Roles of wind and solar energy in China's power sector: Implications of intermittency constraints

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Roles of wind and solar energy in China's power sector: Implications of intermittency constraints

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HIGHLIGHTS

- China wind and solar energy in 2050 is expected to increase by 4–8 times.
- Carbon emissions factor is expected to decrease by more than 30% in 2050.
- CO_2 reductions in 2050 by wind and solar energy are expected to be 530–570 $MtCO_2$.
- VRE Intermittency increases electricity cost and reduces coal generation efficiency.
- Intermittency could reduce VRE deployment by more than 10% (wind) and 15% (solar).

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ABSTRACT

China's wind and solar energy capacities have increased considerably over the previous decade, and these energy sources are playing increasingly important roles in China's power sector. However, because of their variability and intermittency, increasing the supply of wind and solar energy to the electricity grid is a challenge. In this study, we first assessed the integration cost of wind and solar energy together with the coal efficiency penalty attributable to the intermittency of wind and solar energy. Then, with consideration of the intermittency effect, we investigated the roles of wind and solar energy in China's power sector in terms of their electricity generation, generation share, substitution effect, and emissions reduction under two scenarios: i.e., with and without adoption of climate mitigation policies. Finally, we estimated the impact of intermittency on future deployment of wind and solar energy. The results indicated that by 2050 the shares of wind and solar energy in China's power sector under the two scenarios will decline by more than 10% and by more than 15%, respectively, compared with the case without consideration of intermittency. The results also illustrated that the coal share, grid generation cost, and carbon emissions per unit generation will increase by 0.5–1.1%, 1.2–3.7%, and 1.8–4.1%, respectively. Sensitivity analyses indicated that the change in variable renewable energy (VRE) share would be negatively proportional to the changes in VRE integrated cost and coal efficiency penalty.

1. Introduction

The continuation of China's economic growth in the near term is expected to drive further growth in China's electricity demand. China's electricity consumption increased from 2500 TWh in 2005 to 5620 TWh in 2015, an increase by a factor of 2.25 and an annual rate of increase of 8.4% [1,2]. The base year (i.e., the reference year) adopted in this study was 2015. In that year coal, oil, natural gas, hydropower, nuclear, wind, solar photovoltaic (PV), and biomass energy sources accounted for 69.7%, 0.1%, 2.9%, 19.4%, 3.0%, 3.2%, 0.7%, and 0.9% of China's total electricity generation, respectively [1,2]. The total electricity generation from renewable sources was 1392 TWh in 2015, which was provided by hydro (1113 TWh; 80%), wind (186 TWh; 13%), solar (39 TWh; 3%), and biomass (54 TWh; 4%) [1,2]. China's wind and solar PV generation has increased at a rate even faster than this overall growth of electricity consumption. The installed capacity of wind power increased from 1.3 GW in 2005 to 131 GW in 2015, i.e., by a factor of 100 during the previous 10 years, and it is expected to increase to 200 GW by 2020. Solar PV installation has also increased rapidly. The total installed capacity of solar PV increased from 0.07 GW in 2005 to 42 GW in 2015 and it is expected to reach 100 GW in 2020 [3–5].

China's power sector accounted for about 50% of China's coal

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consumption in 2015 [2]; therefore, it has potential to be a major contributor to future CO_2 emissions reductions. In December 2009, China announced two domestic autonomous mitigation targets for 2020: (1) a 40–45% reduction of emissions intensity (CO_2 emission per unit GDP) relative to the 2005 level, and (2) an increase of non-fossil fuel share to 15% of the total primary energy consumption [6,7]. In June 2015, China submitted the Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions to the Secretariat of the United Nations Framework Convention on Climate Change. The document stated the official promise that China would (1) reach a peak level of CO_2 emissions at around 2030, while making efforts to peak earlier, and (2) increase the share of non-fossil fuels in primary energy consumption to 20% [8]. These goals represent daunting challenges and they are highly dependent on the emission reduction efforts of China's power sector [9].

The acceleration of renewable energy deployment is crucial for China to meet the national goal in emissions reduction. Accordingly, several policies and measures have been introduced to support renewable energy deployment. In 2006, China's renewable energy law took effect. In 2007, the medium- and long-term renewable energy development plan for China was released [10]. In 2012, the government development plan for the 12th planning period (2010–2015) was released, and this plan announced a more ambitious near-term target for renewable energy development [11].

Although there is considerable renewable energy potential in China, an unavoidable challenge limiting the dramatic growth of wind power and solar PV is their intermittent availability [12–15]. After several blackouts caused by wind turbine tripping, the Chinese government now requires owners of wind farm to upgrade their equipment with Low Voltage Ride Through capability. While this upgrade can address the main issue of grid disruption from low voltage incidents, it does increase the cost of wind power [16]. In the long term, the capability of wind and solar to contribute to the national power sector will be influenced by a number of other factors specific to China, such as the dominance of coal generation in the power sector, long transmission distances of wind and solar energy, and expense of natural gas generation for variable load balancing.

To date, analysis of integration issues in relation to wind and solar electricity generation remains limited. A number of studies have developed future scenarios for China's power sector over the long term (i.e., 2030 and beyond) using integrated assessment models such as MARKAL, IPAC-AIM, TIMES, 3E, and MESSAGE [17–25]. In these studies, representations of wind and solar energy incorporation in the power sector could be improved because of their intermittency. However, because of this variability and intermittency, if the penetration of wind and solar energy is increased in the long term, China's power grid could face considerable challenges.

Within this context, the focus of this study was to investigate the role of wind and solar energy in China's future power sector with consideration of their intermittency. Specifically, the investigation was motivated by the following three questions. What are the roles of wind and solar energy in China's power sector in the long term? By how much can CO_2 emissions be reduced by deploying wind and solar energy in the power grid? How do these answers change when the intermittency of wind and solar energy is considered explicitly?

