China has overtaken the United States as the foremost energy consumer in the world since 2011, taking great pressure due to the carbon emission and air pollution caused by its coal-dominated energy system [1]. In 2014, the generation amount of coal-fired power plants, one of the largest carbon emission sectors, was 3951 TWh, accounting for 70.5% of total electricity generation [2]. In order to mitigate climate change and improve air quality, renewable energy, especially wind power, has been regarded as the fundamental solution for sustainable development by China [3]. Wind power has seen significant progress in China, particularly after the Renewable Energy Law came into force in the beginning of 2006. By the end of 2015, the cumulative on-grid wind power capacity reached 129 GW, which is the world’s largest wind industry and has contributed 186.3 TWh power, accounting for 3.3% of electricity generation [4]. Meanwhile, the Chinese government has announced its ambitious goal of achieving a wind-installed capacity of 100 GW by 2015 and 200 GW by 2020 [5]. Although the installation of wind turbines is increasing, the annual growth rate of wind capacity has decreased below 33% since 2011 [6]. Besides, the National Energy Administration has announced a decrease in the adjustment of feed-in-tariff for wind power by the end of 2014, which cast a shadow on the rapid development of the new installation in the future [7].

In order to reach the 2015 and 2020 wind power capacity target [5], allocating new installations in different regions with heterogeneous resource and demand characters must be considered as the leading question for future development. From the perspective of carbon emission mitigation, three main types of policies exist to

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**Keywords**

China, CO₂ mitigation cost, GIS analysis, wind curtailment, wind power resources

**Introduction**

China has overtaken the United States as the foremost energy consumer in the world since 2011, taking great pressure due to the carbon emission and air pollution caused by its coal-dominated energy system [1]. In 2014, the generation amount of coal-fired power plants, one of the largest carbon emission sectors, was 3951 TWh, accounting for 70.5% of total electricity generation [2]. In order to mitigate climate change and improve air quality, renewable energy, especially wind power, has been regarded as the fundamental solution for sustainable development by China [3]. Wind power has seen significant progress in China, particularly after the Renewable Energy Law came into force in 2006. By the end of 2015, the cumulative on-grid wind power capacity reached 129 GW, which is the world’s largest wind industry and has contributed 186.3 TWh power, accounting for 3.3% of electricity generation [4]. Meanwhile, the Chinese government has announced its ambitious goal of achieving a wind-installed capacity of 100 GW by 2015 and 200 GW by 2020 [5]. Although the installation of wind turbines is increasing, the annual growth rate of wind capacity has decreased below 33% since 2011 [6]. Besides, the National Energy Administration has announced a decrease in the adjustment of feed-in-tariff for wind power by the end of 2014, which cast a shadow on the rapid development of the new installation in the future [7].

In order to reach the 2015 and 2020 wind power capacity target [5], allocating new installations in different regions with heterogeneous resource and demand characters must be considered as the leading question for future development. From the perspective of carbon emission mitigation, three main types of policies exist to
promote the development of wind power among countries: price instrument imposing an external cost of emitted fossil carbon dioxide (CO₂); financial subsidy for wind power to cover the gap between generation cost and market price (e.g., feed-in-tariff); and quantity instrument imposing an emission cap or renewable penetration (e.g., cap-and-trade market). All these policy instruments add an extra cost to the existing power sector in order to reduce CO₂ emission. Therefore, it is critical and essential to investigate the abatement cost and emission mitigation potentials of wind power, which could provide solid supporting information for policy makers. The essential difficulties in estimating appropriate abatement cost and the relevant emission mitigation potential lie in the assessment of regional disparities of wind resource, wind generation cost, and coal power generation cost [8–10]. From the economic perspective, the deployment of wind energy should have the least incremental cost on the existing power system, with the same amount of emission reduction.

