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Costs and benefits of renewable energy development in China's power industry

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ABSTRACT

China's power sector has become the largest contributor to China's carbon emissions because of its coal-dominated power structure. Replacing fossil fuels with renewable energy is an effective way to reduce carbon emissions and, therefore, a series of targets for renewable electricity generation have been put forward in national plans. However, how these targets will be reached is unclear. This paper uses a Long-range Energy Alternative Planning system (LEAP) model to explore the optimum development path of China's power sector from 2015 to 2050, taking into consideration the impacts of the renewable energy targets. Three scenarios are designed to examine the costs and benefits of developing renewable energy and improving the technologies for renewable power generation, comprising a base scenario, a renewable energy policy scenario and a technological progress scenario. The results show that the power generation cost would increase by at least 2.31 trillion RMB and that CO_2 emissions would be reduced by 35.8 billion tonnes during 2015–2050 if power generation follows current planning. Furthermore, every 1% increase in the capacity factors of renewable electricity would on average result in the cumulative CO_2 emissions decreased by 979 million tonnes and average CO_2 abatement cost decreased by 5.56 RMB/tCO_2 during 2015–2050. Based on this study, several policy implications are proposed for the development of power sector in China. Firstly, government may reconsider the current planning for gas-fired power and nuclear power to reach low-carbon electricity generation. Secondly, adjusting the carbon price can offset the additional cost of renewable electricity generation. Thirdly, promoting advanced technologies to match renewable electricity generation can obtain greater economic and environmental benefits. Finally, from the perspective of development potential, reducing the costs of solar power would be the emphasis at this stage.

1. Introduction

China has become the largest contributor to CO_2 emissions around the world, accounting for more than a quarter of global CO_2 emissions since 2009 [1,2]. This results mainly from the large amounts of fossil fuels that are being consumed in progressing China's economic development. In order to mitigate the associated environmental issues, the Chinese government has set targets to cut CO_2 emissions per unit of GDP by 40–45% by 2020 and 60–65% by 2030 relative to those of 2005 levels [3,4]. The power industry is the largest contributor to China's carbon emissions. In the past decade, CO_2 emissions in the power sector have accounted for about 49.1% of China's CO_2 emissions and 32.1% of the world's CO_2 emissions because of the industry's coal-dominated power structure [5]. Therefore, turning to low-carbon electricity generation would have a significant impact in terms of reducing emissions [6]. Due to the lack of natural gas and the safety of nuclear energy, replacing fossil fuels with renewable energy could be an option for achieving sustainable development of China's power sector [7–11].

At present, coal remains the main source for electricity generation in China. The share of coal-fired power in total electricity generation was about 69% in 2015 (see Fig. 1), which is much higher than developed countries [12]. For instance, in 2015, the coal-fired power accounted for 34%, 23% and 2% of the total power generation

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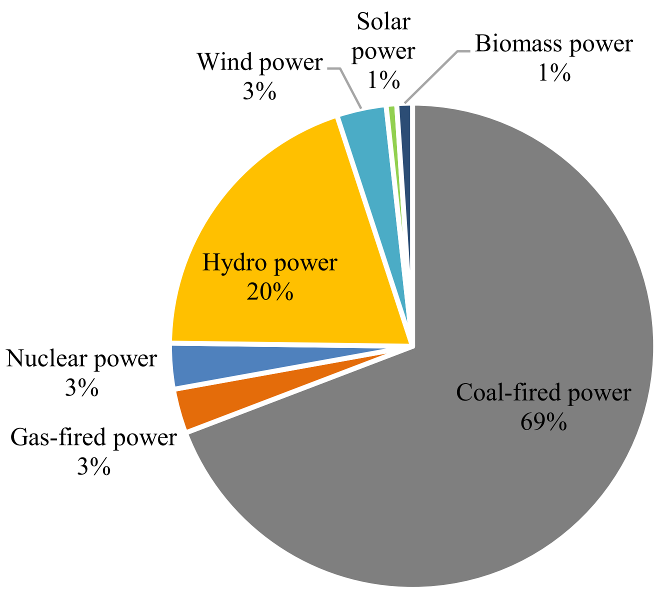

Fig. 1. Share of electricity generated by different technologies in China in 2015 Data source: Planning and Statistics of China Electricity Council.

in the United States (US), the United Kingdom and France, respectively [13]. There is a large gap between China's performance in clean power generation and that of other countries. In order to improve its share of clean energy power generation, the Chinese government has set a series of plans for nonfossil energy. These targets aim to increase the share of nonfossil energy in the total primary energy to at least 15% by 2020, according to China's 13th Five Year Plan, and to 20% by 2030, according to US-China Joint Presidential Statement on Climate Change [3,4]. More detailed medium- and long-term planning for renewable electricity generation has been put forward. For example, there are plans for the capacity of wind power and solar power to reach 210 and 110 GW respectively, by 2020. However, there is no clear instructions guiding the deployment of power generation technologies (including both renewable and non-renewable technologies) to achieve these plans. Moreover, the capital requirements and environmental impacts accompany with these proposed plans are unknown.

To answer these questions, this paper simulates the optimal development path for the power sector, based on minimum costs, using the Long-range Energy Alternative Planning system (LEAP) model. First, the strategies for investment and operations under current planning are proposed. The impacts of renewable electricity planning on costs and CO_2 emissions are determined by comparing a base scenario (BAU) and a renewable energy policy scenario (REP). Further, technological progress in relation to renewable electricity generation is considered. By comparing the REP and a technology progress scenario (TechImp), the impacts of technological progress on costs and CO_2 emissions are assessed.

The structure of this paper is as follows. Section 2 provides literature review and Section 3 presents the methodology and data. In Section 4, we determine the optimal development path for China's power sector and provide a discussion. Section 5 summarizes the main conclusions and Section 6 puts forward corresponding policy implications.

2. Literature review

A myriad of studies have highlighted the importance of renewable energy in decarbonizing electricity generation worldwide by examining the relationship between renewable energy use and CO_2 emissions. Some of the existing studies have analyzed the impact of pollutant emissions targets on the power development path. For instance, Koltsaklis (2014) presented a mixed-integer linear programming (MILP) model for the optimal long-term energy planning of power generation system in Greece considering the national environmental policy. The results show that the installed capacity of wind turbines and solar plants need to reach 5452.4 MW and 2123.7 MW in 2020, and 8452.4 MW and 2723.7 MW in 2030 [14]. Barteczko-Hibbert (2014) developed a multi-period MILP model to explore future pathways for electricity supply in the United Kingdom considering the carbon reduction targets. The results show that the percentage contribution of renewable electricity will reach 40% in 2060 [15]. Anandarajah (2014) analyzed the role of renewables to meet India's climate change mitigation targets in 2050 using a multi-region global energy system model called TIAM-UCL. The results show that renewable energy can play an important role to decarbonize the economy, especially the solar and wind. The renewables will contribute 63% of total CO_2 reductions by 2050 [16]. Muis (2010) developed a MILP model for the optimal planning of electricity generation schemes to meet CO_2 emission target in Peninsular Malaysia. The study predicted that Malaysia has potential to generate up to 9% of electricity from renewable energy based on the available sources [17]. Further studies have directly analyzed the impact of renewable energy consumption targets and capacity planning on power development paths. For example, Park (2016) explored the optimum renewable energy portfolio in Korea considering the 3rd Renewable Energy Basic Plan using TIMES model, which is one of the leading bottom–up models. The study projected that the annual electricity generation amounts would achieve 7205 GWh by solar power and 12268 GWh by wind power in 2030 [18]. Georgiou (2016) proposed MILP energy model for the long-term electricity planning of Greek power supply sector considering renewable energy penetration target. The results show that the share of renewable electricity generation will reach around 50% after 2020 [19]. All these studies showed that developing renewable energy can play an important role for reducing fossil-fuel consumption and CO_2 emissions, and national planning could effectively promote the utilization of renewable energy.

Renewable energy development has attracted much attention in China and many factors influencing electricity generation have been considered. Some studies focus on the promulgated environmental policy, particularly the pollutant emission target and the nonfossil fuels consumption target. For instance, Qi (2014) analyzed the impact of renewable energy development on energy and CO_2 emissions considering renewable electricity target at that time. And the computable general equilibrium (CGE) model, which is a top-down model, is chosen and applied. The study found that temporal renewable electricity targets result in significant additional renewable energy installation and 1.8% reduction of cumulative CO_2 emissions from 2010 to 2020 [20]. Pan (2017) explored how to transform China's energy system towards the 2 °C target until 2100 using GCAM model. The results show that renewable power would dominate the electricity supply, accounting for 47–49% in 2050. In 2100, almost 90% of power is provided by non-fossil sources [21]. Zhang (2012) put forward a multi-period modelling and optimization approach to layout the development of power generation technology considering carbon dioxide mitigation. The study shows that renewable power and nuclear power accounts for more than 1/3 and 1/2 of power generation by 2050, respectively [22]. In addition, other factors, such as taxes, subsidies and GDP growth have been considered. Wu and Zhen (2016) evaluated the effects of implementing two different subsidy programs for renewable energy development [23,24]. Chen (2011) evaluated the effects of improving the resource potential of wind power and nuclear power on power generation technology development [25]. Zhang (2014) evaluated the effects of implementing four policies, which assumed different CO_2 emission caps, a carbon tax payment method and a revenue acquisition method [26]. Lu (2015) explored China's wind power development path considering "Twelfth Five-Year Plan" and evaluated the impact of environmental parameters on wind power, including effects on the GDP growth rate, the investment ratio cap, the learning rate, the carbon permit price and the grid constraint [27]. However, it can be seen that most studies are a little out of dated, which have not considered the capacity planning proposed in the latest and the most important 13th Five-Year Plan for Power Energy Development in China. Although Cong, Chen (2013, 2016) considered capacity planning for renewable electricity until 2020 and 2030, respectively, in their power generation planning models, their studies focused on the power planning and had no in-depth analysis of the impact of planning on emissions and costs [28,29]. Moreover, capacity factors of each electricity generation technologies are treated as fixed values in the previous studies. The impact of capacity factor changes on the power development path for China should also be taken into account with the technological progress.