In this paper, we explore the role of wind and solar energy in China's future power sector based on an integrated assessment model, i.e., the Global Change Assessment Model (GCAM) (http://www.globalchange.umd.edu/models/gcam/download/), with consideration of the special circumstances in China that influence the roles of wind and solar energy in China's future power sector. The remainder of this paper is organized as follows. In Section 2, we discuss the background of variable renewable energy sources including wind and solar within the context of China's power sector. In Section 3, we describe our research methods and key assumptions. Section 4 discusses the results of our experiments, and in Section 5, we summarize our research conclusions and key findings.

2. Challenges of wind and solar energy

Wind and solar energy without storage capacity are considered variable renewable energy (VRE) technologies that are intermittent. Their availability to meet electricity demand is less predictable compared with conventional thermal electricity sources (e.g., coal) and reservoir hydropower because these renewable energy resources fluctuate temporally. Without storage options, they can only generate electricity intermittently. Although variability is not a new phenomenon in the power sector, the high penetration rates of VRE pose challenges for the management of the power grid because VRE technologies are not dispatchable, i.e., they cannot be called upon to operate at any desired time [26]. Hereafter, VRE is used to refer to wind and solar energy without storage capacity.

The issue of VRE intermittency in the power supply can be addressed in a number of ways. The most common measure is to use backup energy sources such as reservoir hydropower and gas turbines, which are able to respond rapidly to unexpected changes in power demand. Another approach is to use energy storage technologies to store generated electricity in storage media, e.g., pumped hydro storage (PHS), compressed air energy storage, batteries, fuel cells, flywheels, and super capacitors. Generally, PHS is regarded as the optimum large-scale energy storage technology currently available in China, because of its relatively low levelized cost compared with other storage technologies [27–30].

If available, reservoir hydropower is generally the preferred option for balancing variability in the supply and demand of electricity because it has excellent start-up and load-following characteristics, and because it is less expensive than other options such as PHS and gas turbines. For example, Denmark uses Norwegian and Swedish hydropower to balance most of its wind energy intermittency. However, the capacity of reservoir hydropower available in China to balance wind and solar energy intermittency is limited. China currently has the largest hydropower production in the world (total installed capacity in 2015: > 300 GW); however, most of the hydropower stations are used to meet the growing electricity demand and to balance variability in thermal plant generation. Therefore, the capability of China's existing reservoir hydropower capacity to mitigate wind and solar energy intermittency is limited. Moreover, most existing hydropower stations (70%) are located in southwestern China where water resources are abundant, while wind and solar resources are concentrated in northern and northwestern China. Because of the intervening long distances (several thousands of kilometers), the major hydropower sources in southwestern China are unsuitable for balancing wind and solar energy intermittency in northern and northwestern China.

The second option for balancing wind and solar intermittency is PHS, which also has considerable potential in China ranging from 100 to 300 GW in the long term [5]. However, the added cost of using PHS to balance intermittency would increase the total generation costs of wind and solar energy substantially. Assuming an initial investment of about 5000 RMB/kW, the annual operational time is the same as a wind farm (about 2000 h), the project life is 30 years, the discount rate is 8%, and the PHS efficiency is 75%, the additional cost from PHS would be about 0.27 RMB/kWh, even without considering the costs of operation and maintenance. This added cost would constitute about 40% of the total wind generation cost.

Another option is to use natural gas plants to balance wind and solar intermittency. However, existing gas turbine facilities are generally located near the centers of electricity demand in eastern China, far from the wind and solar energy sources. Moreover, natural gas generation in China is expensive in comparison with coal generation.

The capability of China's electricity grid for balancing VRE is limited. The power grid in China is dominated by coal electricity generation with hydropower playing a supporting role, while natural gas

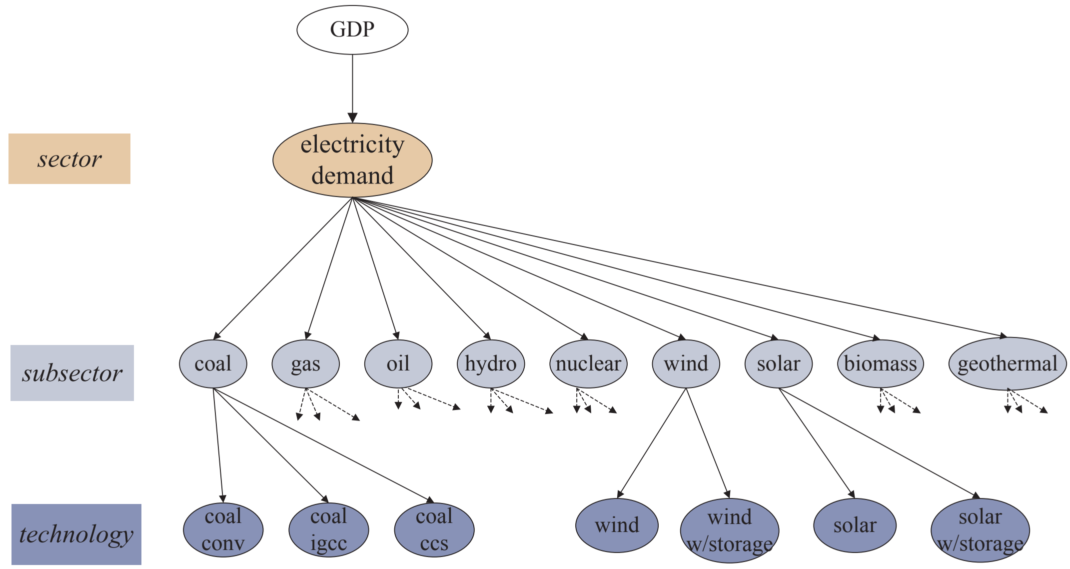

Fig. 1. Structure of power sector and competing technologies.

generation accounts for only 3% (in 2015) [1]. The dominance of coal is strikingly different from other developed countries, which tend to have greater diversification [31] with coal, oil, gas, nuclear, hydro, and renewable accounting for 32%, 3%, 24%, 18%, 13%, and 10%, respectively. Although coal fired electricity generation can, in principle, be used to balance VRE electricity, fluctuations in VRE increase the frequency of ramp-up/-down procedures, causing coal power plants to operate less efficiently in stabilizing the grid and in meeting the electricity demand. It implies that, when a large share of wind and solar generation is connected into the power grid, the grid needs to dispatch coal plants for balancing VRE at the cost of reduced coal generation efficiency (i.e., the coal efficiency penalty).

