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Research article

Towards the prospect of carbon-neutral power system 2060: A Power-Meteorology-Society systematic view

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ABSTRACT

With the target of achieving carbon peaking and neutrality in the power sector in China, both State Grid and China Southern Power Grid have made plans of a rapid increase of renewables in future years towards 2060. However, considering the interactions between the power system and meteorological, society factors, whether those plans would lead to CO_2 emission peak in 2030 and carbon neutrality in 2060 is still questionable and needs further analysis. Therefore, a Power-Meteorology-Society System is formulated and interactions between these factors will impact the CO_2 emission of the power system is studied. Case study shows that these environmental, social factors as well as their interactions will have significant negative impact to the CO_2 emission reduction in China's power grid; With current trend of generation and transmission development and higher-than-expected CO_2 emission, while the grid could still reach its target of carbon peak in 2030, there will be some challenge for the grid to reach carbon neutrality in the year 2060. Based on that, the authors analyze some potential solutions such as transmission construction, energy storage and the Carbon Capture, Utilization and Storage (CCUS), and try to find a relatively cost-benefit path to reach carbon-neutrality for the grid in 2060.

1. Introduction

THE rapid growth of world economy has significantly contributed to the growing demand for all types of energy resources. As the main energy resources since the industrial revolution, traditional fossil fuels including coal, petroleum and natural gas are facing not only the crisis of depletion, but more importantly the environmental problems. According to the recent published report [1], 50% of all greenhouse gases and 85% of CO_2 global emission come from the combustion of fossil fuels, which under certain circumstances causes global climate extremes and threaten the development of human beings. Therefore, the reduction of greenhouse gas emission (also called "carbon emission") has become the focus of current environmental protection.

In response, a large number of countries, including China, and regions have proposed "zero carbon" or "carbon neutral" targets and introduced corresponding policy plans in recent years [2–4], which has triggered the attention of many scholars. Reference [5,6] simulate various scenarios for achieving carbon neutrality, and suggests that improving the quality of economic growth in an environmental-friendly way will propel China to achieve carbon neutrality by 2060. Reference [7] forecasts South Korea's carbon

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emission trajectory by GM(1,1) model and shows that the country can meet its 2050 carbon neutrality goals owing to the joint actions of CCUS and forest carbon sinks. Reference [8] analyzes carbon neutrality goals of Africa's ten biggest economies covering the years 1990–2018 and suggests that adjusting the policies about financial development, population and renewables will assist in their carbon neutrality target.

In the context that "peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060" has been widely recognized by Chinese industry and academia [9], a series of initiatives in the power sector were proposed at the Climate Ambition Summit, such as the total installed capacity of renewables reaches more than 1.2 billion kilowatts by 2030 [10]. Subsequently, China proposed the concept of a new power system led by renewables, which clearly defined the direction for energy transition and development [11]. As defined by the International Energy Agency of the United States, renewable energy (or so-called "renewables") refers to the sustainably-supplied energy that is obtained directly or indirectly from the sun or from the interior of earth. Traditional thermal power generations burn fossil fuels to convert into electricity, which inevitably brings excessive CO_2 emission and can cause greenhouse effect [12]. In comparison, renewable energy, represented by the wind and solar power, much lower CO_2 emissions during its construction and generation processes, is destined to harness an indispensable strength to improve the energy structure, coping with climate change and achieving carbon neutrality targets as scheduled. However, despite its contributions in CO_2 emission reduction, the development and higher penetration of renewables also brings other challenges to the power system. On account of the uncertainty and instability of renewables, the stability of the power system may be degraded, abandonment of renewables, increased costs for backup generators and severe disruptions to system operations may occur. Therefore, both economic and safety factors need to be taken into account carefully under the high penetration of renewables in future.