Regarding the methods widely used for exploring and evaluating the development of renewable energy in the power sector in existing literature, they can be summarized into two types, namely top-down and bottom-up models. The CGE model is the representative of the top-down model, which is able to analyze the interaction between energy consumption, environmental influence and economic outputs, but with an aggregate description of the technologies [18]. While, the bottom-up model is superior on simulating the details of technology development on the energy consumption and environmental impacts [30], but alongside a poor link with the whole economic system. From the perspective of instructing the deployment of power generation technologies by taking the renewable energy plans into consideration, the bottom-up model seems to be more appropriate. Among them, the LEAP model is a widely used model attributing to its simple maneuverability. For instance, Kumar (2016) introduced the national power planning of renewable electricity into study to explore the development pathway of renewable electricity and accessed its impact on CO_2 emissions in India using LEAP model [31]. Özer (2013) analyzed the CO_2 mitigation potential in the Turkish electricity sector using LEAP model [32].

Consequently, building on the existing literature and methods, this paper considers the renewable electricity capacity plan mentioned in the 13th Five-Year Plan for Power Energy Development, other long-term national plans and technological progress in renewable generation by adopting the LEAP model. Further, the impacts of these plans and technological progress on power generation costs and CO_2 emissions are analyzed. In this way, we aim to provide a more comprehensive and accurate evaluation of renewable energy generation performance.

3. Methodology

3.1. Research framework

The research framework is presented in Fig. 2. First, a series of basic data, including electricity demand, existing installed capacity, power generation costs, resource potential and so on are entered into the LEAP model as input data. With the goal of minimizing the total costs (including investment and operation and maintenance (O&M) costs), the appropriate development pathway in the power sector is obtained by applying the LEAP model. The model considers the following constraints, power demand, the capacity factors, maximum capacity additions of each generation technologies, the resource potential of all renewable energies. In addition, the national plans about renewable energy development are also taken into account. Following configuration of the model, this paper develops three scenarios, including the BAU scenario, the REP scenario and the TechImp scenario, by considering different constraints. We compare the optimal development paths derived from the three scenarios to explore the impacts of renewable energy plans and technological progress in renewable electricity generation on the total monetary costs and CO_2 emissions in the power sector. And a sensitivity analysis on some key parameters (including total power demand, carbon price, fossil fuel price and reduction rate of renewable investment cost) are further conducted to test the robustness of simulation. Finally, major conclusions are summarized and corresponding policy implications are put forward.

3.2. LEAP model

The LEAP model was built by the Stockholm Environment Institute in the 1980s [33]. Because the LEAP model is used to simulate the entire energy system, it is also known as an end-use energy consumption model [33]. Such a model is usually used to calculate energy demand and GHG emissions in energy or nonenergy sectors [34]. Because of its strong accounting functions, it is also used to conduct socioeconomic cost-benefit analysis [35]. Since 2014, it has been possible to apply an optimization function of LEAP model. The optimization function integrates the open source energy modelling system (OSeMOSYS) model, based on linear programming. "Optimization" is defined as the process of satisfying the power demand with the lowest net present value (NPV) of costs, including investment costs and variable and fixed O&M costs, over the whole planning horizon [36]. The objective function is defined as follows:

$$\text{Minimize } C = \sum_{(\forall t \in Year, \forall i \in Technology)} (PG_{t,i} \times VOM_{t,i} + IC_{t,i} \times FOM_{t,i} + ICA_{t,i} * UI_{t,i}) * (1+r)^{-(t-2015)} \quad (1)$$

in which

C is the total cost of power generation during the whole time horizon;
$PG_{t,i}$ is the power generation of technology i at year t;
$VOM_{t,i}$ is the variable O&M costs of technology i at year t;
$IC_{t,i}$ is the installed capacity of technology i at year t;
$FOM_{t,i}$ is the fixed O&M costs of technology i at year t;
$ICA_{t,i}$ is the installed capacity additions of technology i at year t;
$UI_{t,i}$ is the unit investment cost of technology i at year t;
r is the discount rate.

The main constraints are defined as follows:

$$\sum_i IC_{t,i} * 8760 * OR_i \times (1 - ELS) \geq PD_t \quad (2)$$

$$OR_i \leq CF_i \quad (3)$$

$$ICA_{t,i} \leq ICA_{t,i,max} \quad (4)$$

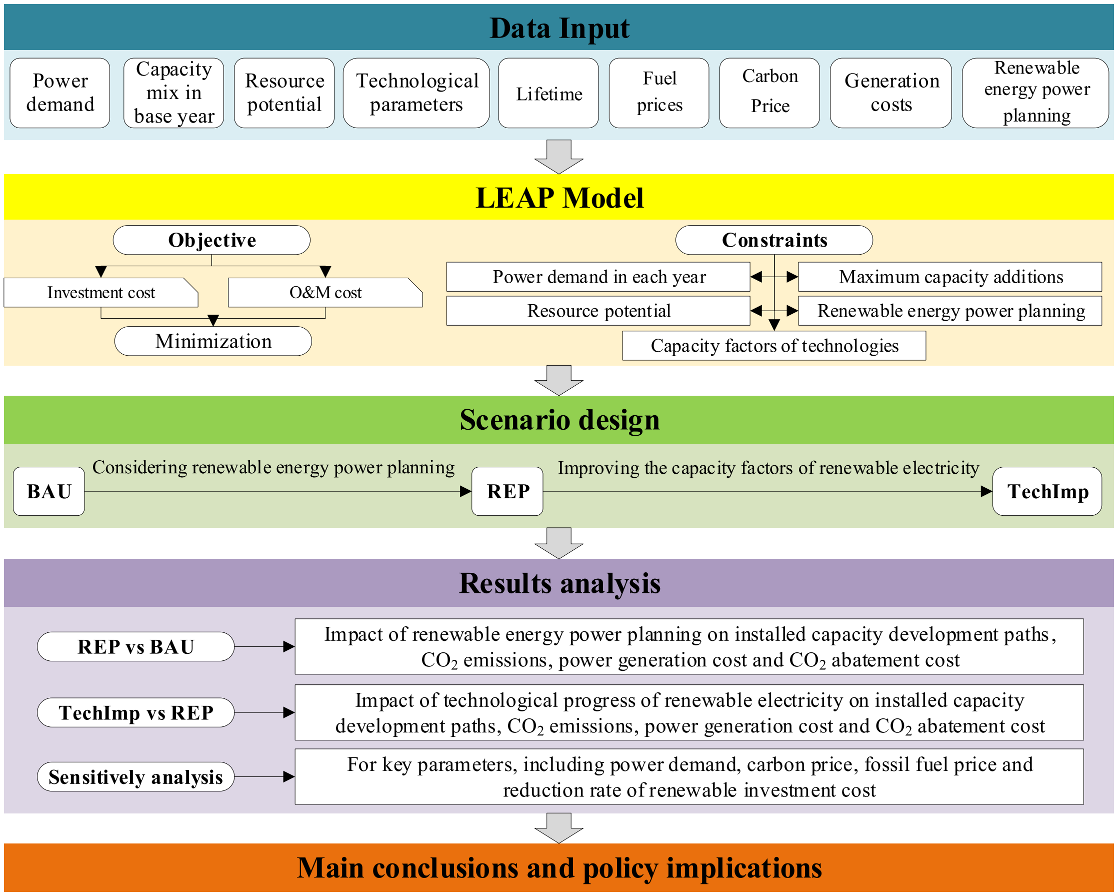

Fig. 2. Research framework.

$$IC_{t,i} \le IC_{t,i,max} \; i \in (nuclear, \; hydro, \; wind, \; solar, \; biomass) \tag{5}$$

$$IC_{t,i} \ge P_{t,i} \; i \in (wind, \; solar, \; biomass) \; t \in (2020, 2030, 2050) \tag{6}$$

in which

OR_i is the operating rate of technology i;
PD_t is the power demand at year t;
ELS equals to (power generation-power consumption)/power generation;
CF_i is the upper bound of operating rate of technology i;
$ICA_{t,i,max}$ is the upper bound of installed capacity additions of technology i at year t;
$IC_{t,i,max}$ is the upper bound of installed capacity of technology i at year t;
$P_{t,i}$ is the planning installed capacity of technology i at year t.