A widely used methodology to estimate how costly it would be to achieve the specific emission reduction is the marginal abatement cost curves (MACCs). The MACC can plot the corresponding cost after tightening the emission mitigation target further, which links marginal cost of abating an incremental emission to an emission potential. The purpose of our study was to generate the cost curve of carbon emission for wind power utilization, providing the emission mitigation could be reached by the deployment of wind power and the related emission abatement cost at high spatial resolution. The two important factors influencing carbon emission abatement cost by wind power for each region are the generation cost of wind and the coal-fired power cost, assuming the replacement of traditional coal power to wind power [11]. Thus, the carbon emission abatement cost is defined as the incremental electricity cost between wind power and coal-fired power, divided by the carbon-emitted gap between coal-fired power and wind power.

To investigate the economics of wind deployment, the purpose of our study was to evaluate the reduction in the potential and cost of carbon emission by wind power from the regional perspective. The paper first reviews the existing wind potential assessment in China and describes the wind resource as well as the on-going development plan. Thereafter, the methodology and data are used to calculate the wind power CO₂ mitigation potential as well as the abatement cost. Finally, the results could supply an overall message regarding the cost and amount of CO₂ abatement by wind power, providing some support for both national and local policy makers, investors, and other stakeholders.

**Wind Power Potential and Development Plan**

The existing assessment on wind potential in China mainly focused on physical capacity or generation of wind resource potential, which represents the upper limit of usable wind electricity with an assumption that all wind generation would be accepted by the power grid. Leading literatures have concluded that China’s total wind power capacity ranges from 832 to 2600 GW [12–14], which is several times more than that of China’s national targets of 200 GW wind installation by 2020 [5]. The China Meteorological Administration has developed a wind energy numerical simulation and evaluation system, indicating that the theoretical wind resource potential ranges from 2000 to 3400 GW [15]. He and Kammen combined the geographic information system (GIS) and wind hourly profile simulation to make high spatial resolution resource analysis at the provincial level, which indicates technical wind potential varies from 1243 to 2643 TWh due to different assumptions of wind turbine spatial density [14]. For offshore wind, Hong and Möller [16] reported that offshore wind in China could technically contribute 2450 TWh in 2020 and 2758 TWh in 2030. McElroy and Lu concluded that approximately 10% of CO₂ emission in China could be reduced if 0.62 PWh wind electricity is generated per year to replace coal-fired power, below the levelized cost of 0.4 RMB/kWh [17]. In summary, previous studies paid attention to wind resource assessment while the potential to mitigate carbon emission and the related abatement cost were simply calculated using national average coal-fired power generation cost, while the regional heterogeneity of the rest of power system except wind power is overlooked.

Specifically, the majority of existing installed wind turbines are located in provinces with abundant wind resources including high wind density and available land, such as Inner Mongolia, Hebei, Gansu, Jilin, and Xinjiang. By the end of 2014, 16 provinces exceeded 1 GW in terms of cumulative wind installation, and the 10 leading provinces account for more than 80% of the national wind installation, shown in Figure 1 [18]. Along with the existing high level of capacity concentration, the National Energy Administration of China has released development planning for seven 10-GW large-scale wind power installations by the end of 2020. In 2012, China’s 12th 5 year plan for renewable energy has announced the 100 and 200 GW wind installation targets respectively by 2015 and 2020, followed by regional targets for wind installations [19]. Most of the announced 10-GW large-scale wind power installations are located in the north and northeast parts of China shown in Figure 2.
Methodology and Data

As the 10 leading provinces in wind capacity cover more than 80% of existing wind installation, we focused on the carbon emission mitigation potential of these provinces including Jiangsu, assuming that the provincial capacity target by 2020 is going to be perfectly implemented. In order to generate provincial-level supply cost curve for CO$_2$ emission mitigation of wind power, annual wind generation and emission abatement cost are necessary. This study combines GIS system analysis and cost–benefit assessment to evaluate the abatement cost and emission that could be avoided. The purpose of introduction of GIS analysis is to provide detailed description of regional capacity factor, which is inevitable for calculation of abatement cost and emission reduction. The logical framework and data utilization are listed as follows in this section. Particularly, this study shed light on onshore wind while offshore wind is not included.

