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A realistic pathway for coal-fired power in China from 2020 to 2030

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ABSTRACT

While long-term coal transition is clear, the short and medium-term coal-fired power development in China is more uncertain. Therefore, the development pathways of coal-fired power in China after 2020 were widely discussed. Based on the unit-based coal-fired power data, this paper explored the optimized pathway of China's coal-fired power from 2020 to 2030 at the provincial level. Considering national development goals, interprovincial transmissions, and other physical limits in power planning, our model integrated the supply and demand side to assess a reasonable capacity of coal-fired power in 2030. The results and robust analysis indicate that China's coal-fired power capacity in 2030 may stay around 1100 GW. Furthermore, future policies and regulations to deliver this pathway are also proposed.

1. Introduction

With the "13th Five Year Plan" period (2016–2020) is approaching an end, the short and medium-term development plans after 2020, including the "14th Five Year Plan" (2021–2025) and "15th Five Year Plan" (2026–2030) are being debated and discussed by government departments, enterprises, and scholars in China. As the largest carbon emission sector in the energy industry, the power industry, which accounts for about 40%–45% of China's total carbon emissions, is the core of high-quality energy development (NDRC, 2017) in the future. On the basis that the substantial increase in the proportion of renewable energy power (mainly variable renewable energy) generation is a necessary pathway to high-quality energy development, how to balance the share between coal-fired power generation and renewable power generation is the biggest uncertainty at present (Zheng et al., 2019). The core questions of "should China continue to build new coal-fired power plants?", "should China rebuild the postponed coal-fired power units during 2020 and 2030?", "what's the role of coal-fired power in China's electricity system from 2020 to 2030" needs to be addressed.

Existing literature on the prospect of China's future coal-fired power capacity can be grouped into two approaches: one focuses on achieving climate change and carbon mitigation goals, and the other focuses on industrial sustainable development. Under the views that climate change poses serious potential risks to China, most of their research on medium and long term power development policies and pathways focused on the self-contribution on coal control targets (especially the carbon emission peak targets) proposed around the Paris Agreement by Chinese government, discussing the possibility of carbon emissions peak, action plans, sub-sector contributions, and costs. (IPCC, 2018) provided more and more evidence to show the attributing causality relationship between human activity and the climate system to remind the governments to implement low-carbon policies (Mora et al., 2018). Highlighted the fact that GHG emissions pose a broad threat to humanity by intensifying multiple hazards to which humanity is vulnerable (Duan and Wang, 2019). Analyzed the long-term impact

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of the strategic adjustment of the global temperature control target from 2 °C to 1.5 °C in China to clear potential challenges and meaning in the decarbonizing process. (Ma and Chen, 2016) explored carbon emission peak level and pathway in 2030, as well as evaluated the emission reduction contributions of major sectors and key measures, and proposed the emission reduction target for the power sector based on the analysis (Jiang et al., 2016). Concluded that carbon emission from energy activities could reach the peak in 2020–2022, which could be driven by economic structure transformation, energy efficiency improvement, development of renewable energy and nuclear energy, carbon capture and storage (CCS) technology diffusion, and low-carbon lifestyle changes. In this case, coal-fired power capacity should not be increased (He, 2018). Highlighted that China has made and will continue to make important contributions and play a leading role in such areas as global climate governance reform, energy, and economy low-carbon transition and mutually beneficial international cooperation. (Mo et al., 2018) evaluated the government goals of energy and climate change in the Paris Agreement and concluded the measures and cost to achieve the goals, which indicated that the collaborative design of energy and climate goals was needed, as well as the low-carbon power structure would be better. Energy research institute, such as IEA, IRENA, NDRC Energy Institute, National Renewable Energy Center, also analyzed China's power industry development goals and structure in the context of climate change constraints which usually from a series of scenarios, majority of their scenarios related to the energy development NDC scenario, 2 °C scenarios, and 1.5 °C scenarios. These scenarios are mainly based on the vigorous development of renewables after 2020. Their models indicated that not only were new coal-fired power units no need but also the current capacity of coal-fired power should be greatly reduced. In scenarios of 2 °C and 1.5 °C, the coal-fired power capacity in 2030 even should remain below 1000 GW (CNREC, 2018; IRENA, 2018a; IEA, 2018; Energy Research Institute of National Development and Reform Commission, 2018). From the perspective of climate change, carbon emission reduction has become the main decision-making goal. The main characteristics are the significantly reduce the capacity of coal-fired power and rapidly increase the proportion of VRE power generation at the same time, which means huge challenges for the current power system in China because of enormous coal-fired power capacity (large scale of coal-fired power industry) and uncertainty of VRE power generation. So many cases required to decarbonize, however, few of their studies fully considered the actual situation (based on industry operation data, plant data, and unit data) of the industry.