At a small share of generation in the power grid, VRE provides no more of a challenge than normal variation in electricity demand. However, as the share of electricity generated by wind and solar increases, intermittency becomes a greater problem because of the limited availability of reservoir hydropower and the costs of PHS and natural gas generation. Although other backup and storage technologies are available to maintain grid balance, most increase electricity costs substantially.

In summary, because of VRE intermittency, the additional grid cost (i.e., the integrated cost) and the reduced coal generation efficiency (i.e., coal efficiency penalty) for reaching the rated capacity from VRE with the same quality and quantity is expected to be significant compared with conventional generation options. The integrated cost and the coal efficiency penalty have important implications for future wind and solar energy development. These impacts of these two factors are analyzed in detail in Section 3.3.1.

3. Method

In this study, we used a modified version of the GCAM 4.2 to analyze China's wind and solar energy in the power sector. In this section, we describe the GCAM model and our adopted parameterization scheme to elucidate its application for the analysis of wind and solar intermittency in China. We made five primary modifications to the GCAM model. (1) The model was calibrated to 2015 using China's latest energy statistics (Section 3.2.1). (2) Power generation and the technology mix were adjusted to reflect the estimates of the Chinese government and academia for 2020 (Section 3.2.1). (3) Electricity demand was calibrated to follow a development path for the long-term electricity demand per capita similar to that observed in Europe and Japan (Section 3.2.2). (4) The costs of wind and solar were adjusted to reflect China-specific estimates of the incremental costs of grid integration (Section 3.3.1). (5) The penalty of coal generation efficiency, resulting from the use of coal power plants for grid balancing, was considered in this study (Section 3.3.2).

3.1. GCAM integrated assessment model

GCAM 4.2 is a global integrated assessment model with 32 geopolitical regions, operating on five-year time steps through to the end of the century. China is represented as a single region. GCAM has been used extensively in numerous assessments and modeling activities, e.g., the Stanford Energy Modeling Forum (EMF), U.S. Climate Change Technology Program (CCTP), U.S. Climate Change Science Program (CCSP), and Intergovernmental Panel on Climate Change (IPCC) assessment reports [32]. GCAM is a community model, the source code, data, and executable module of which are available at http://www.globalchange.umd.edu/models/gcam/download/. Unless specified otherwise (see below), we used the default parameters in the release version of GCAM 4.2.

Ultimately, electricity demand is driven by GDP, population, and the price of the energy services, e.g., lighting and temperature control. GCAM uses a vintage representation of electricity generation capital stocks. Existing plant and equipment are assumed to operate until retired. New vintages are added in each period to serve new demands and to replace retired capital stocks, with alternative technology options competing at the investment margin. The mix of new capital investment in electricity generation technology depends on the expected levelized cost of production over the course of the unit's lifetime. The distribution of investment in new technologies (i.e., liquids, gas, coal, hydro, nuclear, wind, solar, biomass, and geothermal) is modeled using a logit choice model [33]. The cost of providing electricity for each technology includes two components: a fuel cost and a non-energy (capital and operation) cost. Non-energy costs and technology efficiencies improve over time to reflect technological change. Fuel costs evolve with improving technology efficiencies and changes in the price of input fuels, which could include price increases associated with carbon prices. Technology options for the power sector and its subsectors are shown in Fig. 1. Typically, for each subsector, several technologies are available. For example, coal generation technologies include conventional pulverized coal generation, Integrated Gasification Combined Cycle generation, and coal generation with carbon capture and storage (CCS).

GCAM uses a reduced-form representation to account for the inclusion of wind and solar sources in the power sector. Electricity generation of wind and solar (PV and concentrated solar power) is grouped into two categories: one without storage capability and the other with backup technologies to maintain reliability of the power grid. Therefore, it is possible to include generation with storage as a means by which to reduce the limitations attributable to intermittency. As the percentage of solar and wind without storage increases, increasing quantities of backup power from reservoir hydropower, PHS, and natural gas generation are required to maintain system integrity and reliability. Considering the dominance of coal power plants in China, in this study, we incorporated a generation efficiency penalty to represent the use of coal generation technologies as backup power.

As a popular integrated assessment model, GCAM has been used extensively for studies at the regional level (e.g., in China and the US). The results obtained from GCAM modeling have been verified reliable following evaluation in many studies. For example, GCAM has been used to model the energy and CO_2 emissions in building, industry, and power sectors in China both nationally and regionally [34–41]. Moreover, GCAM is an open source model. All parameters and data used in the GCAM model are transparent.

3.2. Calibration based on China's statistics and projections

3.2.1. Base year calibration

GCAM (release version) was calibrated for the base year of 2010 using IEA and OECD data sources [42], which are generally consistent with official Chinese energy statistics. However, differences exist between the default GCAM projections and those from official Chinese sources for 2015 and 2020. For example, the total electricity generation in 2015 and 2020 in the release version of GCAM is only 86% and 87% of the current situation and the government target, respectively. The breakdown by electricity generation technology (i.e., hydro, nuclear, wind, biomass, and solar) falls within a 30–70% range of difference compared with current deployment levels (in 2015) [1,2,5].