Constraint (2) is a statement of the relation between installed capacity and power demand. It means that the total power generation ($\sum_i IC_{t,i}*8760*OR_i$) deducting gap between power consumption and power generation, should meet the electricity demand at year t (PD_t); Constraint (3) limits the ratio of the actual power generation to the theoretical maximum power generation for different technologies (OR_i) must be less than the capacity factors (CF_i); Constraint (4) limits the expansion speed of each power generating technology caused by the annual maximum capacity additions ($ICA_{t,i,max}$) because of finite equipment manufacturing capacity; Constraint (5) ensures the cumulative capacities of the nonfossil being within their maximum potential ($IC_{t,i,max}$) because of finite available resources; and the renewable energy policies are taken into account in constraint (6) by setting a lower bound ($P_{t,i}$) for wind, solar and biomass electricity, respectively.

3.3. Scenario design

Scenario analysis is the core use of the LEAP model [37]. Through the development and comparison of different scenarios, the impact of policy implementation and technological progress can be evaluated. In this study, we aim to answer the questions of how would the development of renewable energy in the power sector proposed in the latest national plans influence the technology deployment of all power generation technologies, and what would be the impacts on the energy consumption, CO_2 emissions and investment cost. To that end, the REP scenario is designed to represent the effect of national plans for the renewable power generation. BAU is set as the reference scenario which do not consider the national plans for the renewable power generation. Moreover, considering the operating efficiency of renewable technologies (e.g., wind and solar power) could be further improved in the future, hence, in addition to REP scenario, we further design a TechImp scenario to investigate the impacts of technology improvement. Consequently, three scenarios are developed to assess the impacts of capacity planning and technological progress of renewable electricity. The details are explained as follows (see also Table 1).

BAU: This scenario is not influenced by renewable power

Table 1
Scenarios and descriptions.

Scenario		Capacity planning			Capacity factor (%)
		2020	2030	2050	
BAU	Hydro power	–	–	–	39.75
	Wind power	–	–	–	20.63
	Solar power	–	–	–	14.41
	Biomass power	–	–	–	52.53
REP	Hydro power	–	–	–	39.75
	Wind power	210 GW	400 GW	1000 GW	20.63
	Solar power	110 GW	400 GW	1000 GW	14.41
	Biomass power	15 GW	20 GW	–	52.53
TechImp	Hydro power	–	–	–	40.15
	Wind power	210 GW	400 GW	1000 GW	20.84
	Solar power	110 GW	400 GW	1000 GW	14.55
	Biomass power	15 GW	20 GW	–	53.06

Notes: All of the capacity planning figures for 2020 are cited from the 13th Five-Year Plan for Power Energy Development; the capacity planning figures for wind power and solar power in 2030 and 2050 are cited from China's Renewable Energy Development Roadmap 2050; the capacity planning figures for biomass power in 2030 is cited from China's Power Statistical Yearbook.

capacity planning, that is, the selection of the power generating technology is solely based on achieving the minimum cost. Hence, low-cost fossil fuel technologies are given priority.

REP: This scenario takes into account the capacity planning mentioned in China's national plans, in which the expansion of renewable power has been emphasized. It should be noted that there is few potential remaining to develop hydro power in China after a long-term development, and that hydro power is competitive with fossil fuel power generation because of low cost. Hence, the renewable power capacity planning that is considered in the REP scenario does not include hydro power. In addition, because biomass is not unconditionally cleaner and significantly cheaper than fossil fuels [38,39], this scenario considers the definite biomass power planning by 2030.

TechImp: This is a technology progress scenario. The capacity factors of all renewable generation technologies (hydro, wind, solar and biomass power) are improved by 1% in the TechImp scenario compared to the corresponding capacity factors in BAU and REP scenarios which are set as the maximum values from 2010 to 2015. While all other settings in TechImp remain the same as that in REP scenario. The capacity factor means the maximum operating rate that is calculated as the ratio of the actual power generation to the theoretical maximum power generation [40], which is affected by the actual production load and the actual operating hours of the equipment. As for the feasibility of improving the capacity factor of renewable electricity generating technologies, many previous studies have concluded that this can be achieved through both technological improvements and more effective operations, taking into consideration the specific conditions of power plants [40–42]. Moreover, the 13th Five-Year Plan for Renewable Energy Development aims to promote the applications of advanced technologies, such as flexible direct current transmission and energy storage technology, in the renewable energy field. Over time, this may contribute to solving the mismatch between renewable electricity generation and power demand, consequently improving the capacity factors of renewable electricity. Therefore, this study regards the improvement of capacity factors as representative of technological progress. Technology in this context refers to any of the advanced technologies that can increase renewable electricity generation and its utilization efficiency.

3.4. Data

This paper simulates the development path of China's power generation from 2015 to 2050. Meeting the power demand during this period is the ultimate purpose of the power plan. The power demand data is cited from the 13th Five-Year Plan for Power Development and China's Power Statistical Yearbook. As shown in Table 2, 2030 is a demarcation point from rapid growth to slow growth.

Data related to power generation, including technology parameters and cost data, are shown in Table 3. The power generation cost comprises investment costs, fuel costs, fixed O&M costs, variable O&M costs and externality costs. The investment costs and O&M costs have a downward trend over time because of technological progress. There are a few points worthy of attention. First, as can be seen in Fig. 3, the investment cost for gas-fired power is lower than that for coal-fired power over the planning horizon, because of the lower initial investment cost of gas-fired power plants [26]. However, the scarce resource of gas and energy safety issues limit the development of gas-fired power in China in the past. Second, the generation costs for emerging wind, solar and biomass power are high and enhanced by their short lifetimes. The low capacity factors for wind power and solar power increase costs even further. However, their cost reductions are more likely to emerge for these technologies than for the traditional technologies [43]. According to the assumptions of this study, the investment cost for wind power will fall, such that it becomes the lowest cost technology, even more so than gas-fired power, after 2044. Third, nuclear power has a high investment cost, but it is cost-effective as a result of its long lifetime and high capacity factor. Similarly, the long lifetime of hydro power makes its power generation costs lower. Taking into account the adverse impact on the ecological environment, the migration of residents, and the occupation of cultivated land required for hydro power [44], it is assumed that its investment costs do not fall over time.

There is a maximum operating rates (capacity factors) for each generating technology. In particularly, the capacity factors for the renewable generation technologies are low and unstable because of the great influence of natural conditions on their generation. Thus, wind power and solar power have the lowest capacity factors. The power capacity factors used in this paper are derived from the maximum values of various power generating technologies during 2010–2015, reflecting both the recent level of various power generating technologies and the recent state of natural conditions.

The discount rate in this study is set at 5%. Based on the difference between power consumption and power generation from 2010 to 2015, the energy loss rate is set at 0.6%. The planning reserve margin is calculated as 30% according to historical data [32]. In accordance with the average trading price on the Beijing carbon market in 2015, the carbon price is set at 41.18 RMB/tCO_2 [45].

4. Results and discussion

4.1. The impacts of renewable energy development on installed power capacity

Following the principle of cost minimization without any renewable policy intervention (BAU scenario), the cumulative

Table 2
Electricity demand from 2015 to 2050.

Year	2015	2020	2030	2050
Electricity demand (Trillion kWh)	5.7	7.2	11.3	13.3

Notes: The power demand for 2015 is cited from the China Electric Power Industry Statistics; the power demand for 2020 is cited from the 13th Five-Year Plan for Power Energy Development; the power demands for 2030 and 2050 are cited from China's Power Statistical Yearbook.

Table 3
Data for the main inputs of the parameters.

Parameters		Coal-fired power	Gas-fired power	Nuclear power	Hydro power	Wind power	Solar power	Biomass power	Data source
Capacity (2015)	GW	900	66	27	320	121	42	13	[12]
Lifetime	year	40	30	60	80	25	25	20	[22,46],
Capacity Factor		59.49%	36.37%	89.27%	39.75%	20.63%	14.41%	52.53%	[12]
Maximum Capacity	GW	Unlimited	Unlimited	400	540	1000	100000	50	China's Power Statistical Yearbook [22,47],
Maximum Capacity Addition	GW	40	30	20	8	30	30	5	[22]
Efficiency		40.01%	50.11%	100%	100%	100%	100%	100%	China's Power Statistical Yearbook
Investment Cost	RMB/kW	4569	3249	13662	6637	8103	14788	7840	[44,48],
Reduction Rate of Investment Cost		1.5%	1%	0	−0.11%	4%	5%	2%	[44]
Fixed O&M Cost	RMB/kW	133.3	100.8	600	105	310.9	216	390	[49]
Variable O&M Cost	RMB/kWh	0.028	0.031	0.028	0.007	0.014	0.00049	0.048	[49]
Reduction Rate of O&M Cost		1%	0	0	0	1%	1%	1%	[50]
Fuel Price		597.62RMB/tce	3.22RMB/m^3	157.25RMB/foot-pound	–	–	–	600RMB/tonne	Wind database [51],

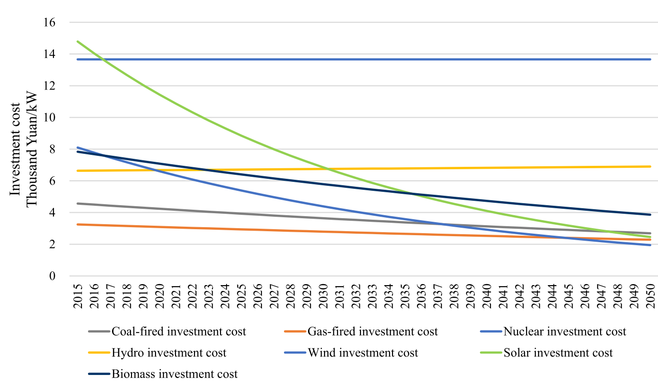

Fig. 3. Investment costs of power generation technologies by source.