Industry energy research institutes headed by China Electricity Council and State Grid Energy Institute also made prospects for the future development of coal-fired power. From the perspective of the sustainable development of the industry, it often insisted on the view that coal-fired power still is the main power source in China (Liu, 2019). They adopted more conservative constraints for integrating VRE in planning models which means the capacity of coal-fired power in the future is higher compared with the results given in the climate change scenarios. What they predicted was that new coal-fired power should continue to be built in 2020–2030 and the capacity of coal-fired power in 2030 should remain the extent of 1170–1300 GW (SGERI, 2018). Under these scenarios, the peak capacity of coal-fired power will appear around 2030, which will slow down the time of China's carbon emissions peak, however, it can mitigate the pressure of the coal-fired power industry in recent years and ensure that the system has sufficient stability to cope with the high proportion of renewable energy.

Coal-fired power construction, which has a large scale of investment, long payback period and may have many external costs such as environmental costs in the future so that new units to build should be decided carefully. The too low scale will affect system stability, on the other hand, the excessive scale will also cause a series of social problems (such as poor corporate efficiency and employees laid off, investment waste, etc.). Reasonable planning not only can greatly balance the government's concerns on emission reduction and the benefits of enterprises, but it can also establish a sustainable development example to countries such as India and Indonesia who also confuses about how to optimize such a huge capacity of coal-fired power in the future. At the time that all the benefit-related organizations pay close attention to the development issue of coal-fired power, this paper tries to use a definition of reasonable scale to explore China's capacity development area and optimization pathway of coal-fired power from 2020 to 2030 based on the real coal-fired power units data, policy goals, power system flexibility (which should be fully considered in the future) and other physical limits in power planning as well as a higher resolution at the provincial level to support decision-making for the energy regulatory department and enterprises in the power area. The layout of this paper is as follows: Section 2 presents the methods and parameter hypothesis. Section 3 reports the results and provides a relevant discussion. Section 4 addresses policy implications and concludes the paper.

2. Methods and parameter hypothesis

2.1. Quantitative model for the reasonable capacity of coal-fired power

When calculating the reasonable capacity of coal-fired power, this paper constructs a reasonable capacity calculation model integrated both sides of supply and demand. By setting reasonable reserve ratios, available supply factors, power input and output, demand response power, additional reserve capacity, and various scenarios of supply and demand, the extent of the reasonable capacity in each province was calculated. The specific expression is as follows:

$$P_{1,y}^{endGen} = \frac{(1+\delta)*L_y^{max}*(1-\gamma) - \left(\sum_2^m P_{2,y}^{endGen}*\beta_2\right) - L_{in} + L_{out}}{\beta_1} + \alpha \tag{1}$$

$$\text{s.t.} \quad \sum_m P_{m,y}^{endGen} * \beta_m + \sum P_{n,y}^{DR} \geq L_y^{max} \tag{2}$$

$$\sum_m E_{m,y}^{endGen} \geq E_y^{max} \tag{3}$$

$$P_{m,y-1}^{endGen} + P_{m,y}^{newGen} \leq P_{m,y}^{maxGen} \tag{4}$$

$$P_{n,y-1}^{DR} + P_{n,y}^{newDR} \leq P_{n,y}^{maxDR} \tag{5}$$

$$P_j^{min} \leq P_j \leq P_j^{max} \tag{6}$$

where, $P_{m,y}^{endGen}$ is the power capacity of source m at the end of year y; $P_{1,y}^{endGen}$ is the reasonable capacity of coal-fired power at the end of year y; β_m is the available supply factor of source m; δ is reasonable to reserve ratios; γ is the ratio of demand response load to the highest load in the year y; α represents the extra reserve capacity to be considered under a high proportion of renewable energy in the system in the future (considering the installed scale and output characteristics of small coal-fired power units just like 300 MW and below, this section is mainly undertaken by these small units in our research); L_{in} indicates the power which was received from other provinces; L_{out} indicates the power sent out to other provinces; $\sum P_{n,y}^{DR}$ represents demand response load in the year y; L_y^{max} is the highest load in the year y; $E_{m,y}^{endGen}$ represents generation electricity by source m at the end of year y; E_y^{max} represents the total electricity consumption at the end of year y; $P_{m,y-1}^{endGen}$ indicates the power capacity of source m at the end of year *y-1*; $P_{m,y}^{newGen}$ represents the new installed capacity of source m at the end of year y; $P_{m,y}^{maxGen}$ represents the cap capacity of source m at the end of year y; $P_{n,y-1}^{DR}$ represents demand response load in the year *y-1*; $P_{n,y}^{newDR}$ represents the increased load by new demand response in the year y; $P_{n,y}^{maxDR}$ represents the cap load of demand response in the year y; P_j^{min} represents the minimum output of unit j; P_j^{max} represents the maximum output of unit j.