In this study, we calibrated the base year of GCAM to 2015 and we re-parameterized the model for consistency with the official targets of the Chinese government for the power sector in 2020. This brought both the total and the individual technology generation estimates into line with the latest targets of the Chinese government and other authoritative reports. The calibration was performed through a two-step process. In the first step, we calibrated the total electricity demand in both 2015 and 2020 by adjusting China's income elasticity of demand to be consistent with the actual situation and the official targets of the Chinese government. In the second step, we calibrated the fuel mix of electricity generation (i.e., the shares of coal, oil, gas, nuclear, hydro, wind, solar, and biomass) in both 2015 and 2020 by adjusting the parameters (i.e., share weights of fuel types) in the logit choice function in GCAM. With these two steps, the total electricity demand and the fuel mix of electricity generation were in accord with the current situation in China.

3.2.2. Long-term electricity demand

We examined the trend of future electricity demand per capita in China and compared it with the trends in other developed economies to ensure that our modeling assumptions relevant to future electricity growth were consistent with the experiences of other countries. Fig. 2 shows historical per capita electricity demand mapped against per capita income in China together with presently industrialized economies that include Western Europe (WEU: i.e., Belgium, France, Germany, Italy, Spain, and the United Kingdom), Japan, and Korea [43]. We assumed that China's per capita electricity demand would grow with per capita income in a manner similar to the pattern observed in WEU and Japan rather than that seen in the USA or in Canada. We chose the WEU/Japan growth pathway because this reflects more closely China's special circumstances, particularly its limited availability of energy resources and the government's focus on reducing energy intensity, energy use, and CO_2 emissions. Under this assumption, electricity

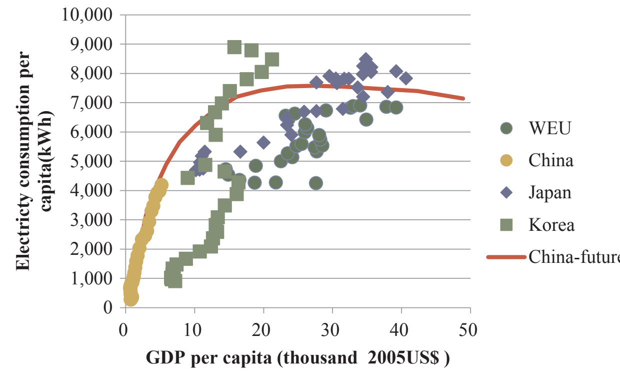

Fig. 2. Relationship between per capita income and electricity demand. The points show historical data and the red line is the projected pathway for China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

demand per capita in China is expected to be 7550 kWh in 2050 (the 2005 average level in WEU/Japan). After 2050, the change of electricity demand per capita is forecast to be relatively minor.

3.3. Incorporation of wind and solar intermittency

3.3.1. Integration cost for wind and solar energy

Integration cost typically refers to the additional cost incurred when operating VRE in reaching the rated capacity from VRE with the same quality and quantity as from conventional generation options. The incremental integration cost could constitute a considerable proportion of the total generation cost and it could become increasingly significant as the share or penetration of VRE in the electricity grid increases [44]. Integration cost can vary dramatically spatially because of the availability of different VRE resources. A number of studies have shown that the integration cost could range from 18% to 30% of the generation cost when the share of wind generation reaches up to 20%, and it could reach up to 50% of the generation cost when the share of wind generation reaches up to 30–40% [44–54].

At the power grid level, two principal factors influence VRE integration cost: balancing cost and grid cost. Balancing cost depends substantially on the availability of flexible resources within the system. For example, because Denmark is connected to the European power grid, excess wind energy generation can be exported, and when domestic wind energy generation is insufficient, Denmark can import electricity. Therefore, the integration cost in Demark is relatively low. Nevertheless, the integration cost in Denmark is about 20–30% with a wind generation share of 20%. If standby capacity in the form of gas turbines is required, then the balancing cost could add one-third to the cost of electricity from wind alone [48,49,54–56]. If flexible resources are inadequate or unavailable, requiring additional storage facilities such as PHS or backup capacities for the peak period to be deployed, the integration cost could be even higher. In terms of the grid cost, long-distance transmission could also add about 33% to the generation cost of VRE [53].

In China, because of the limited availability of reservoir hydropower and the expense of both PHS and natural gas for balancing VRE, as stated in Section 2, the balancing cost is higher than in other countries. Furthermore, transmission distances in China are long. For example, the distance from the wind farms in Jiuquan of Gansu Province to the demand centers in the coastal zone is about 1500–2500 km. For the wind farms in Xinjiang Province, the distance is even longer (3000–4000 km). Therefore, the integration cost (balancing and grid) in China's power sector is expected to be significant, which has important implications for wind and solar energy development. According to previous studies in other countries [44–54], and with consideration of China's current relatively advanced technologies [31], this study assumed an integration cost of 20% for wind and solar energy electricity at the penetration rate or market share of 20%. The integration cost is proportional to the wind and solar energy penetration rate or market share, which means that if the share of wind and solar energy were 10%, then the integration cost would be 10% proportionally.

3.3.2. Coal efficiency penalty

In principle, coal fired electricity generation could be used to balance VRE generation. However, the cost and technical problems associated with cycling a coal plant (i.e., sudden increases/decreases in power generation output) generally make it the least attractive option if other options such as reservoir hydropower are available. However, coal is the dominant source of electricity generation in China, which could be and has been used for load balancing. Fluctuations in VRE increase the frequency of ramp-up/-down procedures, causing coal power plants to operate less efficiently when stabilizing the grid and meeting the electricity demand. This means extra fuel would be used because of the decreased efficiency of coal generation; thus, the reduction of CO_2 emissions could be less than anticipated because of the coal plant cycling. The decrease in coal generation efficiency is referred to as the coal efficiency penalty. A previous study found an increase of 8–10% in both fuel consumption and emissions for a wind turbine of average power in comparison with the steady operation of thermal power plants [50]. It implies that the thermal efficiency could be reduced by 8–10% under high rates of wind and solar penetration.