Some researches have examined how renewable energy fit into China's low-carbon transition process. For example, reference [13] uses the carbon peaking and neutral power planning package GESP-V to optimize Chinese different development scenarios to obtain the power supply structure, CO_2 emission reduction and costs changes in the future. Reference [14] designs multiple politic and temperature-control scenarios to analyze the low-carbon transition path, technical support and investment costs for China's power system. Reference [15] establishes a joint optimization model for both long and short-term operation, then identifies a low-carbon transition path of China's power industry. Reference [16,17] study China's energy development trend from 2020 to 2050 by combining the source-grid-load-storage coordination theory with the help of a platform for global energy research developed by the State Grid Energy Research Institute. Reference [18] creates an overall optimized and coordinated planning model of power source-grid-load-storage, solves the development scale of each source with the target of minimizing the production and operation cost of power system. Although the current researches study the impact of renewables on power system in the long term, they rarely take real-time power system operation into consideration, and neglect some other important factors in the future power system such as transmission, storage and environmental changes.

At the same time, the interaction between climate change and the power system has become the focus of several researches. Reference [19] explores the influence of various geographical resolutions on the stability evaluation in Texas' power grid and reveals that a high-resolution model is able to recognize emergency occurrences with greater accuracy. According to Ref. [20], a stochastic-robust optimization approach might cause a considerable gap in generation dependability between different scenarios due to uncertainties in renewables potential. Reference [21] analyses the results of over 220 researches to estimate how the climate will affect power system both locally and worldwide. More specifically, with regard to the impact of meteorological factors on renewables, reference [22] investigates five individual wind farms in Iowa, U.S. by satellite-measured ground temperature data, finding an irrefutable nighttime warm relative to the wind turbines' geographic configurations. Reference [23] uses ground temperature data from year 2003–2013 to evaluate the effects of three wind farms in Illinois, U.S., and observes an increase in area mean of 0.18–0.39 °C over the farms, especially in winter months of December–February. Reference [24] performs comprehensive 3D simulations of a 1 MW part of a photovoltaic (PV) plant in North America using the CFD models. The results are compared with realistic recorded data, demonstrating that the yearly average warming can reach up to 1.9 °C. In an empirical investigation of the heat island (PVHI) impact, reference [25] reports that nighttime temperatures above a PV plant were consistently 3–4 °C higher than those in wildlands, therefore suggesting an integrated solution to mitigate the PVHI. Reference [26] considers the turbine density and CO_2 emission and uses the WRF v3.3.1 high-resolution regional model, finding that only using wind energy to meet the US's current electricity demand (0.5 TWe) would result in a 0.24 °C increase in surface temperatures. Reference [27] uses a fully linked regional climate mode to simulate 1 TWe hypothetical solar arrays finding the arrays can raise afternoon temperature by as much as 0.4 °C.

Caused by global warming, peak load will have the potential to keep rising. Reference [28] analyzes the relationship between China's yearly peak load and highest temperature, drawing a conclusion that each 1 °C increase in maximum temperature increases peak load by an average of 0.385 GW. Reference [29] analyzes the climate data from 30 provinces between the year 1995 and 2016, forecasting that load will grow by 0.094% or 0.061% for every 1% increase in CDD or HDD.

In contrast to previous paragraph's references, these studies pay more attention to the specific climatic impact of renewables, but these findings are not practically applied in the study of CO_2 emission reduction and renewables development and lack of guidance on carbon neutral pathways.

Therefore, going beyond the current studies on China's CO2 emission reduction and renewables development, this manuscript creates a Power-Meteorology-Society Systematic feedback loop to study the impact of meteorological and environmental factors on future power system operation, establishes a more precise estimation of China's future power grid until the year 2060, and suggests the most economical paths to achieve carbon neutrality.

This paper is organized as follows: Section 2 introduces the formulation of Power-Meteorology-Society System and its components; Section 3 shows case study under current estimations and demonstrates the CO_2 emission and environmental change from year 2020–2060; Section 4 analyzes the impacts of the corresponding support facilities and further proposes a most economic solution to reach carbon neutrality.

2. Power-meteorology-society system

Under the blueprint of carbon neutrality target, China's CO_2 emission has the goal of peaking by the year 2030 and achieving carbon neutrality by the year 2060. Therefore, this manuscript will focus on analyzing the power system operation as well as CO_2 emission between the time range of the recent year 2020 (the year we have sufficient data to train our model) to the year 2060 (the expected year of carbon neutralization).

Therefore, in order to comprehensively consider the system operations, CO_2 emission and other meteorological factors and the interactions between them in the carbon-neutral path, a Power-Meteorology-Society System is established as shown in Fig. 1. The components of this system include.