2.2. Basic parameters

2.2.1. Available supply factors

Power balance is very important in the power extension models, therefore, high-resolution parameters were set in this paper. In the peak load balance of the expected year, we set different output factors of different power sources which were called available supply factors in this paper to simulate the real situation. Hydropower and nuclear power are the baseloads in power supply so that their capacity factors could be used as available supply factors (EIA, 2019; CEC, 2011-2018). Due to the randomness and uncertainty of renewable energy output such as wind power and photovoltaics, historical data were referred to as predictors (CEC, 2013–2018). (Among them, for the majority of wind power capacity in China is on-shore wind power and the gap between different resource areas is large, the average available supply factors setting in this paper is low which also could be seen in a report by LBL, 2016). Coal-fired power, gas power, and biomass-fired power are currently in a special situation that their annual utilization hours are far below the design value or capacity factors which is underestimated seriously in China because of the excess power supply. In our model, we used maximum output that could be produced by these sources as their available supply factors to avoid resource waste (CEC, 2011-2018). At the same time, not only were average values referred but also a diverse setting was employed based on the real investigation by each province to maximize the simulation of the real situation (Table 1).

Table 1
Average values setting of available supply factors in the model.

Power sources	Available supply factors
Coal-fired	95%
Gas	95%
Hydro	40% (60%)
Wind	12%
PV	20%
CSP	90%
Nuclear	95%
Biomass-fired	80%
Pumped storage	100%

Note: The hydropower available supply factors of Yunnan, Guizhou, Qinghai, and Sichuan is 60%.

2.2.2. Power capacity in 2030

Integrating the historical growth rates of installed capacity, the technical economics and development potential analysis of different industry reports, the upper and lower limits of the potential scale of different power sources in 2030 could be seen in Table 2. Among them, meeting the national "energy revolution strategy" policy goals (the proportion of non-fossil energy consumption accounts for 20% and the proportion of non-fossil energy generation accounts for 50%) is a basic constraint (NDRC, 2017); In this part, we also listed the potential scale of coal-fired power proposed by the other research to be compared and analyzed later. The upper limit of coal-fired power is the maximum forecast value and the lower limit based on the simple estimation that it will no longer build new units and only rebuild the currently suspended units in 2019 (Endcoal, 2018; Greenpeace, 2016). The specific reasonable capacity will be discussed later, here is the theoretical upper and lower limits. The potential installed capacity of hydropower and nuclear power is sorted out based on the actual construction and application projects; the potential development scale of wind power and solar power is derived from the actual historical growth trend from 2011 to 2018 and industry report (CEC, 2011-2018) (Table 2).

2.2.3. Reasonable reserve rate

The system reserve rate is the proportion of the supernumerary capacity that needs to be added to the total capacity so that the power system can still guarantee the power demand in the case of equipment maintenance, accidents, and frequency modulation. Too low reserve rate indicates that the safety and reliability of the power system cannot be guaranteed, while too high reserve rate indicates that the power system capacity is redundant or resource waste. Referring to the National Energy Administration and the US power market standard of reasonable reserve rate (Johannes et al., 2013; National Energy Administration, 2017), the reasonable reserve rate of different provinces in this paper is the extent of 12%–15%.

2.2.4. Distribution principle of new power capacity

Integrating the regional energy development goals, constraints of resources characteristics, energy development strategy, UHV transmission channel, new power projects distribution have the same conclusion with SGERI in this paper (SGERI, 2018). The gas power station will be built along the central and eastern coasts, hydropower stations concentrated in the southwestern region, and the wind power station dominated in the "Three Norths" district. For photovoltaic station, the western region is equal to the central and eastern regions.

Table 2
Potential power capacity in 2030.