Wind resource analysis

Wind resource assessment relies heavily on the method of retrospective analysis, or re-analysis. This study uses Modern Era Retrospective-analysis for Research and Applications, which is undertaken by The National Aeronautics and Space Administration’s (NASA) Earth Observing System satellites [20]. With high spatial resolution dataset of 0.5° latitude by 0.67° longitude, the annual capacity factor for each grid cell could be calculated by eliminating yearly variation. Based on hourly wind speed at the hub height of 80-m conducted by GEOS-5 Atmospheric Data Assimilation System for each grid cell, hourly wind output is generated assuming that a sole 80-m hub height Sinovel 1.5-MW turbine is fully equipped for all the wind projects. The power curve is shown in Figure 3 [21]. Thus, the annual capacity factor is calculated as the annual wind output divided by the product of nameplate turbine capacity (1.5 MW) and 8760 h (1 year), presented in Figure 4. From the perspective of capacity factor, it is intuitively observed that the high capacity factor areas are highly consistent with planning...
wind installations except the Tibet Plateau with harsh natural environments.

We used NASA’s Shuttle Radar Topography Mission and land-cover categories of China to remove unavailable areas for turbine siting, such as urban regions, sloping fields with greater sloping factor than 10%, lakes and rivers, cropland, natural protection zones, and major industrial and transportation infrastructures [22]. Wind turbine density is another significant factor to determine the physical upper limit of wind power capacity installation, which ranges from 2 to 5 MW/km² in previous studies [12, 23]. As the other types of unavailable land like natural parks, wetland, and military basements are removed due to deficiency, the lower case of turbine density, 2 MW/km², is selected to calculate the potential wind capacity for each grid cell which equals the product of available area and wind density. Thus, the wind generation potential for each grid equals the product of capacity potential, local capacity factor, and 8760 h. The physical on-shore wind generation potential density for China is shown in Figure 5.

**CO₂ abatement cost calculation**

**Levelized production cost**

Carbon dioxide abatement cost of wind power is defined as the gap between wind generation cost and coal-power generation, divided by avoided emission per generation unit. Levelized production cost (LPC) was widely used to calculate electricity production cost which reflects the average cost of one production unit (kilowatt or kWh) during the power station’s entire expected lifetime [24–26]. The total generation costs over the lifetime of power plant are discounted at the start of operation by a predetermined discount rate, while LPC is derived as the ratio of the discounted total cost and total generation output over lifetime shown as follows:

\[
\text{NPV} = \sum_{i=1}^{N} \left( \text{LPC} \cdot E - \text{COM}_i - \text{LoanPay}_i - \text{Profit}_i \right) \cdot (1 + r_d)^{(i-1)}
\]

\[
\text{LoanPay}_i = \text{DebRate} \cdot \text{CapC} \cdot \left(1 + r_d\right)^{15} - \frac{1}{(1+r_d)^{15} - 1}, \quad i = 1 \sim 15
\]

\[
\text{Profit}_i = \text{EquRate} \cdot \text{CapC} \cdot r_e, \quad i = 1 \sim 20
\]

\[
E = \text{WindCap} \cdot \text{CapacityFactor} \cdot 8760.
\]