installed capacities until 2050 will reach 100.8 billion kilowatts. It will need 1878, 2842 and 3705 million kilowatts installed power capacity for meeting the power demand in 2020, 2030 and 2050. And in the above three years, as shown in Fig. 4, the respective share of renewable electricity capacity is 30.4%, 23.3% and 27.1%. The fossil fuel electricity account for a large proportion (between 62% and 65%) over the planning horizon. If taken into account the expansion of renewable electricity following current national plans (REP scenario), the installed power capacities for meeting electricity demand in 2020, 2030 and 2050 are respectively 1981, 3289 and 5112 million kilowatts. And the corresponding share of renewable electricity is 36.3%, 39.2% and 50.7%, which shows a rising trend. In contrast, the share of fossil fuel electricity decreases, accounting for 57.2%, 50.8% and 41.5% in 2020, 2030 and 2050. The capacity factors for renewable electricity are lower compared to

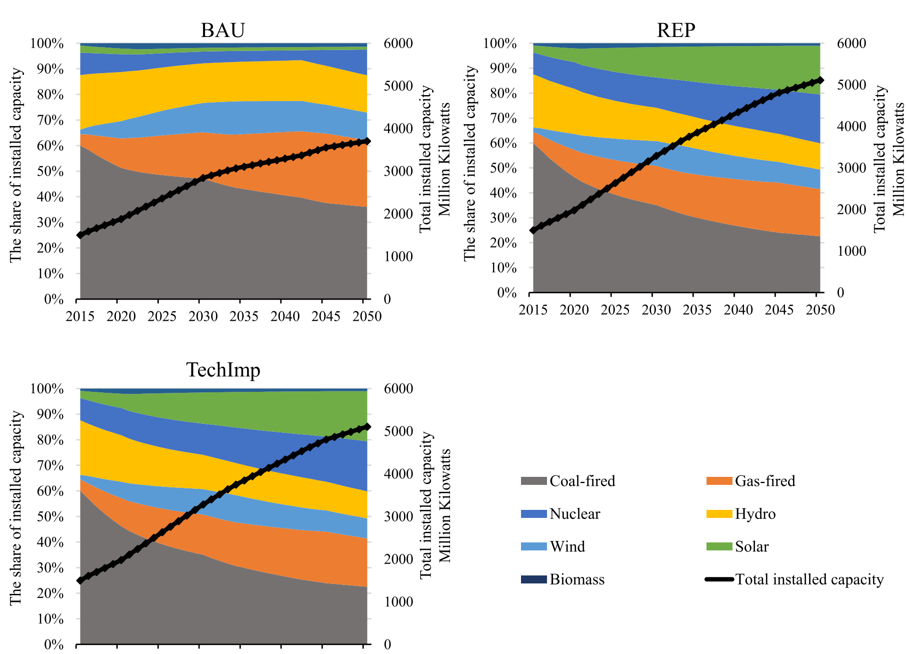

Fig. 4. Total amount and structure of installed power capacity in three scenarios.

other resources, especially for wind and solar power, which are considered to be key technologies for development. Hence, under the REP scenario, the cumulative installed capacities of all power types become 124.5 billion kilowatts, which is 23.50% higher than that under the BAU scenario. Further improving the capacity factors of renewable electricity technologies by 1% based on REP scenario (TechImp scenario) will increase the renewable power generation in the condition of same installed capacity. As a result, the total installed power capacity decreases for meeting the predetermined electricity demand in the TechImp scenario, among which the coal-fired power and biomass power decrease by 179 and 1 million kilowatts respectively. The capacity structure under TechImp scenario is similar to that under REP scenario, but with the share of renewable electricity capacity increasing and fossil fuel electricity decreasing slightly.

Figs. 5 and 6 show the development path of the installed power capacity for different resource types under BAU and REP scenarios. In BAU scenario, those cheaper power generation technologies will be developed rapidly, with hydro power, nuclear power and biomass power will reach their maximum potential in 2043, 2034 and 2023, respectively. In contrast, the installed capacity of wind power and solar power will not be enlarged because of the high costs. The solar power maintains the 2015 production scale and, similarly, wind power maintains the 2015 production scale until 2043. After that, wind power's installed capacity begins to slightly grow because its cost starts to be competitive. However, if following the current mid- and long-term national planning for renewable power generation (REP), the installed capacities of wind, solar and biomass power will increase continually to reach the renewable electricity capacity planning targets. In order to minimize the power generation cost under the constraint of promoting development of renewable energy, the installed power capacity of hydro, nuclear, gas-fired power will not change, but the accumulated installed capacity of coal-fired power and biomass power will decrease by 4912 and 7.5 million kilowatts, respectively. Due to the larger capacity factor of coal-fired power compared to renewable power, the reductions of coal-fired installed power capacity are less than the additions of renewable installed power capacity. Consequently, promoting the renewable power generation will result in more installed power capacity for meeting the same electricity demand.

4.2. *The impacts of renewable energy development on total CO_2 emissions*

The CO_2 emissions of the power sector arise mainly from coal-fired and gas-fired power. As shown in Fig. 7, in the BAU scenario

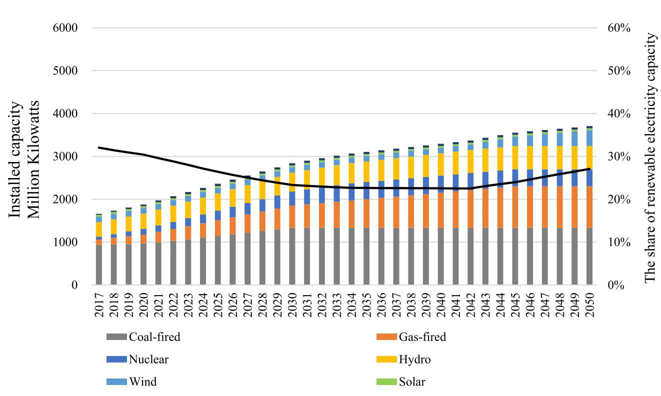

Fig. 5. Installed capacity under the BAU scenario by resource type.

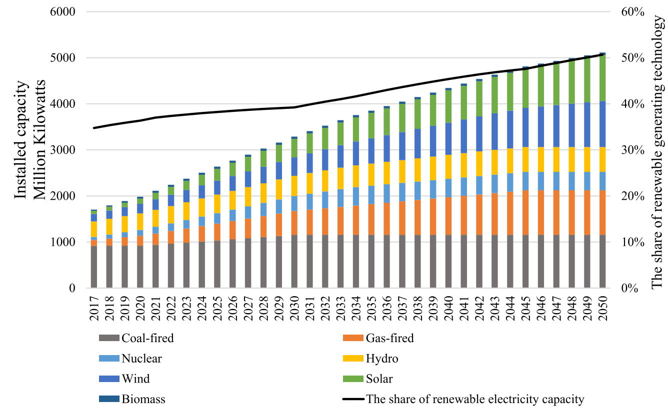

Fig. 6. Installed capacity under the REP scenario by resource type.

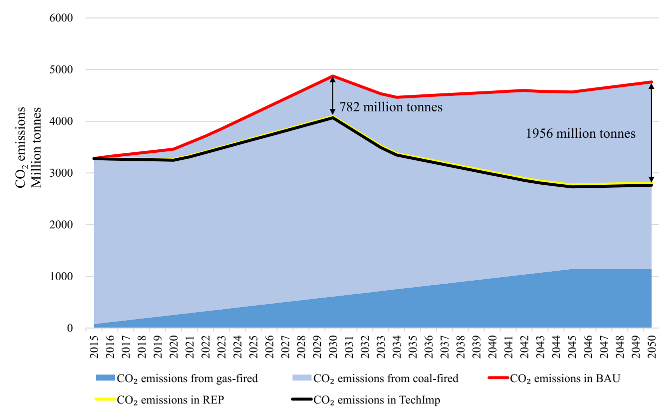

Fig. 7. CO_2 emissions under BAU and REP scenarios.

without efforts for developing renewable energy, the accumulated CO_2 emissions is about 154 billion tonnes from 2015 to 2050, of which 84% from coal-fired power and 16% from gas-fired power. The CO_2 emissions have a rising trend in the whole planning horizon with a short-time downward trend during 2030–2034, appearing an emissions peak at 4874 million tonnes in 2030. But Fig. 7 also shows that the CO_2 emissions start to rebound after 2034 because the nuclear power stop increasing, resulting the total CO_2 emissions are likely to exceed the 2030 peak after 2050. In the REP scenario that considers the specific planning on renewable power generation, the total CO_2 emissions will be 118 billion tonnes from 2015 to 2050. Among them, gas-fired power has the same CO_2 emission path with BAU. About 43 trillion kilowatt hours of coal-fired power are replaced by renewable electricity, bringing about a 35.8 billion tonnes reduction of CO_2 emissions compared to BAU scenario. The CO_2 emissions will peak at 2030 under REP scenario, with 4092 million tonnes of CO_2 emission generated. In 2050, the CO_2 emissions will decline to 2805 million tonnes, which is 1956 million tonnes less than that under the BAU scenario. This indicates that the current strategy of developing renewable energy can help reduce the total CO_2 emissions and, meanwhile ensure that the CO_2 emissions for the power sector will peak in 2030.