(1) *Power System Operations Model* to estimate the real-time economic dispatch of thermal power and renewables, which will be described in detail in Section 2.A.
(2) *Meteorological Model of Renewable Generations* to consider several meteorological factors that may impact the Power System and Society, including the wind kinetic energy around wind farms and the anthropogenic air aerosol emissions. The greenhouse effect and CO_2 emissions are also considered as the output of generation. The detailed model is described in Section 2.B.
(3) *Social Demand Model* to describe how the social electricity demand (also called the "total load") is impacted by the temperature increase and how it will affect the power system operations. The detailed model is described in Section 2.C.

Between the above three models, meteorological factors influence CO_2 emissions by affecting power generation, which in turn leads to deviations in electricity load and feed back into the power generation.

A. Power System Operations Model.

In this subsection, the power system operations model is introduced considering several factors such as.

- Cross-regional power transmission between seven divisions;
- Four-season typical system demand and generation status formulation;
- Unit commitment and economic dispatch model to achieve optimal generation each year.

Therefore, a proper unit commitment model considering transmission, generation and demand status will provide a good estimation of future system operation, as well as calculating the CO_2 emissions per year.

2.1. Spatiotemporal Typical Load Curve Formulation

In order to model the real-time operations for China's power system in the future years, the estimation of future electricity demand (or named as "load" in the power sector) is essential. As China is a country with large territory, clear seasonal features of load and a gigantic power system with a huge number of electric buses, it is nearly impossible to study the real-time operations in each bus, each real-time interval, and each day in the time range of 40 years (2020–2060). Therefore, a set of spatiotemporal typical load curves for seven regions in the mainland China is formulated. These load curves could be used in power system operations model more efficiently without losing the characteristics of electricity demand over regions, time and seasons.

First of all, taking into account the geographic and economic divisions as well as the service area of the two big Independent System Operators: State Grid and Southern Power Grid Company, mainland China's power grid can be divided into seven regions: North, East, Central, Southwest, Northwest, Northeast and South, as shown in Fig. 2. The intra-connection of power transmission lines is neglected

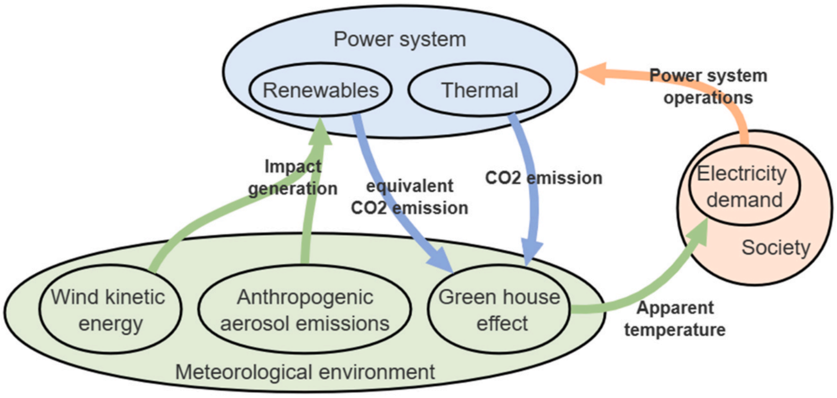


Fig. 1. The Power-Meteorological-Society System structure.

within each region since China usually has enough transmission capacities within regions. Therefore, only the aggregated load for each region should be considered. Inter-regional connection capacities are still limited since they are usually HVDC and HVAC lines with limited capacities. An inter-connection adjacency matrix is used to describe the simplified inter-connection topology of China's power grid, and this matrix will be used in the upcoming economic dispatch model.

Furthermore, the seasonal features of the regional loads are extracted and four typical load curves can be formulated as spring (March to May), summer (June to August), autumn (September to November) and winter (December to February). These seasonal typical days' load curves are obtained by adjusting yearly typical day load curve with the seasonal multiplier [30]. The resolution of each typical load curve is 1 h, which is sufficient to reflect the system condition in the scope of system planning and the CO_2 emission calculation.