A coal efficiency penalty of 5% was used in this study when the VRE share reached 20% of the total electricity generation, based on the findings of previous studies in other countries [50] and "learning by doing" through the world's largest accumulated installed capacity of coal generation in China (IEA, 2016). The decrease of coal efficiency is proportional to the VRE penetration rate or market share; thus, if the VRE share were 10%, the efficiency would decrease by 2.5% proportionally.

3.4. Future scenario setting

In this study, we investigated the roles of wind and solar energy in China's power sector under two scenarios: a reference scenario (REF) and a climate mitigation scenario (CMS). These two scenarios were identical in terms of their social and macroeconomic drivers [57], having the same per capita electricity demand, as discussed in Section 3.2.2. They differed only in that in the CMS, an economy-wide carbon price was imposed on greenhouse gas emissions in all time periods. The carbon price started at \$20/tCO_2^{-1} (2005 US\$ price) and it increased at a rate of 5% per annum through to the end of the century [58]. Both the REF and the CMS considered VRE intermittency through the system integration cost and the coal efficiency penalty. We investigated the impact and difference between the results of the two scenarios both with and without consideration of VRE intermittency, especially in relation to high penetration of wind and solar energy in the power sector over the long term.

4. Results and discussion

To demonstrate the implications of VRE intermittence, we first present results with consideration of VRE intermittence, including wind and solar electricity generation (Section 4.1), contribution of wind and solar in the power grid (Section 4.2), substitution effect of wind and solar energy (Section 4.3), and CO_2 emission reduction (Section 4.4). Then, in Section 4.5, we compare the difference in cost per kWh, CO_2 per kWh, and fuel share both with and without consideration of VRE intermittence. Finally, with consideration of the uncertainty of the parameters of integrated cost and coal efficiency, sensitivity analyses are performed on wind and solar intermittency in Section 4.6.

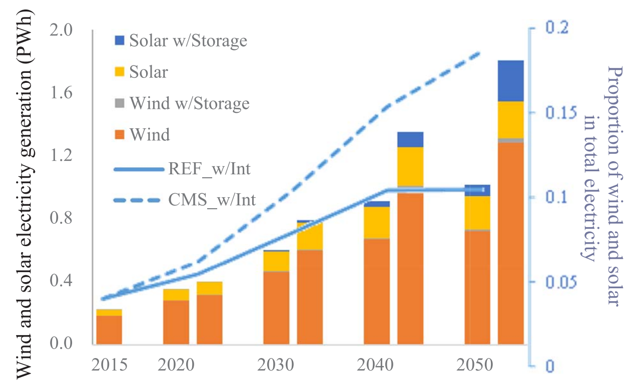

Fig. 3. Wind and solar electricity generation in the REF (left) and CMS (right).

4.1. Wind and solar electricity generation

Wind and solar electricity generation continue to grow rapidly until 2050 in both scenarios (REF and CMS). In the REF (left bar in Fig. 3), the total electricity generation of wind and solar in 2050 is about 4.5 times that of the level in 2015 (0.22 PWh). Their electricity generation share increases from 4% in 2015 to 10% in 2050. This result largely represents the outcome of a world without policy interventions that might increase the trend of wind and solar deployment. However, actual wind and solar deployment will be influenced by the policies adopted by China that are designed explicitly to increase wind and solar deployment to address environmental concerns. Such concerns are considered in the CMS (right bar in Fig. 3). The imposition of a carbon price accelerates the deployment of wind and solar energy in comparison with the REF. The total electricity generation of wind and solar in 2050 is about eight times that of the level in 2015, and the share of the total electricity generation increases to around 20%, i.e., substantially higher in comparison with the REF. The total wind and solar electricity generation in the CMS is about twice that of the REF because of the substitution of wind and solar energy for fossil energy. The carbon price drives the power sector to switch energy fuel to low carbon energy types, such as renewable energy, nuclear, and fossil fuel with CCS.

With respect to individual wind and solar (including PV and concentrated solar power) technologies, the deployments of wind, wind with storage, solar, and solar with storage all expand through to 2050. Compared with 2015, wind and solar without storage in 2050 will increase by several times (i.e., by 4.0 and 5.5 times in the REF, and by 7.0 and 6.0 times in the CMS), while wind and solar with storage will increase by more than 10 times because of their comparatively small amounts of generation in the base year (2015).

4.2. Contribution of wind and solar energy

In 2015, coal dominates the generation mix. Coal fuel provides about 70% of the total generation, compared with 19% from hydropower, 3% from natural gas, 3% from nuclear, 3% from wind, and 1% from solar, biomass, and others. This generation mix evolves gradually to low carbon fuels in both the REF and the CMS in the future. In the REF, the coal share will decrease to 63% in 2030 and to 56% in 2050 (left bar in Fig. 4). The non-fossil fuel share will increase to 32% in 2030 and to 36% in 2050. Among the non-fossil fuels, the wind and solar share will increase to 8% in 2030 and to 10% in 2050. In the CMS, the most prominent change in the power sector's structure is observed for coal without CCS, the share of which is reduced to 30% in 2050. However, the share of electricity generated by coal with CCS will increase from nearly zero in the REF to 5% in the CMS in 2050. At the same time, the share of nuclear will increase from 8% to 15% in 2050. For wind and solar energy, the share will increase from 10% to 20% by 2050.