With assumption that capital cost (CapC) is a combination of 80% (DebRate) loan and 20% (EquRate) equity for each wind farm, LoanPay is the payment of principal and interest to the loan during 15-year payment period while Profit is the required profit for the internal equity. Operation and maintenance cost, COM, includes cost for regulatory operation fees, local taxes, and insurance. E represents the wind farm annual energy output, which is the product of nameplate capacity, local capacity factor, and 8760 h of 1 year. For a given discount rate \(r_d\) (7%), the expected return rate \(r_e\) (10%) and loan interest rate \(r_e\) (6.55%), LPC equals to the price to make the net present value (NPV) as zero, assuming a 20-year lifetime for wind project.
As operation and maintenance cost is relatively smaller from a system perspective, capital cost is the dominated factor to calculate LPC, including wind turbine, transmission, construction, and land use [27, 28]. China Wind Power Outlook [29] showed an obvious decrease in capital cost of wind turbine in from 6000 RMB/KW in 2008 to 4300 RMB/KW in 2014. The capital cost structure of wind power in 2013 and 2012 and related parameters is shown in Table 1.

**Estimation of future capital cost**

The decreased cost and changing structure of wind power reflects the economies of scale that could be estimated using the learning curve approach [31–33]. Learning curve describes the evolution of new technology resulting in costs reduction by assuming that the change in the costs (C) between two time segments “t1” and “t2” is a power function of the change in the capacities (Q) between the time segments, shown as follows:

\[
\frac{C_t}{C_{t_1}} = \left( \frac{Q_t}{Q_{t_1}} \right)^{-b}
\]

where \(C_t\) and \(C_{t_1}\) represent the costs of the examined new technology at the moments \(t\) and \(t_1\), respectively, and \(Q_t\) and \(Q_{t_1}\) represent the cumulative installed capacity of the technology at the moment \(t_1\) and \(t_2\). \(b\) is the exponent coefficient of the learning curve (usually defined as learning rate), meaning the decrease in new technology cost when the cumulative capacity of this new technology doubles. The cost of the technology at the moment \(t_2\) can be calculated using the next equation.

\[
\log(C_{t_2}) = \log(C_{t_1}) - b \cdot \log\left( \frac{Q_{t_2}}{Q_{t_1}} \right)
\]

As \(Q_{t_2}\), \(Q_{t_1}\), and \(C_{t_1}\) are obtained, the key issue for applying equation (3) to estimate the future cost of wind systems is the learning rate \((b)\), which is related to the historical variation trend in the cost and the cumulative installed capacity of wind turbines, and the cost reduction potentials of key components. Previous studies focusing on China’s wind power have investigated different types of learning curve models, indicating that learning rate ranges from 4.1% to 11% [34–37]. Here, a medium learning rate of 7% is adopted in this paper, while the analysis of learning rate is not our focus. In order to simulate LPC in 2020, we have implemented learning curves analysis on wind power toward 2020. Assuming that the accumulative installation of wind capacity would grow with the same annual increase rate from 2014 to 2020, the capital cost decrease trend in China is simulated under a fixed learning rate in Figure 6, while the averaged capital cost for plain and hills in 2013 listed in Table 1 is set as the benchmark for learning-curve calculation. Despite the variation of capital cost among projects, we utilized projected capital cost of 7252 RMB/kW for overall wind farms in 2020 all over the country.

**Wind power CO₂ mitigation cost**

The CO₂ abatement cost of wind power means the additional cost of avoiding one unit of CO₂ emission by substituting wind power for baseline units, calculated in

\[
\text{AbatementCost}_{r,i} = \left( \frac{\text{LPC}_\text{wind},i - \text{LPC}_\text{Coal},r}{3.6 \cdot \text{EmFactor}_\text{Coal}} \right) \cdot \text{Eff}_{r,i}
\]

where AbatementCost\(_{r,i}\) means the CO₂ abatement cost of wind power in grid cell \(i\) of province \(r\), while the gap of levelized cost of wind and coal power is calculated as \(\text{LPC}_\text{wind},i - \text{LPC}_\text{Coal},r\), \(\text{Eff}_{r,i}\) is the average generation efficiency of coal-fired power in each province, and \(\text{EmFactor}_\text{Coal}\) equals to 0.096 kg/MJ which is the emission factor of coal.