In order to formulate the regional 96 typical points (four typical curves with 24 points in each one), the typical daily load curves of each province in 2020 are obtained from the National Energy Administration [31]. According to related reports and researches [15–18, 32], China's electricity consumption is expected to grow faster in the upcoming decades. Specifically, the load demand grows with an average annual rate of more than 4% starting from 2020 and reaches 14.19 kTWh in 2040, and maintains a relatively lower growth (2%) until the year 2050, which will double on the basis of 2020 in 2050. After the year 2050, the development enters a plateau period roughly at 15.6 kTWh. In addition, we assume that there is no difference of load growth between regions; Therefore, load growth rate of all regions remains the same.

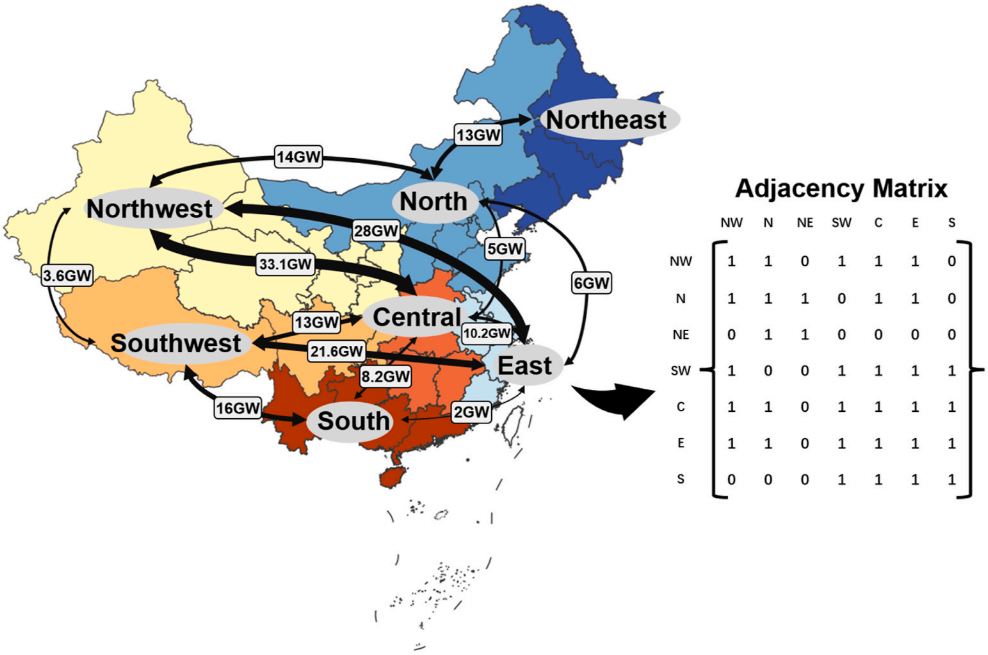
2.2. *Power System Transmission Model Formulation*

As mentioned before, due to the regional imbalance of economy, population and power resources, inter-regional transmission congestions should be carefully considered. Therefore, a 7-bus inter-regional transmission model is established with each region defined as one node. As explained before, intra-regional congestions are neglected. The directions of the inter-regional transmission lines are not predetermined; However, within one time interval, there is only one direction for each transmission line between two regions. The transmission capacities of the base year 2020 refer to the State Grid 2020 Social Responsibility Report [33]. Reference [15] expected that the cross-regional link capacity will reach two to three times of the current capacity in 2030 and three to seven times of the current capacity in 2050, on which the annual data for the year 2020–2060 is fitted.

2.3. *Unit Commitment and Economic Dispatch Model*

As a commonly used tool in real-world power system operations, Unit Commitment (UC) aims at minimizing system cost by optimizing each generator's operation status considering economic and physical constraints. Traditional Unit Commitment (UC) uses binary variables (0 and 1) to represent the ON/OFF status of each generator, which will usually too many binary decision variables.

Considering the complex power grid in mainland as well as the long-term simulation from year 2020–2060, we think that using Clustered Unit Commitment (CUC) instead of BUC to reduce the computational complexity is acceptable. In CUC, the same or similar



$$\begin{array}{c|ccccccc} & NW & N & NE & SW & C & E & S \\ \hline NW & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ N & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\ NE & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ SW & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ C & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ E & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ S & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{array}$$

Fig. 2. Chinese mainland power system division.

units are categorized as one unit cluster, then multiple binary variables are replaced by a single integer to represent the number of ON/OFF units, in order to reduce the dimension of this optimization problem [34–36]. A visualized comparison between BUC and CUC is shown in Fig. 3, in which only 4 integer variables in CUC can represent 12 binary variables in BUC. Considering the standardized design and production of power generators in China, it makes sense to cluster the units into groups with similar physical parameters.