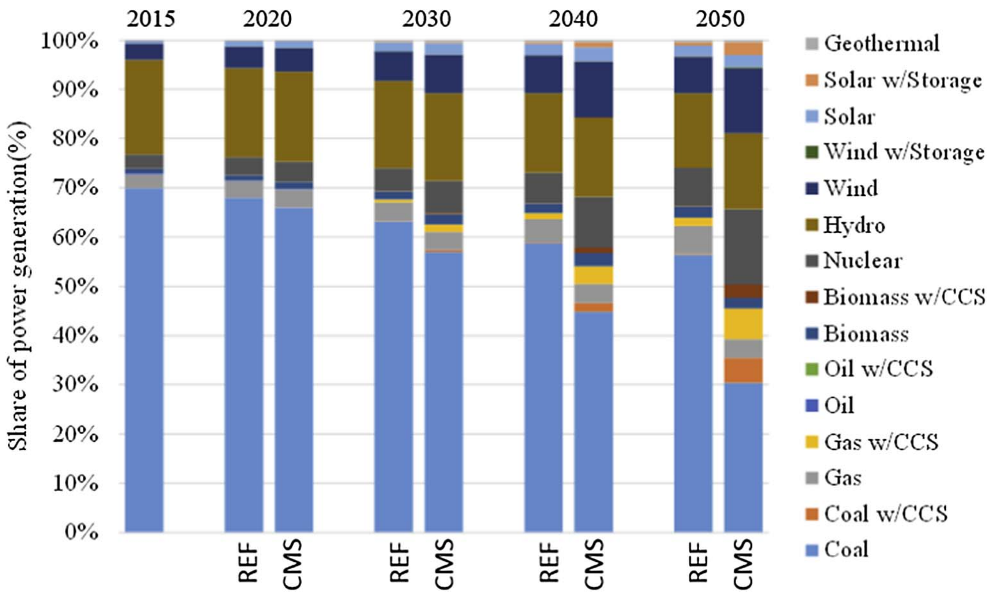

Fig. 4. Power generation share in the REF and the CMS.

Hydropower dominates renewable electricity generation in 2015, contributing more than 80% of all renewable electricity. Moving forward, hydropower generation follows a fixed pathway that is independent of other assumptions [5]. There is therefore no change for hydropower between the REF and the CMS. Following this fixed pathway, its share decreases steadily after 2020 to reach 15% by 2050. The decline in the relative contribution of hydropower represents an assumption that relatively low potential for hydropower remains available after 2020. Biomass without CCS is less advantaged compared with wind and solar and it increases slowly because of the effects of increasing costs in relation to bioenergy collection and production. Geothermal deployment increases gradually but its deployment by 2050 remains low in absolute terms.

4.3. Substitution effect of wind and solar energy

The substitution effect refers to the electricity generation portfolio (fuel mix) in the case without the availability of wind and solar power. It reflects the magnitude of per unit electricity from non-wind and non-solar electricity sources (coal, oil, gas, hydropower, nuclear, and biomass) that is replaced by wind and solar energy electricity. The substitution effect was calculated in two steps. First, wind and solar electricity generation was assumed zero. Then, the shares of other non-wind and non-solar fuels were calculated.

The substitution is the marginal replacement of electricity generation resulting from wind and solar energy availability and it is shown as a normalized share in Fig. 5. The substitution effect between the REF and the CMS is not simply a case of increasing wind and solar energy by replacing coal. Before 2030, wind and solar electricity generation largely replaces electricity from coal generation and hydropower in both the REF and the CMS. By 2050 wind and solar electricity generation replaces substantially different technology mixes in the REF and the CMS. In addition to the replacement of coal and hydropower, natural gas (including gas with CCS) and nuclear are also replaced in the CMS and the shares of the replaced electricity generation sources are much more diverse.

4.4. CO_2 emissions reduction

China's power sector shows considerable progress along its low carbon pathway from 2015 to 2050 under the two scenarios. As shown in Fig. 6, carbon emissions per unit generation decrease gradually in both scenarios. The grid emissions factor is calculated as the generation-weighted average CO_2 emissions per unit net electricity generation of all generating power plants within the grid system. The grid emissions factor in China's power sector is 0.73 tCO_2/MWh in 2015; by 2050, it decreases to 0.52 tCO_2/MWh in the REF and to 0.31 tCO_2/MWh in the CMS. Thus, compared with the emissions level in 2015, the emissions factor by 2050 will decrease by about 30% in the REF and by about 60% in the CMS.

The reduction in carbon emissions attributable to wind and solar energy was calculated as the electricity generated by wind and solar energy multiplied by the grid carbon emissions factor under the two scenarios. Wind and solar electricity generation reduces CO_2 emissions by 160 $MtCO_2$ in 2015. In 2050, the corresponding CO_2 reduction is 530 and 570 $MtCO_2$ in the RES and the CMS, respectively. Compared with the REF, the emissions reduction in the CMS by 2050 is only about 8% more and it is not proportional to the difference of wind and solar electricity generation, which is about twice that of the RES. The reason for this disproportionate difference is that the carbon emissions factor in the CMS is lower than in the REF. The smaller reduction by 2050 in the CMS is because wind and solar electricity not only substitutes fossil fuels but also other low and non-emissions technologies such as nuclear, hydropower, and CCS.

4.5. Implications of wind and solar intermittency

When intermittent wind and solar energy comes online, coal generation ramps up/down to meet electricity demand. This decreases the operating efficiency of coal generation plants, resulting in higher emissions than if they had not been cycled. To explore the integrated influence of intermittency in the power sector, we compare the following key indicators with and without consideration of intermittency at high penetration rates of wind and solar energy in 2050 in the REF and the CMS.