**Table 1.** Averaged wind power capital cost structure in China from selected projections[30].

| Unit (RMB/kW) | 2013 | 2012 |
|--------------|------|------|
| Equipment purchase | 5072 | 5079 | 5072 | 5186 | 5194 | 5186 |
| Installation | 489 | 627 | 689 | 531 | 676 | 747 |
| Construction | 861 | 1384 | 1333 | 830 | 1298 | 1255 |
| Rest | 402 | 461 | 416 | 558 | 565 | 572 |
| Basic reserve | 171 | 189 | 188 | 142 | 155 | 155 |
| Interest during construction | 189 | 209 | 208 | 196 | 213 | 214 |
| Total capital cost | 7184 | 7949 | 7906 | 7443 | 8102 | 8129 |

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factor of coal from IPCC [38] and 3.6 in formulation (4) is the conversion coefficient which keeps energy unit consistent. The fundamental hypothesis here is that wind power utilization is assumed to replace coal-fired power perfectly in each province, while provincial coal power efficiency disparity is to distinguish the difference in technology of coal-fired power, coal categories, and coal quality in each province. As coal-fired power technology is relatively mature in China, we assume the energy efficiency for coal power will be consistent till 2020. The provincial coal-fired power generation efficiencies for provinces included in this study in 2012 are listed in Figure 7.

### Supply curve of CO₂ emission mitigation

Based on the calculation of LPC of wind power for each grid cell in the 11 leading provinces, CO₂ abatement cost could be generated with formulation (4), assuming that wind capital cost remains constant for all provinces and the benchmarking on-grid price of coal-fired power excluding taxes for each province is applied to represent the LPC of coal-fired power of each province. The strong projection for coal-power LPC will be affected by coal price, and there is no clear and believable prediction due to various factors. Therefore, emission abatement costs of each grid cell for all provinces are ranked in ascending order of abatement cost, indicating the least-cost order for wind deployment from the perspective of emission mitigation. The amount of carbon emission mitigation for each grid cell is proposed as the local mitigation potential divided by coal power generation efficiency, based on the grid cells of each province. With the assumption that provincial capacity targets would be perfectly finished, the provincial supply curve of carbon emission mitigated by wind power could be generated with aggregating all the grid cells from least to highest emission abatement cost with a certain emission mitigation potential.

Particularly, the average abatement cost of all the grid cells in each province by generation potential would be used to represent the provincial overall cost. Although our emphasis of wind resource evaluation is focusing on the technical available output of wind power in each grid cell, the grid connection issue of wind power to the existing electricity system in China is another vital factor that constrains the technical-feasible wind output from wind farms, which is estimated to be caused by incomplete electricity market, inflexible pricing mechanisms, and inaccurate wind prediction [40–43]. In the following section, we consider two scenarios with different curtailment rate and analyze the underlying influences caused by wind curtailment.

### Results and Discussion

#### Cost curve of carbon emission abatement

**Scenario with wind curtailment**

Here we assume that the wind curtailment rate by 2020 is the same as that in 2012, which is the share of wind production refused by electricity grid in the total technical-feasible production of wind plants, due to the reasons mentioned above. Each bar in Figure 8 shows the projected abatement cost and CO₂ mitigation potential for each province if the 2020 wind target is perfectly implemented, while the abatement cost is the additional cost between wind LPC and coal-power LPC. Generally, the average abatement costs of grid cells for 10 provinces are positive, which means that the generation cost of wind power is higher than the current electricity price of coal-fired power in most of the provinces. However, the abatement cost of Liaoning
province is negative, which means the generation cost of wind in 2020 could be cheaper than that of coal-power. We have identified an abatement potential of 500 Mt costing below 250 RMB/t of the CO₂ equivalent. The result indicates that approximately 370 million tons of CO₂ emission (almost 75% of total) could be avoided with an abatement cost lower than 100 RMB/t- CO₂ (16 USD/t- CO₂) in 2020. The overall average abatement cost for the wind installation provinces is 72 RMB/t- CO₂, which is much lower compared to that reported at 38 USD/t- CO₂ (230 RMB/t- CO₂) or 32 Euro/t (210 RMB/t- CO₂) in the existing literature [44, 45].