B. Meteorological Model of Renewable Generations

Renewables generate electricity by extracting energy from natural resources such as solar and wind, so its ability to generate electricity is closely related to the quantity and state of the corresponding natural resources. For example, reference [37] indicates that lower wind speeds due to dense deployment of wind turbines can reduce the efficiency of wind turbines. Reference [38] finds that power extraction grows linearly before convergent to a saturation potential, with increasing density of wind turbine deployment in the region. As for solar power, reference [39] finds that severe air pollution blocks sunlight and greatly reduces China's solar output, especially in winter, and air pollutants also reduce power production by contaminating the solar panels themselves.

Considering the above existing researches, if those environmental factors such as wind speed and air pollution are not properly treated, it may lead to a biased forecast of the renewable generation as well as the biased CO_2 emission estimation in the long-term study. Firstly, for the wind power, the wind turbine generation process requires constant extraction of kinetic energy from the atmospheric motion, which slows down the wind speeds around the turbines and alters the exchange of heat, moisture, and momentum between the ground and the atmosphere. In the future plan of higher wind capacity installation in China, the density of turbines in the wind farm area may generally increase, which reduces the wind speed at the height of the turbine hub, decreases the output of turbines and leads to a decrease in the overall wind farm utilization hours, and eventually makes the output of the entire wind farm becomes saturated. Reference [26] uses the WRF v3.3.1 high-resolution regional model to simulate the output with different turbine densities, and finds that as the turbine density increases from 0.5 MW/km^2 to 2 MW/km^2, the capacity factor decreases from 40% to 20%. After eliminating all unsuitable land types for wind farms strictly, reference [40] estimates that China's technical potential of onshore wind power can be up to 3097.04 GW unevenly distributed across provinces, based on possible technical factors including wind speed, turbine types, land type and topography [41]. Based on the above conclusions, we introduce a scaling factor μ to represent the effect of increasing turbine density on the capacity factor. When the new wind power installations exceed the technical potential in a province, μ will decrease correspondingly, limiting the wind power generation to no more than the cap. Equation (1) expresses a reduction in the maximum output per wind capacity:

$$0 \leq P_m^W(t) \leq \mu\rho_m^W(t)C_m^W, \forall m \in \varphi^W, \forall t \in \varphi^T \tag{1}$$

where μ is a scaling factor and $0 \leq \mu \leq 1$, meaning that increasing turbine density results in a decrease in maximum wind output.

Secondly, for solar power units, their outputs are indirectly affected by aerosol and changes in cloud, especially anthropogenic aerosol emissions. Anthropogenic aerosol emissions, including SO_2, black carbon, PM2.5 and other constituents, can modify the surface solar radiation by scattering and absorbing the incoming radiation. Since 1970, combustion of heavily polluting coal in industry and power generation results in air pollution accumulation and decreases solar energy potential. But as China's CO_2 emission probably peak by year 2030, air pollution is estimated to decrease with reduction of CO_2 emissions afterwards [42]. Considering the development of renewables and the retrofitting of coal power units to reduce emissions [43], anthropogenic aerosol emissions are expected to continue to decline from now until 2060, allowing for a consequent increase in the potential for solar generation [44]. Following the study [45], it's assumed that China's anthropogenic aerosol emissions in 2060 will be at the same level with that of 1960, yielding only 0.3% increase in PV outputs per year from 2020 to 2060. Therefore, we introduce a scaling factor γ to represent the effect of reducing anthropogenic aerosol emissions. γ increases by 0.3% per year to represent the increase in the maximum output limits of the PV. Equation (2) expresses an increase in the maximum output per solar capacity:

$$0 \leq P_n^{PV}(t) \leq (1+\gamma)\rho_n^{PV}(t)C_n^{PV}, \forall n \in \varphi^{PV}, \forall t \in \varphi^T \tag{2}$$

where γ is a scaling factor and $\gamma \geq 0$.