Compared with the case without consideration of wind and solar energy intermittency, the REF has a reduction of 2.5% in coal efficiency by 2050, which makes coal a less attractive option. However, because of the additional integrated cost of wind and solar energy, the share of coal generation will still increase by 0.5%. Furthermore, the grid generation cost per kWh (average generation cost of coal, oil, gas, nuclear, hydro, and renewable weighted by their generation) and the CO_2 emissions per kWh will increase by about 1.2% and 1.8%, respectively (left bar in Fig. 7). In the CMS, these changes will be doubled or tripled (right bar in Fig. 7). Therefore, with consideration of wind and solar intermittency, the reduced energy efficiency in coal generation will

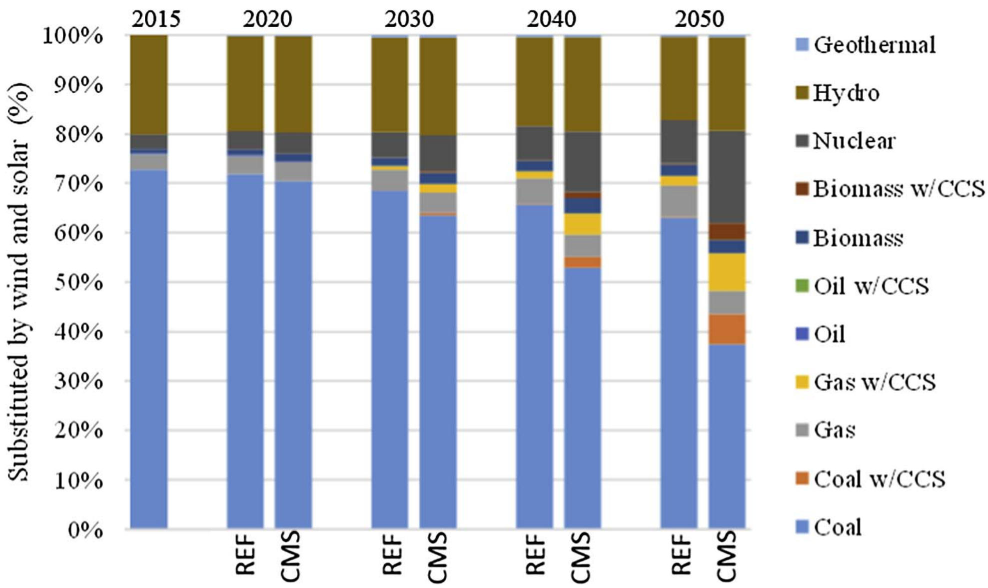

Fig. 5. Substitution effect by wind and solar electricity in the REF and the CMS.

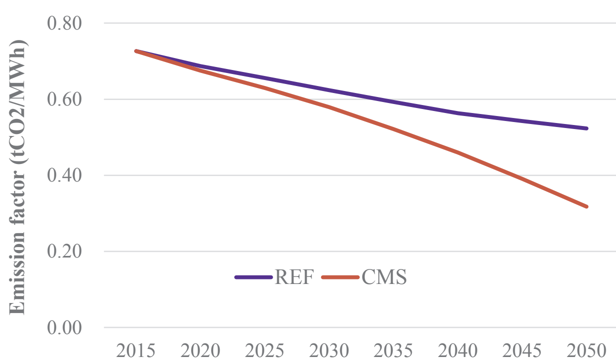

Fig. 6. Carbon emissions factor in China's power sector (tCO_2/MWh).

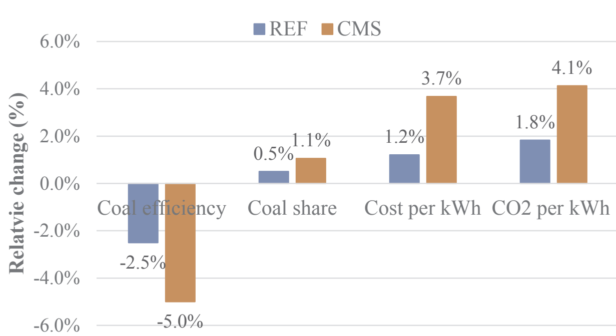

Fig. 7. Integrated influence of wind and solar intermittency in 2050.

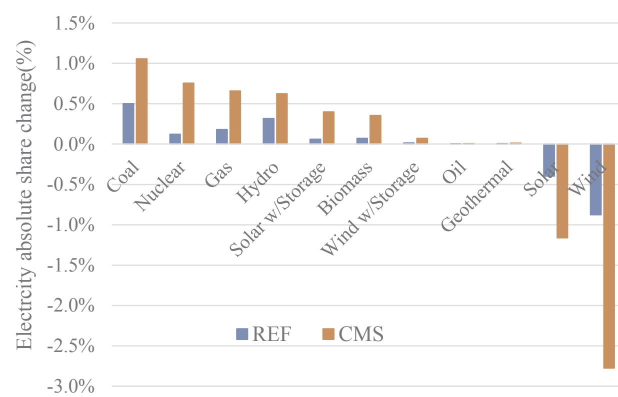

Fig. 8. Influence of wind and solar intermittency on electricity generation share in 2050.

result in an increase of CO_2 emissions per kWh of coal electricity produced, canceling out some of the emissions reduction brought about by the expansion of wind and solar electricity generation.

To demonstrate the integrated influence of intermittency on electricity generation mixture, we compare electricity generation with and without consideration of intermittency in the REF and the CMS in 2050. The changes in the absolute shares of electricity generation by fuel type are shown in Fig. 8. To meet the same electricity demand, wind and solar power without storage capability by 2050 will lose generation share of 0.4% and 0.9%, respectively, in the REF and 1.2% and 2.9%, respectively, in the CMS. Conversely, the generation shares of coal, nuclear, natural gas, hydropower, solar with storage, biomass, and wind with storage will increase in the range of 0.1–0.5% in the REF and in the range of 0.1–1.0% in the CMS. The integration cost for wind and solar power shows an important impact on the technology mix of electricity generation in China. In particular, by 2050, wind and solar without storage capacity make the share of wind and solar electricity decrease by more than 10% and by more than 15%, respectively, in comparison with the case without consideration of the intermittency of wind and solar energy.

In summary, when considering the intermittency of wind and solar energy, the importance of wind and solar energy in China's power sector could diminish in the long term. Moreover, CO_2 emissions per kWh increase by about 1.8% and 4.1% in the REF and the CMS, respectively (Fig. 7). Considering both the decrease of wind and solar share and the increase of CO_2 emissions per kWh, the reduction of CO_2 emissions anticipated following the deployment of wind/solar energy in China's power grid would be lower than without consideration of VRE intermittence in the REF and the CMS.