Table 2 illustrates the average capacity factor simulated by GIS analysis, expected wind output, as well as abatement potential linked with abatement cost for each simulated provinces with large-scale wind capacity. Liaoning, Hebei, and Inner Mongolia have the lowest abatement cost below 50 RMB/t- CO₂, and they are also the leading three provinces in terms of wind resource. Especially, all those make Inner Mongolia the province with the largest abatement potential and relatively low abatement cost. But the abatement costs have different order with capacity factors in the provinces, which indicates that wind resource is not the only factor determining abatement cost while the generation efficiency and generation cost of coal power should be taken into consideration among regions. Inner Mongolia, Xinjiang, and Gansu account for 60% of the total mitigation potential. The highest abatement cost lies in Ningxia province, due to its low capacity factor and low generation cost of coal-power. According to the results, approximately all the mitigation potential could be reached with abatement cost lower than 150 RMB/t.

Table 2. Averaged capacity factor, wind output, and abatement potential by province.

| Province      | Curtailment rate (%) | Real avg. CF | Planned capacity (GW) | Expected output (TWh) | Coal power efficiency (%) | Abatement potential (Mt- CO₂) | Abatement cost (RMB/t) |
|---------------|----------------------|--------------|-----------------------|-----------------------|---------------------------|-----------------------------|------------------------|
| Liaoning      | 6                    | 0.344        | 8                     | 24.09                 | 37.7                      | 22                          | -1                     |
| Hebei         | 12                   | 0.304        | 16                    | 42.66                 | 37.0                      | 40                          | 19                     |
| Inner Mongolia| 9                    | 0.403        | 58                    | 204.60                | 36.3                      | 195                         | 41                     |
| Shanxi        | 6                    | 0.296        | 8                     | 20.75                 | 36.2                      | 20                          | 69                     |
| Shandong      | 1                    | 0.251        | 15                    | 33.03                 | 37.4                      | 31                          | 74                     |
| Jilin         | 15                   | 0.275        | 15                    | 36.09                 | 37.9                      | 33                          | 76                     |
| Heilongjiang  | 12                   | 0.255        | 15                    | 33.44                 | 35.7                      | 32                          | 95                     |
| Gansu         | 11                   | 0.286        | 20                    | 50.08                 | 36.8                      | 47                          | 126                    |
| Jiangsu       | 0                    | 0.225        | 10                    | 19.72                 | 39.5                      | 17                          | 136                    |
| Xinjiang      | 15                   | 0.311        | 20                    | 54.56                 | 33.0                      | 57                          | 142                    |
| Ningxia       | 0                    | 0.240        | 4                     | 8.42                  | 37.2                      | 8                           | 240                    |

 Scenario without wind curtailment

The wind curtailment rate of 2012 has been applied in the former calculation, which is based on the assumption that wind integration would still be limited in some provinces by 2020. However, enforcement of flexible generation capacities, market-based pricing system, and regional connection have been planned to improve the integration of large-scale wind power. With the most optimistic prediction, the marginal cost curve can be redraw when wind power is integrated perfectly.