C. Carbon Feedback Chain in PMSS

The emission of carbon dioxide, originated from the power and other industries, has been proved to be closely associated with the global warming and even climate damages [46–48]. According to the study of Intergovernmental Panel on Climate Change (IPCC), the

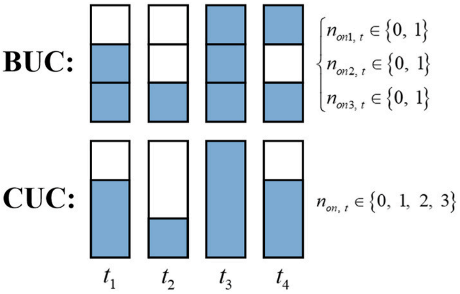


Fig. 3. Comparison between the BUC and CUC.

global average surface temperatures have risen by 0.85 °C between 1880 and 2012, and are forecasted to rise by 1.5 °C at the end of 21st century [49,50]. Obviously, power consumption may fluctuate greatly due to the effect of temperature on heating and cooling loads [51]. For example, during hot summers, higher temperatures mean that air-conditioning will consume more energy [52–54]. Therefore, CO_2 emission leads to an increase in temperature, the electricity demand as well as power generation subsequently. If the power structure is not completely clean, greater demand for power generation will lead to more carbon dioxide emission, creating a positive feedback chain as illustrated in orange color in Fig. 1.

2.4. *Power Generation to CO_2 Emission*

Existing studies [55,56] shows that the majority of CO_2 emission in the power system comes from thermal and gas plants burning fossil fuels. Other power plants (such as hydropower, wind and solar) have much less CO_2 emission density (measured per kWh) in their operation but the CO_2 emission during their constructions may not be negligible. In details, coal power generation accounts for 71.13% of China's power generation. Natural gas, which is also a fossil fuel, also produces a large amount of CO_2 emission, but its CO_2 emission per unit of power generation is only about half that of coal power. Although renewables do not generate CO_2 emission during generation, they will also have a non-negligible environmental impact during its entire life cycle (including material manufacturing, transportation, construction, maintenance and decommissioning). This will become pronounced when more renewables are installed in the low-carbon power system. By using the method of life cycle assessment, reference [57] converts the whole life cycle CO_2 emission of various energy into CO_2 emission per unit of power generation shown in Table 1. This data will also be used in our case study in Section III and IV.

2.5. *CO_2 Emission to Temperature Increase*

CO_2, as a massive greenhouse gas caused by human activity, can cause an increase in temperature by absorbing infrared radiation and trapping heat into the atmosphere, which is known as greenhouse effect [58].

CO_2 emission first results in direct impact on atmospheric CO_2 levels, and then it will slowly decrease as CO_2 can be absorbed by the oceans and terrestrial biosphere. As a result of such thermal inertia of the oceans' upper layers, global temperature will rise in response to the CO_2 forcing. Reference [59] combines a carbon cycle modeling data with data from the Coupled Model Intercomparison Project phase 5 (CMIP5), and uses CIMP5 to evaluate the climate response to a pulse input of CO2 and provides a quantitative description of the cumulative impact of carbon emissions on global temperature:

Assuming that one year's CO_2 emissions are emitted simultaneously at one point in this year, these CO_2 emission will result in higher temperature over the next century following Equation (3):

$$\Delta T(t) = 1.756 - 2.308e^{-\frac{t}{2.241}} + 0.743e^{-\frac{t}{35.75}} - 0.191e^{-\frac{t}{97.18}} \tag{3}$$

where decision variable t is the number of years since CO_2 emission began, and $\Delta T(t)$ is the warming (millikelvin) per GtC CO_2. In other words, this relationship shows that the increasing temperature in each year is determined by the CO_2 emissions from each of the previous 100 years.

In our model, the cumulated impact on temperature from CO_2 emissions is taken into account. Due to the differences of CO_2 emissions per kWh, the composition of generators in the power system will significantly affect power industry CO_2 emission. As the electric power sector contributes around 40% of China's total CO_2 emission [60], assuming this ratio remains constant in China's "carbon neutral" process, China's annual CO_2 emissions from the year 2020–2060 can be calculated after power industry CO_2 emissions is simulated year by year. Annual CO_2 emissions before 2020 come from the database [61]. With these annual CO_2 emissions data, it is possible to calculate the cumulative temperature impact each year.