4.6. Sensitivity analysis of wind and solar intermittency

Because of limited research and actual data regarding the integrated cost and coal efficiency penalty of VRE in China, we based our assumptions (see Section 3.3.1) on data from other developed countries. Considering China's specific situation and the technical improvements of recent years and those possible in the future, optimistic values of the integrated cost and coal efficiency penalty were used in this work. Considering the uncertainty of these two important parameters, a

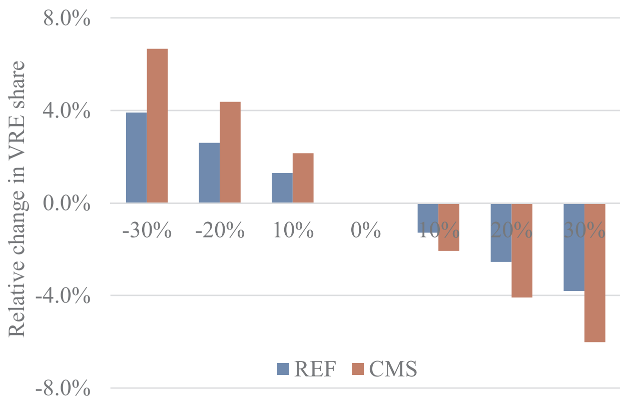

Fig. 9. Sensitivity analyses of the VRE share to the VRE integrated cost and coal efficiency penalty in 2050.

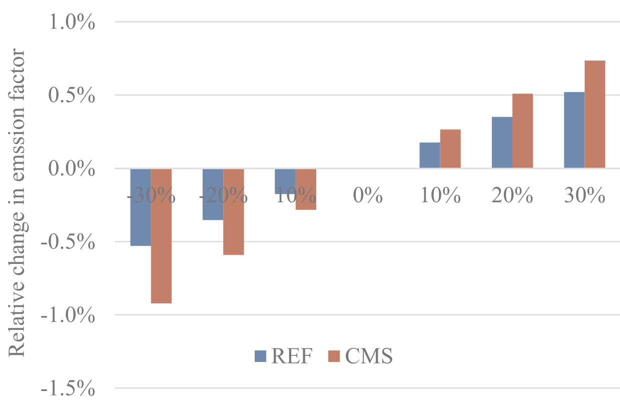

Fig. 10. Sensitivity analyses of the grid emission factor to the VRE integrated cost and coal efficiency penalty in 2050.

sensitivity analysis is performed.

We evaluate the uncertainty of these two parameters in terms of two trends: overestimation of the VRE intermittence effect, which implies the VRE integrated cost or coal efficiency penalty could be overestimated, and underestimation of the VRE intermittence effect. A range of ± 30% with an interval of 10% is implemented in the sensitivity analysis (Fig. 9). Here, ± 30% means the integrated cost or coal efficiency penalty increases or decreases by 30%. It is unsurprising that the VRE share in 2050 increases with reduced VRE integrated cost and coal efficiency penalty compared with the case using the reference parameters, and that the share decreases with increased VRE integrated cost and coal efficiency penalty in both the REF and the CMS. It is also found that the VRE share decreases by 1.3% and 2.1% in the REF and the CMS, respectively, when the VRE integrated cost and coal efficiency penalty increase by 10%. The reason for the different behaviors in the REF and the CMS lies in the different VRE shares in these two scenarios; generally, the VRE share in the CMS is higher than in the REF.

Similar to the VRE share, the change of grid CO_2 emission factor in 2050 (compared with the case using the reference parameters) shows an approximately linear trend with the change of VRE integrated cost and coal efficiency penalty (Fig. 10). It implies that with an increase of 10% in the VRE integrated cost and coal efficiency penalty, the grid CO_2 emission factor increases by 0.2% and 0.3% in the REF and the CMS, respectively. This difference between the two scenarios is due to the different VRE shares.

5. Conclusions

This study explored the potential long-term roles of wind and solar energy in China's power sector by consideration of the problem of their intermittency. Most importantly, we explored the impacts of the intermittency of wind and solar (i.e., integration cost and coal efficiency penalty) on wind and solar electricity generation and on their shares within China's power sector. The sensitivity of the VRE share and grid CO_2 emission factor to the important factors of integration cost and coal efficiency penalty was also investigated.

We found that wind and solar energy in China's power sector would continue to grow dramatically up to 2050 in both the REF and the CMS. Carbon tax will play an important role in increasing wind and solar development, as indicated by the increase by 2050 of wind and solar in the CMS of about twice that in the REF. The development of wind and solar energy will gradually change the evolution of the electricity generation mix. We found that wind and solar electricity, prior to 2030, will primarily replace coal and hydropower generation under both scenarios. With the adoption of climate mitigation policies, wind and solar electricity will increasingly replace nuclear and gas generation by 2050. Increasing wind and solar generation will reduce CO_2 emissions in China's power sector. We estimated that the grid carbon emissions factor will decrease by about 30% and 60% by 2050 compared with the 2015 level, and that the corresponding CO_2 reductions attributable to wind and solar will be 530–570 $MtCO_2$ in the REF and the CMS.

Intermittency of wind and solar energy has an important effect on its economic attractiveness and deployment. We estimated that the combined effect of the integration cost and the coal efficiency penalty for wind and solar energy, without storage capability, would reduce their deployment, i.e., by 2050, the shares of wind and solar energy would decrease by more than 10% and by more than 15%, respectively, compared with the case without consideration of intermittency. Moreover, the coal share, grid generation cost, and carbon emissions per unit generation would increase by 0.5–1.1%, 1.2–3.7%, and 1.8–4.1%, respectively. The sensitivity analysis showed that the VRE share is negatively proportional to the VRE integrated cost or the coal efficiency penalty.

In this paper, the conclusions regarding VRE intermittency and its impact on China's power sector are drawn from analyses on the macro level over the long term. Investigations of intermittency on the micro level and on the technical level are also highly desirable in order to elucidate the importance of this issue.

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