We examined the abatement cost as well as the mitigation potential for no-curtailment assumption, shown in Figure 9. As all available wind generation is 100% absorbed in the electricity grid, the total abatement potential has increased by 10% to 550 Mt- CO₂ compared with the current wind curtailment scenario; meanwhile, the
...averaged abatement cost has decreased by almost 40% to 44 RMB/t-CO₂. The significant change in abatement potential and the related cost indicate the importance of wind integration on economic potential of wind power to replace coal-fired power. Hebei, rather than Liaoning, have become the lowest abatement province. And both provinces have negative abatement cost, suggesting that the expected wind generation is cheaper than coal-fired power. According to the simulation results, approximately 95% of the total emission mitigation potential could be reached with an abatement cost lower than 100 RMB/t. Inner Mongolia, Xinjiang, and Gansu still occupy the leading three places in mitigation potential ranking with 214, 67 and 52 million tons of CO₂. The highest abatement cost reaches the same as the scenario with wind-curtailment scenario in Ningxia province. Compared with the former scenario, here the abatement cost for each province has a similar pattern, but with a slightly different rank, as provinces with severe integration issue such as Hebei, Jilin and Xinjiang would benefit the most from integration improvement.

The provincial differences in abatement potential and the corresponding abatement cost showed that detailed analysis on wind generation cost, integration situation, as well as coal power efficiency and generation cost at the regional level is essential to decarbonize China’s power sector by wind power deployment. It is estimated that wind power is a very price-competitive technology to decrease carbon emission; especially, the abatement cost could be negative for some provinces in the near future. However, from a national perspective, financial subsidy or other policy instruments are still needed to achieve the national goal by 2020. The annual wind output could reach 520–580 TWh, representing nearly 500–550 Mt CO₂ emission mitigation. The main abatement potential concentrated in Three-North area in China including North China, Northeast and Northwest, which is the home of rich wind resource and low-efficiency coal power capacities. In addition, the replacement of existing coal power by wind power could be of mutual benefit to both pollution improvement and the coal-dominated power sector in these provinces.

**Potential contribution of wind power development**

We compared the provincial potential of abatement in Table 3 with the projected total emission for each province of 2020 and showed the potential share of wind power-contributed abatement in total emission at the provincial level. We use projection for provincial emission of 2020 as the benchmark [46] to predict the potential contribution to provincial emission reduction from the overall system perspective. The total emission for each province is related to many uncertain factors, such as economic development, industry structure, and generation mix. Thus, the share of mitigation contributed by wind power in total emission is the key indicator to show the role of wind power in low-carbon transition. Seen from Table 3, the share of emission mitigation potential contributed by wind in total emission at the provincial level varies at great scale, from 1.5% to approximately 65%, which illustrates the role that wind power could play in decarbonizing the power sector by 2020. In the scenario with wind curtailment, the CO₂ reduction by wind could account for nearly 65% of Inner Mongolia’s total CO₂ emitted in 2020. However, for coastal provinces like Jiangsu and Shandong, the potential contribution of on-shore wind power is very limited if they just implement the national planning. Besides, that also makes requests for transmission from wind resources inside other provinces, if wind power is needed to support stringent target of emission reduction. For Inner Mongolia, Xinjiang, and Gansu, wind power could play an important role in

**Table 3. Projected share of mitigation potential contributed by wind in provinces in 2020.**

| Province       | Expected emission (Mt) | Abatement potential with curtailment (Mt) | Share (%) | Abatement potential without curtailment (Mt) | Share (%) |
|----------------|------------------------|------------------------------------------|-----------|----------------------------------------------|-----------|
| Hebei          | 721.7                  | 39.8                                     | 5.5       | 45.3                                         | 6.3       |
| Shanxi         | 322.5                  | 19.8                                     | 6.2       | 19.8                                         | 6.2       |
| Inner Mongolia | 302.2                  | 195.0                                    | 64.5      | 214.3                                        | 70.9      |
| Liaoning       | 549.2                  | 22.1                                     | 4.0       | 23.5                                         | 4.3       |
| Jilin          | 284.3                  | 32.9                                     | 11.6      | 38.7                                         | 13.6      |
| Heilongjiang   | 396.0                  | 32.3                                     | 8.2       | 36.7                                         | 9.3       |
| Jiangsu        | 1173.1                 | 17.2                                     | 1.5       | 17.2                                         | 1.5       |
| Shandong       | 1221.4                 | 30.6                                     | 2.5       | 30.9                                         | 2.5       |
| Gansu          | 151.0                  | 47.0                                     | 31.1      | 52.8                                         | 35.0      |
| Ningxia        | 52.3                   | 7.8                                      | 14.9      | 7.8                                          | 14.9      |
| Xinjiang       | 196.2                  | 57.1                                     | 29.1      | 67.1                                         | 34.2      |
reducing local emission, while the high penetration brings great uncertainties on the electricity grid. Therefore, transmission lines to export wind power produces in these provinces, or flexible generation adjusting peak-load like natural gas capacities are strongly needed to balance energy consumption and production, as well as to guarantee the grid security in highly renewable energy penetration situations.

