (11), 1701-1717.
- 559 24. EPRMC General report on power reliability for the first half years of 2010, 2011
560 and 2012 <http://www.chinaer.org/info.aspx?n=20120926145325967732> (January 20),
- 561 25. Giebel, G., Wind power has a capacity credit. A catalogue of 50+ supporting
562 studies. *e-WINDENG J.* **2005**, vp.
- 563 26. Zhang, N.; Kang, C.; Kirschen, D. S.; Xia, Q., Rigorous model for evaluating wind
564 power capacity credit. *Int Renewable Power Generation* **2013**, *7*, (5), 504-513.
- 565 27. U.S. EIA *Updated Capital Cost Estimates for Utility Scale Electricity Generating*
566 *Plants*; U.S. Energy Information Administration: Washington, DC, April, 2013; p 201.
- 567 28. SERC *A Briefing of the Costs for Electric Power Projects Constructed in 2007*
568 *and 2008*; China's State Electricity Regulatory Commission: Beijing, December, 2009; p
569 87.
- 570 29. Electric Power Statistical Year Book Editorial Board, *Electric Power Statistical*
571 *Year Book 2012*. China Electric Power Press: Beijing, 2013; p 818.

- 572 30. Liu, M.; Wang, H.; Oda, T.; Zhao, Y.; Yang, X.; Zang, R.; Zang, B.; Bi, J.; Chen,
573 J., Refined estimate of China's CO₂ emissions in spatiotemporal distributions.
574 *Atmospheric Chemistry and Physics* **2013**, *13*, (21), 10873-10882.
- 575 31. China Coal Resource Weekly Average Coal Price at Qinhuangdao Port.
576 <http://en.sxcoal.com/76/0/datalist.html> (November 12),
- 577 32. Wang, F.; Zhang, S., Forecasting Long-Run Coal Price in China: Based on the
578 State Space Model. *Statistics & Information Forum* **2011**, *26*, (8), 67-72.
- 579 33. WANG, Z.; SHI, J.; ZHAO, Y. *Technology Roadmap: China Wind Energy*
580 *Development Roadmap 2050*; International Energy Agency and Energy Research
581 Institute: Paris, France, 2011; p 56.
- 582 34. Musial, W.; Ram, B. *Large-Scale Offshore Wind Power in the United States:*
583 *Assessment of Opportunites and Barriers*; NREL/TP-500-40745; National Renewable
584 Energy Laboratory: Golden, CO, September, 2010; pp 108-128.
- 585 35. Chang, J.-H., The Chinese Monsoon. *Geographical Review* **1971**, *61*, (3), 370-
586 395
- 587 36. Hart, E. K.; Jacobson, M. Z., The carbon abatement potential of high penetration
588 intermittent renewables. *Energy & Environmental Science* **2012**, *5*, (5), 6592-6601.
- 589 37. SERC *Regulatory Report on Wind Power Integration in Some Critical Regions in*
590 *China*; State Electricity Regulatory Commission: Beijing, May, 2012; p 111.
- 591 38. IPCC *Special Report on Carbon Dioxide Capture and Storage*; Intergovernmental
592 Panel on Climate Change: Geneva, Switzerland, 2005; p 431.
- 593 39. Li, J. *From Strong to Smart: the Chinese Smart Grid and its relation with the*
594 *Globe*; Asia Energy Platform: Hong Kong September, 2009, 2009; p 10.
- 595 40. BP *BP Statistical Review of World Energy* BP: Oct 4, 2013; p 48.

596