Power sources	Capacity (GW)
Coal-fired	1050–1300
Hydro	440–450
Pumped storage	100–110
Gas	180–250
Nuclear	100–120
Wind	450–550
PV	500–600
CSP	40–60
Biomass-fired	30–40

Reference sources: China Energy Research Association (2016); China Research Net (2016); Yang (2017); IAEA, 2015; National Renewable Energy Centre (2017); Century Renewable Energy Net, 2015; IEA, 2013; EIA, 2015; Lazard, 2011; IAEA, 2015; IRENA, 2018b; Lazard, 2017; EIA, 2018,etc.

2.2.5. Interprovincial transmission channel

At the end of 2016, there are 39 inter-district transmission channels operated in China. 21 of them are DC and the others are AC. Meantime, there are 12 channels in construction now. Besides, 8 DC, 4 AC, and 2 AC channels that have been planned (CEC, 2018b; SGRI, 2018).

Statistics show that the capacity of the inter-provincial transmission channel in China had reached 166 GW by the end of 2017. For the actual inter-provincial power exchange situation is very complicated, the specific situation of the inter-provincial transmission channel is simplified in this paper. It is assumed that the DC channel is the point-to-point transmission, and the transmission capacity is the rated capacity; AC is more complex, the total transmission capacity in the AC channel is the rated capacity, and the provinces around the channel route may send out some power based on the district power balance. For 2030, it is estimated that at least 55 inter-provincial transmission channels will be put into based on the projects in construction and planning and the capacity may exceed 300 GW in this paper.

2.3. Power demand

To cover the multiple possibilities of electricity demand in 2030, this paper simulates three scenarios of electricity demand growth named D1 (low scenario), D2 (middle scenario) and D3 (high scenario) referred the elasticity of electricity consumption growth, GDP growth as well as the relationship between GDP growth and electricity consumption growth in different stages of developed countries such like Japan, United State, Germany, and South Korea, etc. (Huaneng Institute of Economics and Technology, 2011). In these scenarios, the national average annual growth rate of electricity consumption will be 1.5%, 2.2%, and 3% in 2020–2030, and the total electricity consumption will reach 8600, 9300, and 10000 TWh in 2030, respectively. At the provincial level, based on historical data, this paper employed GDP, population, and urbanization rates which are most relevant to the growth of electricity consumption as the main factors to establish a multivariate regression model (National Statistical Yearbook, 2018). Further to use the planning and development goals of each province to predict the electricity consumption in 2030. Among them, the average growth rate at the national level and the strategic positioning goals of different urban agglomerations in China are used as constraints for the prediction model. It's worth mentioning that the results of the prediction only employed the basic linear model of prediction analysis. For future studies, more advanced models such as SVM and PCA should experiment even the Deep Learning network will be applied.

At the same time, for the prediction of the peak power load, this paper takes the traditional method which used electricity consumption multiplied by the experience coefficient to assume the peak load as a constraint and reference standard. According to the geographical characteristics of different provinces and regional economic development degrees (mainly measured by GDP per capita) to establish a temperature load forecast model to predict the peak load in each province in 2030 (Zheng et al., 2019; National Statistical Yearbook, 2018). This model decomposes the annual peak load into two parts: base load and temperature change load. The future baseload forecast is obtained by applying historical data. For the temperature change load, linearizing the relationship between temperature and load by historical data first, and then setting the expected sensitive temperature and saturation temperature to obtain the final peak load. On this basis, the forecast results show that the total peak load in China in 2030 may stay around 1480–1600 GW.

2.4. Demand response and system flexibility

2.4.1. Demand response power in 2030

The transformation of the power supply structure is accompanied by the large scale integration of renewable energy in the power system, and in the future, the power grid will gradually become a large power grid with a high proportion of renewable energy integration. The level of flexibility both in the supply side and user side will have a significant impact on future power systems. Integrating the development trend of intelligent level, energy storage scale, electric vehicle scale, and policy targets, this paper assumes that China's smart grid technology will further progress in 2030 to the level of international advance which means a majority of cities have built self-healing, flexible and adjustable intelligent distribution networks and the inter-provincial transmission capacity has been further improved (State Grid, 2013; NRDC, 2018; NDRC, 2018). With these trends, the continuous improvement of the power market and the increasing demand for energy storage will inevitably reduce the cost of large-capacity energy storage equipment from 2020. The power of demand response that can be mobilized in various regions of China could account for about 8%–10% of the peak load, up to 10% in some optimistic cases. The basic parameter of this paper is 10%, and the levels under other proportions are further measured in the robust analysis.