**Conclusions**

Since the Renewable Energy Law came into force in 2006, wind power in China has seen a remarkable growth, reaching 94 GW of installed capacity by the end of 2014. Existing studies have been focusing on wind resource estimation while the abatement potential together with the corresponding abatement cost are disregarded. Due to the lack of marginal abatement cost for each province, former research does not provide the necessary information to estimate the potential contribution and the economic cost of wind power deployment to reduce carbon emission. China’s ambitious target has set detailed planning installed capacity for several “wind-installation” provinces by 2020. From the perspective of mitigating carbon emission, knowing the cost curve of wind power is essential to reduce carbon emission at the provincial level, which could help the policy makers on wind development to design policy instruments for wind power promotion.

By combining GIS analysis and LPC calculation, we provide provincial-level supply curve of CO₂ mitigation by wind power in provinces with the mentioned planning capacity target in the 12th Five-year plan. A total of 3783 grid cells are used to represent wind resource spatial disparity for China’s on-shore wind, with averaged wind speed data at the hourly level. The available area for wind farms as well as averaged wind capacity factors are then built for each grid cell. Assuming that provincial capacity targets should be perfectly implemented by 2020, the provincial wind capacity factor among grid cells is generated. When learning effect and wind curtailment issues are both considered, provincial abatement cost and abatement potential are estimated by MACCs. Our results indicate significant differences in abatement cost and abatement potential among “wind installations” provinces. The key finding could be used to facilitate or evaluate wind planning by policy makers and academic researchers at both the provincial and national levels.

By 2020, wind power could be a very competitive mitigation option in considering of the current coal-dominated power sector in China. Wind power has the potential to contribute 500 Mt-CO₂ emission reduction, while the overall abatement cost is lower than 75 RMB/t-CO₂. Inner Mongolia, Gansu, and Xinjiang occupied the top three position in terms of abatement potential. The different order of wind resource and abatement cost have indicated that the local power sector as well as wind curtailment should be regarded as key factors for wind investment in the near future. In addition, wind integration issue is another crucial factor to change the marginal curve order, which should require detailed analysis to actually fulfill carbon emission reduction via wind power installation. Furthermore, the share of abatement potential that could be achieved with 2020 wind target indicated that import/export of wind power could also have an important impact on the achievement of wind power.

In summary, this study has extended existing resources by a detailed investigation into the abatement potential and abatement cost in China at high spatial resolution. Economic access of wind power should be carefully considered rather than following the ambitious national planning. However, in this study, we assumed that wind power generation has caused the replacement of coal-fired power but wind power deployment and utilization are much more complex to perfectly simulate. We would like to implement power sector modeling which captures the rest of the power sector, for future studies of wind power and its linked carbon emission reduction.

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**Conflict of Interest**

None declared.

**Notes**

1 Although Jiangsu is not in the list of top 10 provinces with the biggest wind capacity, it is still selected in our analysis as Jiangsu is one of the major wind installations in the 12th Five-year Renewable Energy Development Plan.
2 Wind curtailment rate is collected from the national renewable energy information management center, which is available from: http://news.bjx.com.cn/html/20140904/543677.shtml.

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