2.6. *Temperature to Electricity Load*

The greenhouse effect caused by greenhouse gas emission can trigger global warming. Although countries around the world have started to actively promote emission reduction plans, emission reduction is not achieved overnight, and the effects of global warming are still accumulating in the process. IPCC pointed out in its Sixth Assessment Report AR6 that: the global surface temperature from

Table 1
Equivalent carbon emission per unit of power generation of various energy.

Source	CO_2 emission (kg CO_2/kWh)
Coal	960
Gas	443
Biomass	35
Hydropower	10
Wind	34
Solar	50
Nuclear	66

2001 to 2020 has increased by 0.99 °C, and this warming trend is projected to continue until mid-century.

One of the widely used index for quantifying the impact of greenhouse effect is the average surface temperature. An increase in average ground temperature leads to an increase in human body temperature, which further has an impact on the modeled electricity consumption behavior of customers, such as an increase in cooling load in summer and a decrease in heating load in winter, which in turn has an impact on the forecast of future electricity demand.

Reference [62] studies the relationship between climate change and electricity consumption in Guangzhou, and found that every 1 °C increase in summer temperature increase the load by 2.7%. It is worth noting that since Guangzhou belongs to the subtropical monsoon climate with high average temperature, the electricity consumption in Guangzhou is negligibly affected by the heating load; however, in the northern part of China, the increase in temperature may lead to lower heating load, further affecting the prediction results. In this paper, we make a simplification and consider that a 1 °C rise in temperature will increase national summer electricity consumption by 2.7%.

3. Base case: Analysis of CO_2 emission in 2030 and 2060

In this section, the power system operations between 2020 and 2060 is simulated under the framework of the Power-Meteorology-Society System. The following steps show how the optimization problem is solved by yearly rolling.

(1) The electricity demand line curve is estimated in Section 2.A.1) and used as a pre-established constraint, so the unit data are shown in Appendix. Meanwhile, the influence of Meteorological factors is taken into account (the green arrows in Fig. 1).
(2) By using CUC, system operations problem is solved under the most economical goal.
(3) Based on the system operations analysis, CO_2 emissions and their cumulated impact on temperature are estimated (the blue arrows in Fig. 1).
(4) Changes in temperature have an impact on the load curves in the next year (the orange arrows in Fig. 1). Repeat the steps (1)–(4) until all years are calculated.

3.1. *Trends of power generation*

Fig. 4 shows the trend of power generation structure from year 2020–2060 by simulation.

From Fig. 4 we can see that along with their growing installed capacity, the renewables such as wind and solar have increased proportion in the future's generation structure. However, the output of hydropower changes insignificantly, mainly due to the limited hydrological resources. The proportion of total thermal generation (coal + gas) peaks at around year 2030 and shows a clear downward trend until 2060. However, the gas generation has significant increase in the studied future years, from a negligible amount in 2020 to around 30% of total thermal generation in 2060. This can be explained as the renewables has rapid growth in their capacity and taking as the major part of the power resource; at the same time, the thermal power units (including coal, gas and biomass), especially quick gas generators, will mainly play a role of peak shaving, which is also supported by the calculated increasing startup and shutdown costs and decreasing fuel costs shown in Table 2.