2.4.2. System flexibility demand scale in 2030

With the promotion of the government's renewable energy subsidy policy and tax incentives, VRE power has been fully developed, and the installed scale has gradually changed from a previous small-scale growth to explosive growth since 2013. According to CEC statistics, at the end of 2017, China's wind power installed capacity reached 164 GW, and solar power installed capacity reached 130 GW (CEC, 2018). Judging from the current growth trend, it could be estimated that the installed capacity of wind power will reach 230–250 GW and solar power can reach 180–200 GW by 2020, which means that the total VRE installed capacity share in power system could be about 21%. And further to 31%–38% along this way in 2030. At specific provinces, the renewable energy penetration rate even exceeds 50% in 2030. For these regions with a high penetration rate of renewable energy, the scale of plants providing flexible services needs to be considered when making planning. Therefore, the analysis of flexible demand scale is very necessary. Considering that the operation simulation at the provincial level is extremely complicated because many issues at the micro level need to be considered. This paper focuses on the analysis of the macro-level goals so that the processing is simplified. Referring foreign power market (just like PJM) and actual system operation, pumped storage power and gas power are not only provide flexibility but also set an additional reserve capacity for these provinces whose VRE penetration rates more than 30% in this paper. The capacity of these additional reserves is an equivalent of 20% of the total VRE (solar and wind) power capacity and all of them provided by improved small units of coal-fired power in this paper as the basic parameter.

3. Results and discussion

3.1. Basic result

Integrating all the parameters, the extent of reasonable capacity in each province as follows (Fig. 1).

Summing up the upper and lower limits of the reasonable capacity in various provinces could be seen that the national reasonable capacity extent is 770–1044 GW in 2030. The lower limit of this interval indicates that in this development scenario, the

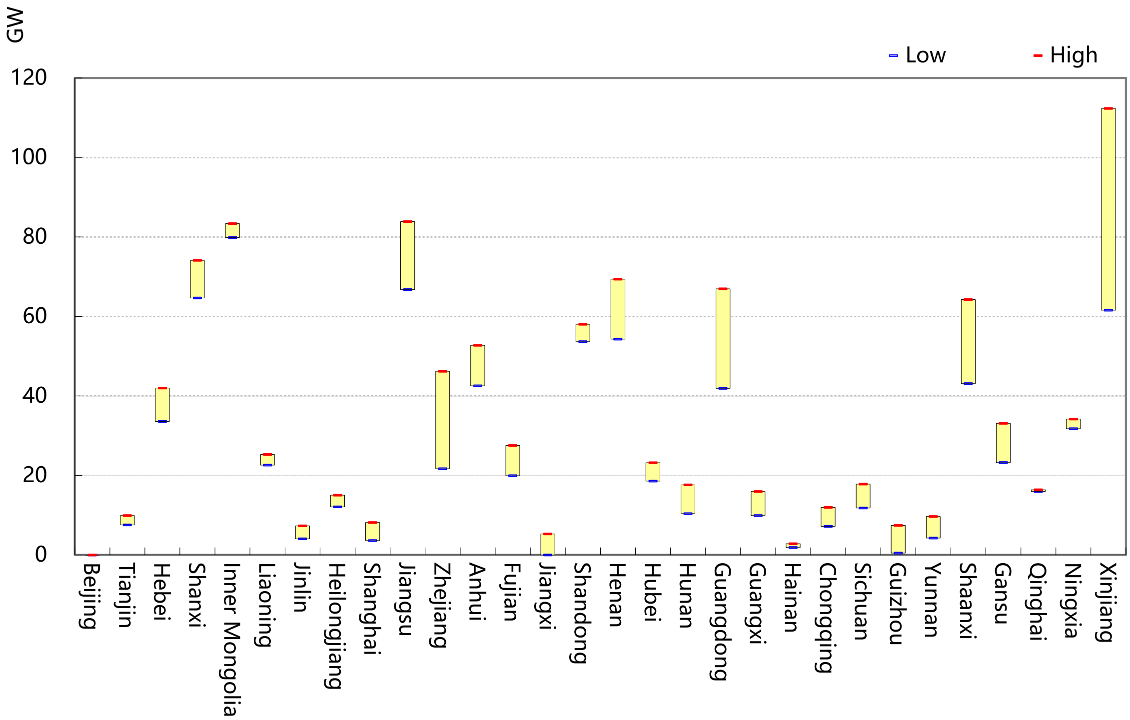

Fig. 1. Reasonable capacity interval of coal-fired power each province.

growth rate of the load will remain at a very low level after 2020; the capacity of VRE power will increase explosively; the capacity of gas power will increase with a very large scale; and no need to build new coal-fired power anymore. However, the upper limits of this interval indicate the development scenario of that, growth rate of power load will remain at a relatively high level after 2020; the capacity of VRE power, nuclear power and gas power will increase at a moderate growth rate; many inter-regional UHV transmission channels have to been built.