Improving the capacity factors of renewable electricity will result in further decline of coal-fired power generation. As shown in Fig. 8, when the capacity factors of all renewable generation technologies are improved by 1% on the basis of REP scenario, hydro, wind, solar and biomass power increase by a total 557, 331, 220 and 70 billion kilowatt hours, respectively. In the case of the

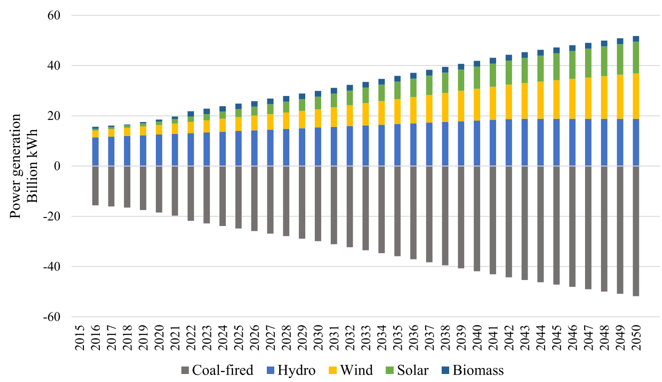

Fig. 8. The impact of improving the capacity factors of renewable electricity on power generation.

constant power demand, coal-fired power generation falls by 1178 billion kilowatt hours. Hence, in TechImp scenario, coal consumption for power generation decreases by about 362 million tonnes of coal equivalents, and the accompanying CO_2 emissions from coal-fired power decrease by 982 million tonnes compared to REP scenario. It can be confirmed that the renewable electricity technological progress play an important role on energy conservation and emission reduction.

4.3. The impacts of renewable energy development on total power generation costs

Without any renewable policy intervention (BAU scenario), the total power generation cost is 33.04 trillion RMB from 2015 to 2050. As shown in Fig. 9, 62.81% and 10.53% of the power generation costs are used to generate coal-fired and gas-fired power. The power generation cost for renewable electricity is only accounting for 9.03%. Taking into account of renewable energy development, the total power generation cost from 2015 to 2050 under the REP scenario is 35.36 trillion RMB, which is 2.31 trillion RMB higher than that under the BAU scenario. This gap can be seen as the additional cost required for developing renewable electricity. In REP scenario, the power generation cost for renewable electricity accounts for 26.24%. It is caused by the substitution of wind power and solar power for coal-fired power and biomass power. Hence, the power generation costs for coal-fired power and biomass power are 3982 and 7 billion RMB less than that under the BAU scenario, respectively. In contrast, the power generation costs for wind and solar power in the REP scenario are, respectively, 2576 billion RMB and 3726 billion RMB higher than that under the BAU scenario.

In the case of improving the capacity factors of the renewable electricity technologies by 1% on the basis of REP scenario, total power generation cost will reach 35.22 trillion RMB, 133.36 billion RMB less than the cost in REP scenario. On the one hand, the renewable energy power generation costs increase by 3.34 billion RMB, mainly as a result of increase in O&M costs and, to a lesser extent, biomass fuel costs. On the other hand, both the installed capacity and the generation of coal-fired power fall simultaneously, affecting investment costs, fuel costs, and O&M costs of coal-fired power. In total, the coal-fired power generation cost falls by 136.69 billion RMB. As a result, the overall power generation cost under TechImp scenario is reduced by 133.36 billion RMB compared to REP scenario. It can be confirmed that the renewable electricity technological progress also has a significant impact on cost savings.

4.4. The impacts of renewable energy development on abatement costs of CO_2

The cost of mitigating unit environmental negatives, such as CO_2 emissions, can be expressed in terms of abatement cost. It is the sum of the difference in annual costs, divided by the annual CO_2 emission savings [52]. There are studies defining this difference in costs and CO_2 emissions as the gap between reference system and the cleaning system [53]. This paper defines the CO_2 abatement cost as the ratio of the cost additions to the CO_2 emission reductions of the scenarios which take into account renewable energy policy (REP and TechImp) compared with the reference scenario (BAU).

As shown in Fig. 10, the annual average CO_2 abatement cost has a downward trend under the REP and TechImp scenario. If the renewable energy policies are implemented (REP scenario), 35.8 billion tonnes of CO_2 savings and 2312 billion RMB of cost additions are distributed over the planning horizon. The CO_2 abatement cost can be calculated by cost additions and CO_2 savings. The annual average CO_2 abatement cost continues to decline at an annual rate of 5.56%. The annual average CO_2 abatement cost is as high as 355.57 RMB/tCO_2 (tonnes of CO_2) in 2016, but it falls to 252.33 RMB/tCO_2 by 2020 and 3.86 RMB/tCO_2 by 2050. According to the definition in the existing study [54], the average CO_2 abatement cost from 2016 to 2020 is 284.64 RMB/tCO_2, which declines to 64.53 RMB/tCO_2 over the whole planning horizon. Improving the capacity factors of renewable generation technologies, the annual average CO_2 abatement cost is 182.09 RMB/tCO_2 in 2016, 173.48 RMB less than that under the REP scenario, and it decreases to 2.55 RMB/tCO_2

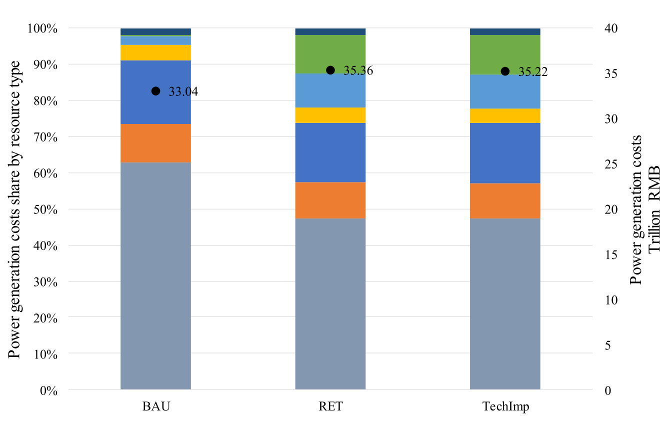

Fig. 9. The difference in power generation costs between three scenarios.

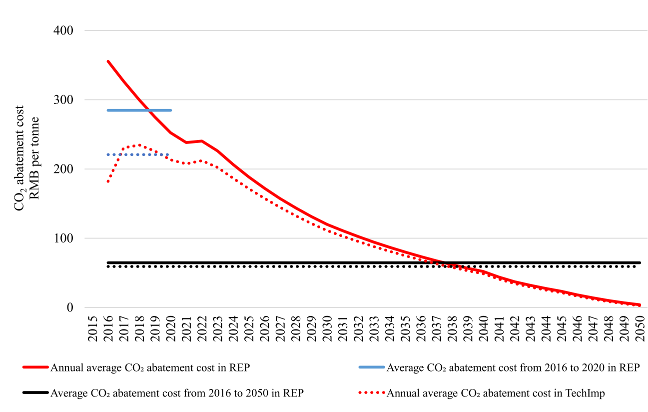

Fig. 10. CO_2 abatement cost in the REP and TechImp scenario.

by 2050, 1.31 RMB less than that under the REP scenario. Over the whole planning horizon, the average CO_2 abatement cost for the TechImp scenario is 59.19 RMB/tCO_2, which is 5.34 RMB less than that under the REP scenario. This implies that improving the renewable electricity technologies can reduce power generation costs and CO_2 emission, obtaining greater economic and environmental benefits.

Although the development of renewable energy in the power sector will bring about some CO_2 emission reductions, the average CO_2 abatement cost is very high in the short term. With technological innovations in renewable electricity generation, the net benefits will gradually increase. However, to strengthen the competitiveness of renewable electricity, some market and administrative measures are required, such as conducting an emissions trading market and subsidizing the renewable electricity generator to make up for economic losses and garnering public support for renewable electricity development [28,55,56].

4.5. The impacts of varying capacity factors of renewable electricity

With the development of energy storage technology, renewable energy can be used more efficiently. However, there might be large uncertainty for the renewable technologies, especially for the wind and solar power, resulting in a likely decreasing operation efficiency of renewable electricity plants. Therefore, the impact of varying capacity factors of renewable electricity (the capacity factors are improved by −5% ~5%) on installed capacity, fuel consumption, CO_2 emissions, power generation cost and CO_2 abatement cost during 2015–2050 is further estimated. As shown in Figs. 11–13, a 1% improvement of the capacity factors of renewable electricity would result in a reduction of about 5.74 million kilowatts of coal-fired power installed capacity, and result in an increase of the share of renewable power installed capacity by about 0.068% in 2030. Due to the increase of renewable electricity generation, the cumulative fossil fuel consumption would be reduced by 362 million tce and the CO_2 emissions would be reduced by 979 million tonnes. In additions, changes in capacity factors of renewable electricity would also affect the power generation cost. When the capacity factors of renewable electricity increase by 1%, the power generation cost would decrease by 133 billion RMB, and the average CO_2 abatement cost per tonne would shrink by 5.56 RMB/tCO_2. It can be further confirmed that improving the renewable electricity technologies has positive impact on cost saving and climate mitigation.