Judging from the growth rate of power consumption in the past five years, there is a high probability that the electricity demand of the whole society will be between 9500 and 10000 TWh in 2030. Therefore, the development scenario near the upper limit may be closer to the current development status of China's power system. Although this lower limit quantity is the same as in some 2 °C and 1.5 °C scenarios, however, the scene-setting in this paper is completely different from those scenarios. In our analysis, the lower limit is almost impossible based on the current database and it is an extreme scenario. Even if are no new coal-fired power plants built after 2020, only the units rebuild which were postponed during the "13th FYP", the total capacity of coal-fired power will arrive 1050 GW in 2030. From an investment perspective, any early decommissioning or shutdown is uneconomical and unreasonable, and the cost of resettlement of these employees due to early decommissioning and shutdown is also a very large expense. In reality, the lower limit capacity of coal-fired power in China should not be less than 1000 GW in 2030. From the structure perspective of coal-fired power units, if the capacity of coal-fired power in China reaches 1170 GW in 2030, the annual utilization hours will remain at 3200–3500 h. In this structure proportion that the unit's capacity of 300 MW and below are less than 20%, while 600 MW and above are higher than 40%, the more capacity will bring the more inefficient operation of large units and uneconomic of the entire industry. If the capacity of coal-fired power is less than 1000 GW in 2030, although the annual utilization hours will rise to 3700–4100 h, the more amounts of gas power and VRE power, as well as multiple inter-provincial transmission channels have to invest which also brings a huge challenge for the power system stability because a more flexible power system is required. The capacity of coal-fired power below 1000 GW requires not only add a large scale optimization investment but also have to the shutdown of a few scales coal-fired generating units in advance, which is not a reasonable choice.

From the basic result, it looks like that 1000–1050 GW is a good choice in 2030. However, guaranteeing a safe and stable power supply is the prerequisite in China. This section concludes the reasonable capacity based on the basic parameters. In the next section, this paper will further test the basic result in variable sensitive key parameter.

3.2. Robust analysis

3.2.1. Demand response power

In recent years, the energy authorities have successively proposed relevant goals for the scale of demand response at the national level. At the end of 2015, National Development & Reform Commission and National Energy Administration supporting documents for power reform proposed the goal of "gradually forming demand-side response load accounts for about 3% of the maximum power load in the process of marketization" (National Development, 2017). In July 2016, the National Energy Administration issued a document explicitly encouraged that "the virtual power plants with various energy in the pilot cities should create the scale of demand response accounts for 5–10% of the city's peak load", and officially proposed a goal of 10% (NEA, 2016d). And in the same month, Jiangsu Province has completed its demand response goal of 3%. In, 2018, the National Development and Reform Commission issued a document that required to strengthen user-side and demand-side load management to establish and improve demand response mechanisms to strive to account for about 3% of local peak load each province (NDRC, 2018).

Some research shows that the scale of demand response in the future could not be 10% while energy storage and electric vehicles could provide new resources for demand response. However, some research demonstrates that the demand response scale in 2030 will account for 8%–10% based on the application of electric vehicles and energy storage equipment as well as potential motivation by the developing electricity market. To further explore, 5%–10% were employed (Table 3).

The results show that, except for the 5% demand response scale, the total reasonable capacity under other proportions within 1100GW.

According to the promotion of current policies, China could be able to create a demand response scale of about 3% around 2020 and strive to create a demand response scale of 5% around 2025. Therefore, according to the average growth rate analogy, the lower limit of the national demand response scale could reach more than 6% in 2030. From the perspective of ensuring power supply and avoiding invalid investment, the scale of 1100 GW will be better.

3.2.2. Additional reserve capacity

The national energy revolution strategy proposes that China's total non-fossil energy consumption will account for 20% of the total consumption by 2030. The national energy development goals are proposed to further accelerate the transformation of the energy structure and accelerate the green and low-carbon process. However, for power systems, large scale renewable energy integration will pose new challenges to the stability of the system. To ensure the smooth operation of the power system, a large-scale auxiliary service must exist in the high-proportion renewable energy scenario.

There are many uncertainties in the power grid dispatching level in 2030, some research shows that the future power grid will be more intelligent and do not need too many extra standby power sources to provide auxiliary services. It can be achieved by mobilizing flexible resources such as pumping, gas, and demand response. To meet the system flexibility needs, extra spares will be wasteful. On the other hand, another part of scholars believes that the stability of the power system is the prerequisite for all transformation and reform. The flexibility requirements of the system must be fully considered in the planning. For the province with large renewable energy integration, additional flexible power sources must be planned to ensure its stability. To further explore the impact of different additional reserve capacity, this section calculates the total reasonable capacity under different additional reserve sizes with other parameters unchanged (Table 4).

Reliability is a basic requirement for the good operation of the power system. Therefore, in the future where the proportion of renewable energy is high, it is essential to provide auxiliary services for variable renewable energy power generation. It is more economical to reasonably use the coal-fired power units currently in service instead of building such high-cost options such as large scale pumped storage and energy storage station. Under the premise of ensuring reliability, the calculation results show that the capacity of 1100 GW coal-fired power not only can fully meet the basic requirements of the system but also it can meet the conditions in a more conservative situation.

Table 3
Reasonable capacity in different demand response scale.

Scenario	The total reasonable capacity of coal-fired power (GW)	
	min	max
10%	771	**1044**
8%	787	**1063**
6%	820	**1101**
5%	837	**1120**

Table 4
Total reasonable capacity in different additional reserve scale.

Scenario	The total reasonable capacity of coal-fired power (GW)	
	min	max
30%	892	**1203**
25%	864	**1160**
20%	771	**1044**
15%	732	**1000**

Based on the analysis of the key two factors, although the coal-fired power capacity above 1170 GW in the industry analysis can meet the power needs of various development scenarios, however, it will lead to annual utilization hours less than 3500 h, resulting in a decline in the industry's profitability and invalid investment from the perspective of effective investment and healthy development of the industry. If the capacity of coal-fired power is less than 1000 GW, it means that a larger scale optimization investment is needed which causes serious diseconomy. Therefore, considering the model calculation results and the robust analysis of key parameters, this paper believes that an optimization option is China's coal-fired power capacity in 2030 may stay around 1100 GW which not only can accelerate the trend of decarbonization, achieve repaid and just roles transition for the coal-fired power in the power system in a certain sense, but also maintain a smooth transition of the coal-fired power industry to avoid greater economic waste and social problems. And in this case, China will not only mitigate the serious levels of air pollution but also complete the promise of climate reduction in advance which means potential damage for public health could be dramatically reduced because of coal-use reduction in energy use.

4. Pathway and policy implications

Based on the quantitative analysis from the provincial level and robust analysis of key parameters, this paper demonstrated that China's coal power capacity in 2030 would be maintained at the 1100 GW level. To achieve this goal, and to minimize unnecessary investment and avoid investment losses, this paper shows that the Chinese coal-fired power industry could implement the following optimization paths during 2020 and 2030:

(1) Rebuilding the coal power units suspended during the 13th FYP in an orderly way based on the advancement of the power market and actual profitability. No new coal power projects should be approved.
(2) Accelerating decommissioning for units that have reached the upper limits of the service period and small old units smaller than 300 MW and those 300 MW units which do not meet emission standards, totaling decommissioning capacity is about 50 GW. Subcritical units of 300–600 MW that are to be retired from the operation and meet the emission standards can be flexibly transformed to delay decommissioning or undergo normal decommissioning based on the reserve resource required by each province. Each province should clarify the number of resources required to balance VRE, total unit capacity for detention decommissioning should remain about 50 GW. Delayed decommissioning units should give priority to provinces such as Hebei, Inner Mongolia, Jiangsu,

Zhejiang, Henan, Shaanxi, Gansu, Ningxia, Xinjiang, Anhui, and Heilongjiang where VRE resources are good.

(3) Pushing forward at least 70 GW of flexibility transformation for subcritical units. Focus on promoting the flexibility of subcritical units in 14 provinces including Shandong, Guizhou, Jiangxi, Yunnan, Guangdong, Guangxi, Shanxi, Jilin, Hunan, Hubei, Sichuan, Qinghai, Yunnan, and Guizhou.