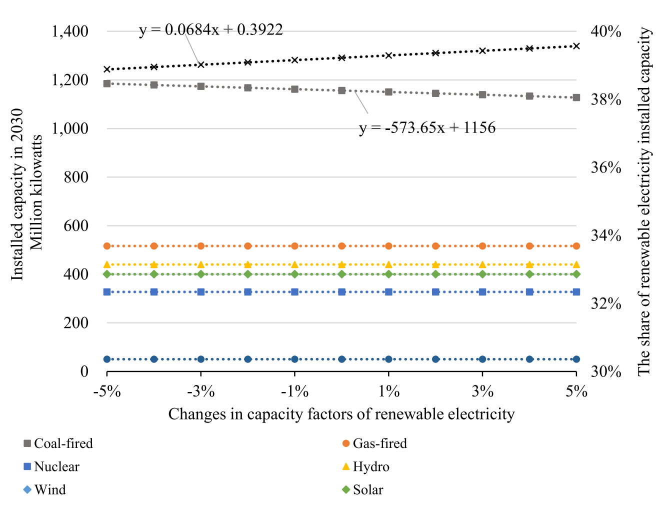

Fig. 11. The impact of varying capacity factors of renewable electricity on installed capacity and the share of renewable power installed capacity in 2030.

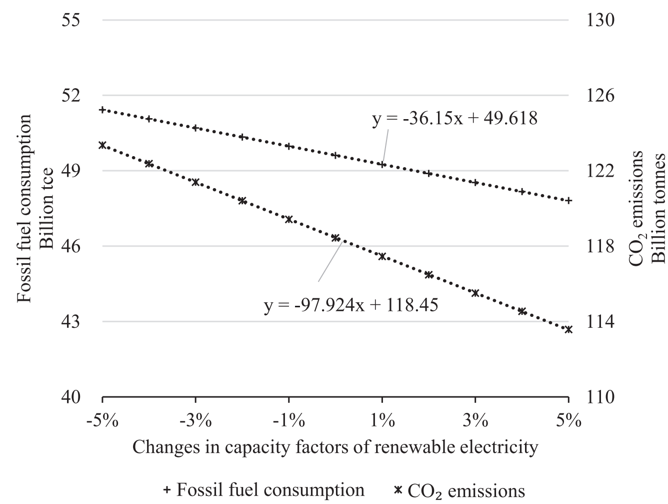

Fig. 12. The impact of varying capacity factors of renewable electricity on cumulative fossil fuel consumption and CO_2 emissions.

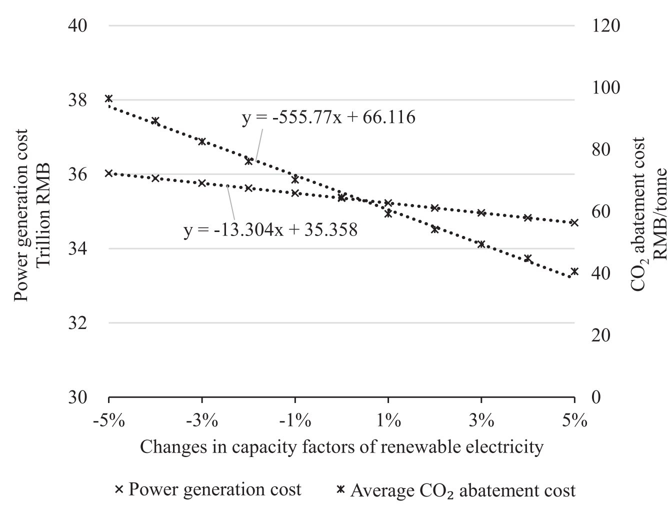

Fig. 13. The impact of varying capacity factors of renewable electricity on total power generation cost and average CO_2 abatement cost.

4.6. Sensitivity analysis of key parameters

To draw a more comprehensive picture, in this part, we will test the sensitivity of key parameters, including total power demand, carbon price, fossil fuel price and reduction rate of renewable investment cost, on the results of power generation technology development, power generation cost and average CO_2 abatement cost based on REP scenario. For power generation technology development, the results of installed capacities in 2050 are taken as the representative results for explanation, while the power generation cost and average CO_2 abatement cost are the results covering the full planning horizon.

4.6.1. Power demand

As can be seen from Fig. 14, due to low power generation cost, the installed capacity of coal-fired power would increase by 23.35 million kilowatts in 2050 when the total power demand increases

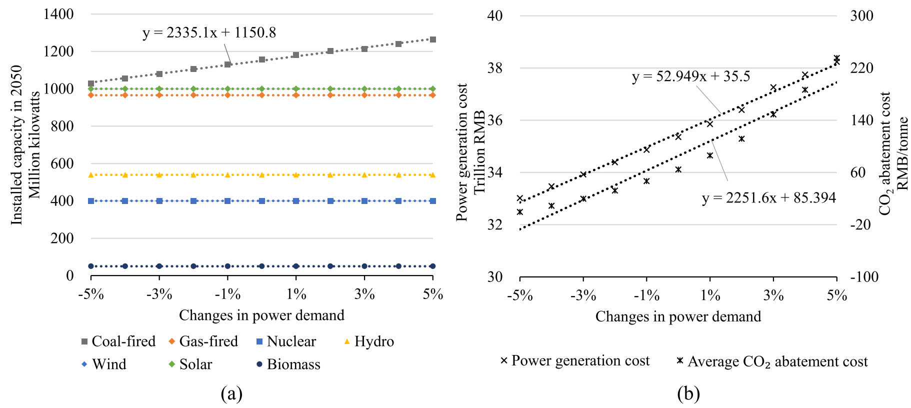

Fig. 14. The impact of changes in power demand on installed power capacity (a) and cost (b).

by 1%, while the installed capacity of other technologies would remain unchanged. In addition, the corresponding power generation cost and the average CO_2 abatement cost per tonne would increase by 529.49 billion RMB and 22.52 RMB, respectively. It can be confirmed that controlling the rise of power demand can substantially reduce coal-fired power generation, thus cut the power generation cost and CO_2 emissions. However, it would not promote the improvement of renewable power generation in 2050.

4.6.2. Carbon price

As shown in Fig. 15, when the carbon price increases by 1%, the solar power installed capacity would increase by 0.75 million kilowatts in 2050, while the installed capacity of other technologies would remain unchanged. The power generation cost would increase by 22.44 billion RMB and the average CO_2 abatement cost per tonne will increase by 0.62 RMB as the carbon price rising by 1%. Hence, as the response to the carbon price increment, the solar power should be installed, but with more power generation cost.

4.6.3. Fossil fuel prices

In the REP scenario, the fossil fuel prices, including coal price and natural gas price, are assumed to be unchanged. In this part, the fossil fuel prices are allowed to show an increasing or decreasing trend. As shown in Fig. 16, as the growth rate of fossil fuel prices increasing by 1%, the coal-fired installed capacity would be reduced by 16.76 million kilowatts in 2050. However, there is no impact on gas-fired installed capacity if the growth rate of fossil fuel prices is more than −2%. If it is equal to or less than −3%, the gas-fired installed capacity would decrease to about 600 million kilowatts in 2050 due to the increase of coal-fired power. For renewable electricity, the installed capacity of solar power would increase by 74.44 million kilowatts in 2050 when the growth rate of fossil fuel prices increases by 1%; while other renewable electricity would not be affected. Hence, increasing fossil fuel prices will promote the development of renewable electricity. However, the total power generation cost is likely to increase by 1.35 trillion RMB and the average CO_2 abatement cost per tonne would increase by 47.49 RMB.

4.6.4. Investment cost of wind power and solar power

In the REP scenario, the reduction rate of wind and solar investment cost are assumed to be 4% and 5%. In this part, higher reduction rates of investment cost will be assumed. As can be seen from Fig. 17, the installed capacity of solar power would increase by 5.38 million kilowatts in 2050 when the reduction rate of wind and solar power investment cost increases by 1%. In additions, the power generation cost would be reduced by 18.03 billion RMB and the average CO_2 abatement cost per tonne would be 0.53 RMB less. Hence, lowering the investment cost of renewable electricity is conducive for promoting the development of renewable electricity and meanwhile savings cost.

4.6.5. Summary

It is effective way to promote the development of renewable electricity by increasing carbon price and fossil fuel prices and developing renewable electricity generation technology to reduce the investment cost. The fossil fuel prices are the most significant factor that impact on the power generation technology

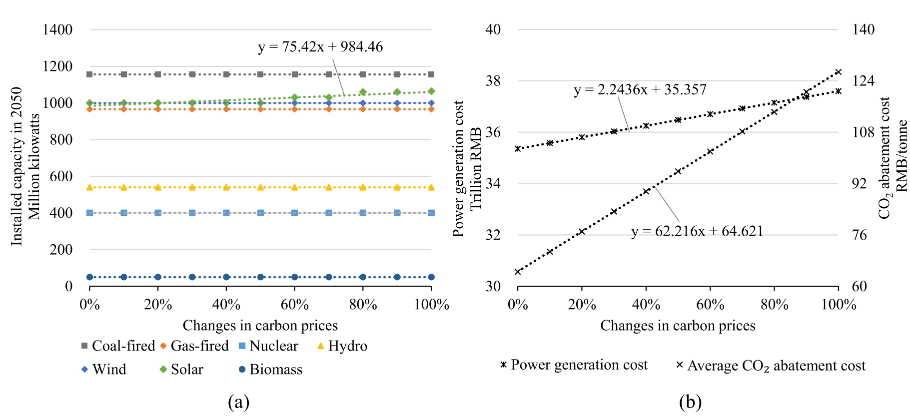

Fig. 15. The impact of changes in carbon price on installed power capacity (a) and cost (b).