(4) According to the reasonable capacity interval each province, build 3–5 new interprovincial transmission corridors. Focusing on sending surplus power from Shandong, Jiangxi, Guizhou, Guangxi, and Yunnan to alleviate some of the problems caused by unreasonable channels and further optimize resource allocation.

(5) After 2025, start planning and pilot CCS retrofit of coal-fired power units. Define the scale of CCS units to be retrofit each year, and promote the CCS transformation of coal-fired power plants in an orderly manner under the total coal power carbon emissions and carbon market quota constraints.

At the same time, to ensure the effective implementation of the high-quality development pathway, this paper suggests that government departments should further strengthen the following aspects of supervision:

a. Establishing a flexible power system plan that meets the efficient integration of the high penetration of renewable energy

The fundamental premise of green and low-carbon transformation is to ensure the stability of the system while addressing the biggest problem in the use of renewable energy and output volatility. Many uncertainties bring serious problems to the system. In the future, the penetration rate of renewable energy will further increase. If the flexibility of the system is limited, it will inevitably hinder the transformation process. Therefore, whether it is power generation or demand, in terms of the requirements of energy transformation, the flexibility plan of a power system should include a high proportion and efficient consumption of renewable energy. One of the core themes of the power plan after 2020 is a flexibility plan for the power system that provides for a high proportion and efficient consumption of renewable energy.

b. Accelerating the building of the power market and utilize accurate price signals to guide rational resource allocation

China still does not have an effective power market except for a few provinces that will be launching the pilot power market, most provinces in the country are still using the “open, fair and just” power dispatch model. Although China has issued a policy of preferentially scheduling renewable energy, its execution has limited success. In addition to the limited overall adjustment capacity, there is largely a lack of market price signals to guide rational resource allocation. Therefore, to steadily push forward supply reforms and optimize the power supply structure, the top priority currently is to accelerate the building of the power market.

c. Break the interprovincial barriers and plan interprovincial transmission channels

Our study shows that serious interprovincial barriers and a lack of interprovincial transmission channel planning cause irrational allocation of resource line transmission and may aggravate the problem of excess coal-fired power in some provinces in 2030. Typical examples such as Shandong and Jiangxi have problems with inward power transfer, whereas Yunnan and Guizhou have issues with outward power transfer. The primary problem that needs to be resolved is breaking interprovincial barriers to achieve a truly optimal resource allocation over a wider range. Second, from the modeling results for 2030 and under the lack of guidance of a national unified interprovincial and interregional transmission channel plan, not only may invest in some transmission channels be wasted, but there will also be severe polarization of coal-fired power overcapacity. This will form a situation where the overall resource allocation in China is not economic. Therefore, it is necessary to research and introduce a more coordinated and scientific interprovincial transmission channels plan as soon as possible by using the long-term power supply and demand of various provinces as the basis for decision-making and determining the needed interprovincial transactions and the actual delivery of the provinces. This will avoid localization and short-term decision-making. The overall planning of the transmission channels should avoid “obstacles at the endpoint and the receiving end is full” as best as possible.

d. Further strengthen the management level of the demand side, rapidly increase the scale of demand response and lower the requirements for power investment

With a greater degree of electricity marketization and under the guidance of price signals, the resources of the demand side will develop rapidly. Judging from the forecast results in our paper, the number of electric cars and charging piles will increase exponentially in the future. If electric cars actively participate in demand response, the scale will be considerable. Besides, the rate of decline in energy storage costs will also accelerate, and the scale of future energy storage participation in the demand response will also increase significantly. As resources on the demand side that can be mobilized develop rapidly, the management level of demand-side should be improved as soon as possible. If the management level of demand of various regions cannot be improved with the increase in resources for demand response that can be mobilized, there will be considerable resource wastage and inefficiency, as well as inefficient power investment. Construct a coal-fired power installation on the supply side end to meet a peak load of less than 50–100 h is the most uneconomical approach, and such an approach will also further exacerbate overcapacity and economic deterioration of coal-fired power. Therefore, greatly enhancing the demand side management level during the process of power marketization is an important foundation for improving the quality of reforms of the coal power supply side.

CRediT authorship contribution statement

Wenhua Zhang: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Qingyou Yan:** Conceptualization, Validation. **Jiahai Yuan:** Conceptualization, Validation, Supervision, Resources. **Gang He:** Conceptualization, Validation. **Tian-Lih Teng:** Validation. **Meijuan Zhang:** Data curation. **Ying Zeng:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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