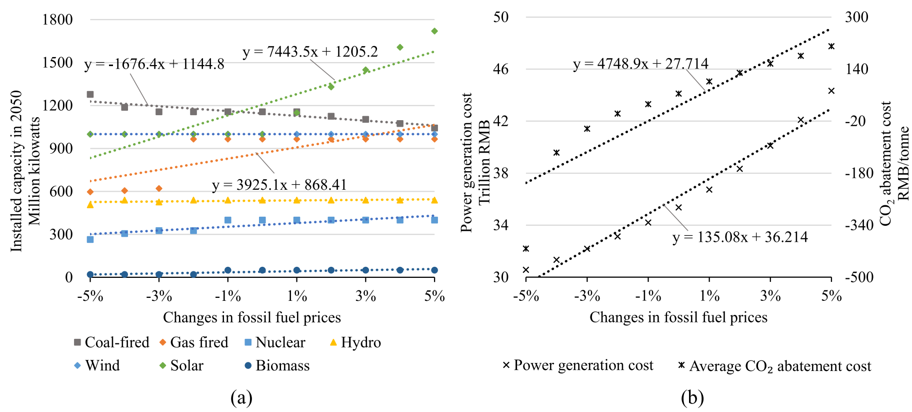

Fig. 16. The impact of changes in fossil fuel prices on installed power capacity (a) and cost (b).

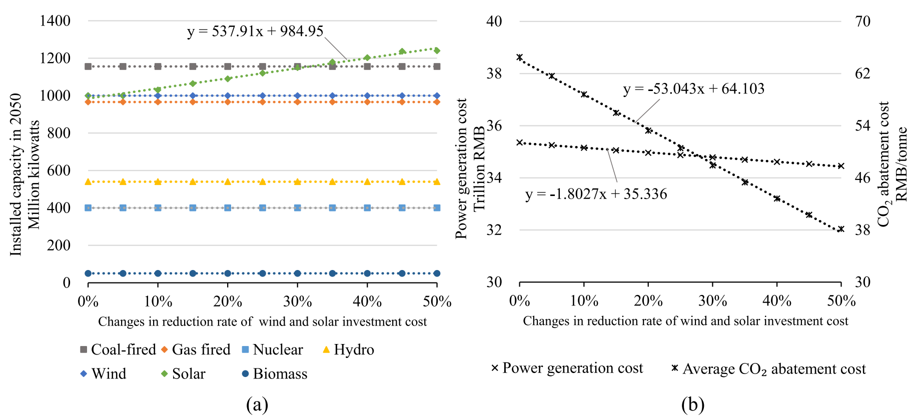

Fig. 17. The impact of changes in reduction rate of wind and solar investment cost on installed power capacity (a) and cost (b).

development. However, the impact of changes in carbon price is not obvious due to the current low carbon prices. Moreover, solar power is frequently influenced by the change of key parameters in terms of installed capacity in 2050. Hence, solar power would be the key of development in the long-term future due to its rapid reduction of power generation cost and large resource potential.

5. Conclusions

The power industry is the largest CO_2 emitter in China, hindering China's progress in achieving sustainable development. A series of renewable energy targets and renewable electricity plans have been announced to achieve sustainable development in the power sector in China. However, how to achieve these plans and what are their costs and benefits remain unanswered questions. This paper uses LEAP model to suggest the optimal development path for China's power sector from 2015 to 2050, taking into account the renewable energy development plans. By comparing three scenarios, the impacts of renewable electricity planning and technological progress on power generation costs and CO_2 emissions are evaluated. Both renewable electricity planning and technological progress were mentioned in the latest Five-Year Plans. Main conclusions are as follows:

(1) The fossil fuel-dominated power structure would be changed under the guidance of renewable energy policies in China. Under renewable electricity planning, the share of emerging renewable energy power, including wind, solar and biomass power, in installed capacity will increase to 18.17% by 2020. In order to minimize power generation costs, the shares of hydro, nuclear, coal-fired and gas power should be 18.17%, 6.41%, 46.34% and 10.90%, respectively. In 2050, the share of emerging renewable energy power in installed capacity will further increase to 40.10%. The shares of hydro, nuclear, coal-fired and gas power should be 10.56%, 7.82%, 22.61% and 18.90%, respectively.

(2) The development of renewable generation can reduce CO_2 emissions and save fossil fuel consumption, but it will increase power generation costs. During the period 2015 to 2020, the development of renewable electricity according to the 13th Five-Year Plan for Power Energy Development will result in a reduction in CO_2 emissions of about 595 million tonnes, but with additional power generation costs of 169 billion RMB. This means that China needs to pay 284.64 RMB for every tonne of CO_2 emissions reductions. During the period 2015 to 2050, the national renewable energy plan will lead to a reduction of about 35.8 billion tonnes of CO_2 emissions with CO_2 emissions peak at 2030, but at an additional cost of 2312 billion RMB. That is, the average CO_2 abatement cost is 64.53 RMB/tCO_2 over the full planning horizon. It can be seen that the high power generation costs of renewable electricity would continue to 2050 if there is no technological progress or other policy interventions.

(3) Improving the capacity factors of renewable electricity generation technologies is an effective way to reduce the cost of renewable energy development and increase environmental

benefits. Compared with the case without changes in capacity factors (REP), every 1% increase in the capacity factors of renewable electricity would on average result in the share of renewable electricity installed capacity increased by 0.068% in 2030, the cumulative CO_2 emissions reduced by about 979 million tonnes, power generation costs reduced about 133 billion RMB and average CO_2 abatement cost decreased by 5.56 RMB/tCO_2.

(4) Increasing the carbon price and fossil fuel prices, and developing renewable electricity generation technology to reduce investment cost are effective measures to promote the development of renewable electricity, especially the solar power.

6. Policy implications

Based on the above conclusions, four policy implications are proposed for the power sector development in China.

(1) If regarding the renewable development targets proposed in the latest 13th Five-Year Plan for Power Energy Development and the middle-long term plans as the priority in China's power sector, under the principle of cost minimization, our results are different from the national planning of capacity for coal-fired power, gas-fired power and nuclear power. The installed capacity of coal-fired power in our result is 182, 194 and 44 GW less than that in national planning in 2020, 2030 and 2050, respectively. However, the installed capacity development of gas-fired power and nuclear power in national planning is hysteretic relative to our results. For instance, the installed capacity for gas-fired power and nuclear power are plan to reach 110 GW and 58 GW by 2020 according to national planning but 216 and 127 GW, respectively, according to our results. Hence, government may reconsider the current planning by properly reduce the capacity for coal-fired power and promoting gas-fired power and nuclear power, so as to reach low-carbon electricity generation and less cost.

(2) The average CO_2 abatement cost caused by promoting renewable electricity generation, is much higher than the current carbon price of Beijing emissions trading market, especially in the short term. Therefore, to promote the development of renewable energy in China's power sector, some measures, such as the promotion of an emissions trading market, adjustments to the carbon price and subsidization of renewable electricity generators, are required to offset the additional cost.

(3) Policy aiming to improving capacity factors for each power generation technologies should be promoted. For those non-renewable electricity generation technologies, the improvement of their capacity factors can be achieved by increasing production load and the actual operating hours. While for renewable electricity generation technologies, improving their utilization efficiency is more feasible for enlarging the capacity factors, considering their capacity factors are difficult to change because the natural resource is finite and renewable electricity generation may mismatch with electricity consumption. Some advanced technologies, such as flexible direct current transmission and storage technology, can allow more renewable electricity to be used. Hence, the promotions of advanced technologies can increase the capacity factors of renewable electricity generation technologies, obtaining greater economic and environmental benefits.

(4) Due to the great potential of the installed capacity increment and cost reduction, the solar power will play an important role in CO_2 emissions reduction in China's power industry in the future. At this stage, it would be helpful to allocate more R&D funding to achieve technological breakthroughs which can further shrink the investment costs of solar power.

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References

[1] BP, BP Statistical Review of World Energy: Carbon Dioxide Emission, 2016.
[2] Y. Li, Z. Lukszo, M. Weijnen, The implications of CO_2 price for China's power sector decarbonization, Appl. Energy 146 (2015) 53–64.
[3] J. Yuan, Y. Hou, M. Xu, China's 2020 carbon intensity target: consistency, implementations, and policy implications, Renew. Sustain. Energy Rev. 16 (2012) 4970–4981.
[4] X. Zhang, V.J. Karplus, T. Qi, D. Zhang, J. He, Carbon emissions in China: how far can new efforts bend the curve? Energy Econ. 54 (2016) 388–395.
[5] M. Meng, K. Jing, S. Mander, Scenario analysis of CO_2 emissions from China's electric power industry, J. Clean. Prod. 142 (2016) 3101–3108.
[6] H. Chen, J.N. Kang, H. Liao, B.J. Tang, Y.M. Wei, Costs and potentials of energy conservation in China's coal-fired power industry: a bottom-up approach considering price uncertainties, Energy Pol. 104 (2017) 23–32.
[7] F. Aliprandi, A. Stoppato, A. Mirandola, Estimating CO_2 emissions reduction from renewable energy use in Italy, Renew. Energy 96 (2016) 220–232.
[8] S. Kumar, H. Fujii, S. Managi, Substitute or complement? Assessing renewable and nonrenewable energy in OECD countries, Appl. Energy 47 (2015) 1438–1459.
[9] S. Schuman, A. Lin, China's Renewable Energy Law and its impact on renewable power in China: progress, challenges and recommendations for improving implementation, Energy Pol. 51 (2012) 89–109.
[10] X. Zhao, J. Wang, X. Liu, P. Liu, China's wind, biomass and solar power generation: what the situation tells us? Renew. Sustain. Energy Rev. 16 (2012) 6173–6182.
[11] P. Chunark, K. Promjiraprawat, P. Winyuchakrit, B. Limmeechokchai, T. Masui, T. Hanaoka, Y. Matsuoka, Quantitative analysis of CO_2 mitigation in Thai low carbon power sector towards 2050, Energy Procedia 52 (2014) 77–84.
[12] China Electricity Council (CEC), Planning & Statistics, 2015. http://www.cec.org.cn/guihuayutongji/tongjxinxi/niandushuju/2016-09-22/158761.html. (Accessed 25 December 2016).
[13] IEA, Statistics, 2015. http://www.iea.org/statistics/statisticssearch/report/?country. (Accessed 8 February 2018).
[14] N.E. Koltsaklis, A.S. Dagoumas, G.M. Kopanos, E.N. Pistikopoulos, M.C. Georgiadis, A spatial multi-period long-term energy planning model: a case study of the Greek power system, Appl. Energy 115 (2014) 456–482.
[15] C. Barteczko-Hibbert, I. Bonis, M. Binns, C. Theodoropoulos, A. Azapagic, A multi-period mixed-integer linear optimisation of future electricity supply considering life cycle costs and environmental impacts, Appl. Energy 133 (2014) 317–334.
[16] G. Anandarajah, A. Gambhir, India's CO_2 emission pathways to 2050: what role can renewables play? Appl. Energy 131 (2014) 79–86.
[17] Z.A. Muis, H. Hashim, Z.A. Mana, F.M. Taha, P.L. Douglas, Optimal planning of renewable energy-integrated electricity generation schemes with CO_2 reduction target, Renew. Energy 35 (2010) 2562–2570.
[18] S.Y. Park, B.Y. Yun, C.Y. Yun, D.H. Lee, G.C. Dong, An analysis of the optimum renewable energy portfolio using the bottom–up model: focusing on the electricity generation sector in South Korea, Renew. Sustain. Energy Rev. 53 (2016) 319–329.
[19] P.N. Georgiou, A bottom-up optimization model for the long-term energy planning of the Greek power supply sector integrating mainland and insular electric systems, Comput. Oper. Res. 66 (2015) 292–312.
[20] T. Qi, X. Zhang, V.J. Karplus, The energy and CO_2 emissions impact of renewable energy development in China, Energy Pol. 68 (2014) 60–69.
[21] X. Pan, W. Chen, L.E. Clarke, L. Wang, G. Liu, China's energy system transformation towards the 2 °C goal: implications of different effort-sharing principles, Energy Pol. 103 (2017) 116–126.
[22] D. Zhang, P. Liu, L. Ma, Z. Li, W. Ni, A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation, Comput. Chem. Eng. 37 (2012) 227–247.
[23] J. Wu, J. Albrecht, Y. Fan, Y. Xia, The design of renewable support schemes and CO_2 emissions in China, Energy Pol. 99 (2016) 4–11.

[24] J.L. Zhen, G.H. Huang, W. Li, C.B. Wu, S. Wang, Electric power system planning with renewable energy accommodation for supporting the sustainable development of Tangshan City, China, J. Clean. Prod. 139 (2016) 1308–1325.
[25] Q. Chen, C. Kang, Q. Xia, D. Guan, Preliminary exploration on low-carbon technology roadmap of China's power sector, Energy 36 (2011) 1500–1512.
[26] D. Zhang, L. Ma, L. Pei, L. Zhang, L. Zheng, A multi-period superstructure optimization model for the optimal planning of China's power sector considering carbon dioxide mitigation: discussion on China's carbon mitigation policy based on the model, Energy Pol. 41 (2014) 173–183.
[27] Z.Y. Lu, W.H. Li, B.C. Xie, L.F. Shang, Study on China's wind power development path—based on the target for 2030, Renew. Sustain. Energy Rev. 51 (2015) 197–208.
[28] R.G. Cong, An optimization model for renewable energy generation and its application in China: a perspective of maximum utilization, Renew. Sustain. Energy Rev. 17 (2013) 94–103.
[29] H. Chen, B.J. Tang, H. Liao, Y.M. Wei, A multi-period power generation planning model incorporating the non-carbon external costs: a case study of China, Appl. Energy 183 (2016) 1333–1345.
[30] N. Zhou, D. Fridley, N.Z. Khanna, J. Ke, M. McNeil, M. Levine, China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model, Energy Pol. 53 (2013) 51–62.
[31] S. Kumar, R. Madlener, CO_2 emission reduction potential assessment using renewable energy in India, Energy 97 (2016) 273–282.
[32] B. Özer, E. Görgün, S. İncecik, The scenario analysis on CO_2 emission mitigation potential in the Turkish electricity sector: 2006-2030, Energy 49 (2013) 395–403.
[33] G. Wu, Y. Fan, L.C. Liu, Y.M. Wei, Progress in energy complex system modelling and analysis, Int. J. Global Energy Issues 25 (2006) 109–128.
[34] N.B. Park, S.J. Yun, E.C. Jeon, An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector, Energy Pol. 52 (2013) 288–296.
[35] S. Hong, Y. Chung, J. Kim, D. Chun, Analysis on the level of contribution to the national greenhouse gas reduction target in Korean transportation sector using LEAP model, Renew. Sustain. Energy Rev. 60 (2016) 549–559.
[36] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. Decarolis, M. Bazillian, OSeMOSYS: the open source energy modeling system : an introduction to its ethos, structure and development, Energy Pol. 39 (2011) 5850–5870.
[37] S.A. Ates, H. Lund, M.J. Kaiser, Energy efficiency and CO_2 mitigation potential of the Turkish iron and steel industry using the LEAP (long-range energy alternatives planning) system, Energy 90 (2015) 417–428.
[38] C. Xu, J. Hong, J. Chen, X. Han, C. Lin, X. Li, Is biomass energy really clean? An environmental life-cycle perspective on biomass-based electricity generation in China, J. Clean. Prod. 133 (2016) 767–776.
[39] M.A. Carriquiry, X.D. Du, G.R. Timilsina, Second generation biofuels: economics and policies, Energy Pol. 39 (2011) 4222–4234.
[40] J.S. Lacerda, J.C.J.M.v.d. Bergh, Mismatch of wind power capacity and generation: causing factors, GHG emissions and potential policy responses, J. Clean. Prod. 128 (2016) 178–189.
[41] Global Wind Energy Council (GWEC), Global Wind Energy Outlook 2016, 2016.
[42] C. Li, P. Li, X. Feng, Analysis of wind power generation operation management risk in China, Renew. Energy 64 (2014) 266–275.
[43] L. Neij, Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology, Energy Pol. 23 (1997) 1099–1107.
[44] R. Cheng, Z. Xu, P. Liu, Z. Wang, Z. Li, I. Jones, A multi-region optimization planning model for China's power sector, Appl. Energy 137 (2015) 413–426.
[45] China Beijing Environment Exchange (CBEEX), Beijing Emissions Trading Association (BETA), Annual Report of Beijing Carbon Market 2015, 2015.
[46] International Energy Agency (IEA), Projected Costs of Generating Electricity, 2010.
[47] Y.M. Wei, G. Wu, Q.M. Liang, H. Liao, China energy Report 2012 : Energy Security Research, Science Press, 2012 (In Chinese).
[48] N. Wu, J.E. Parsons, K.R. Polenske, The impact of future carbon prices on CCS investment for power generation in China, Energy Pol. 54 (2013) 160–172.
[49] M. Ye, Simulation of Emission Control Policies for China's Power Sector Using a Multi-regional Bottom-up Optimization Model, Tsinghua University, 2012 (In Chinese).
[50] Z. Mao, C. Wang, Assessing the Climate Impact of Renewable Energy Targets by Bottom-up Modeling, International Conference on Intelligent System Design and Engineering Application, 2010, pp. 394–399.
[51] Beijing Municipal Commission of Development and Reform, Notice to Adjust the Natural Gas Sale Price for Non-resident in Beijing City, 2015. Beijing.
[52] D. Patteeuw, G. Reynders, K. Bruninx, C. Protopapadaki, E. Delarue, W. D'Haeseleer, D. Saelens, L. Helsen, CO_2-abatement cost of residential heat pumps with active demand response: demand- and supply-side effects, Appl. Energy 156 (2015) 490–501.
[53] T. Rehl, J. Müller, CO_2 abatement costs of greenhouse gas (GHG) mitigation by different biogas conversion pathways, J. Environ. Manag. 114 (2013) 13–25.
[54] D.A.C. Branco, A. Szklo, G. Gomes, B.S.M.C. Borba, R. Schaeffer, Abatement costs of CO_2 emissions in the Brazilian oil refining sector, Appl. Energy 88 (2011) 3782–3790.
[55] D. Chen, C.Y. Cheng, J. Urpelainen, Support for renewable energy in China: a survey experiment with internet users, J. Clean. Prod. 112 (2016) 3750–3758.
[56] Z.Y. Zhao, Y.L. Chen, R.D. Chang, How to stimulate renewable energy power generation effectively? – China's incentive approaches and lessons, Renew. Energy 92 (2016) 147–156.