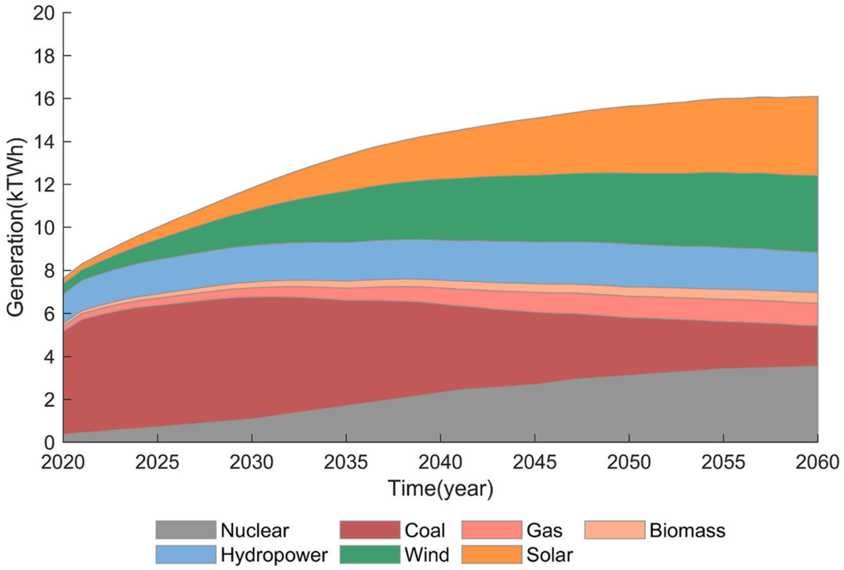


Fig. 4. National power generation structure from year 2020–2060.

3.2. Regional differences in generation structure

China's large territory leads to an inequitable distribution between electricity generation and demand. Coal power mainly comes from the West and North, the wind power and solar power are mainly concentrated in the North and Northwest, and the hydropower resources are concentrated in the Southwest; At the same time, the majority of electricity load is concentrated in the middle east China. Fig. 5 shows that in year 2060, generation in Northwest, North, Northeast and Central all account for about half of the regions' power generation; Southwest, relying on its own abundant hydropower resources, can still meet its own power load demand in the case of insufficient scenic resources, but it is difficult to send a large amount of generation outward as it is now; East, as the load center of China, has a large amount of nuclear power, but its own power generation is still difficult to support the load, needing support from outside regions to maintain a balance between power supply and demand.

On the one hand, plenty of renewables provide in the West and Northwest areas will provide crucial support to China's social electricity load growth; on the other hand, the spatial mismatch between power resource and load may lead to inefficiency in power system operations and more inter-regional transmissions are need for the renewable consumption. In 2060, the nationwide inter-regional power transmission reaches 2.4 kTWh, representing 14.8% of national generation. As shown in Fig. 6, as the main renewable resource areas, transmission lines from the Northwest, North and Northeast areas mainly transmit power outward, while lines in East and Central mainly receive power. And three lines from North to East, Northwest to East and Northwest to Central consistently transmit the most power in both 2030 and 2060.

3.3. Daily output arrangements

Guided by the policy of giving priority to the consumption of renewables, daily output arrangements differ significantly in different seasons. We choose spring and summer to describe their characteristics shown in Fig. 7.

Generally speaking, wind power has an obvious anti-peak characteristic, with highest output at night (0–8 p.m.) and significantly lower at midday when the load demand increases, makes it's unable to support the load peak alone. However, the advantage of wind power is that the peak-to-valley output difference is small, so wind power can still carry a certain percentage of the load during all hours of the day. In contrast, solar output curve trend is similar to load curve, but the peak-to-valley output difference is large, without any output between 18:00 and 8:00. Therefore, with the construction of wind and solar farms, the mismatch between the power generation output curve and the electricity load curve will become more and more serious and may lead to waste of renewables.

From a seasonal perspective, the trend of power output arrangement within each season remains basically the same, differing only in terms of values. For loads, summer and winter will lead to an overall upward shift in the load demand curve due to increased cooling and heating demand, while spring with suitable temperatures is generally with the lowest load demand. However, wind power output is generally greatest in the spring, smallest in the summer. Solar output is closely related to the amount of sunlight radiation and the amount of sunlight radiation received by solar panels and its maximum output tends to occur in the spring and autumn. This results in a large amount of wind and solar curtailment the spring shown in Fig. 8.

The main causes of renewables waste can be divided into two categories. First comes from the safety constraints: considering the operation safety, the operation reserve constraint is added, implying that the maximum output must be greater than the demand. So, it will always require a part of thermal power units as an operating reserve to participate in the system operation with a lower output which occupy a certain proportion of generation, leading to renewables cannot reach the maximum outputs. This kind of waste is limited by the parameters units and cannot be avoided by adjusting the arrangement if the adjustment capability of the unit does not significantly improve. Second derives from the economics of the operation: The startup and shutdown of large thermal power units are often costly and time-consuming, so the arrangement may be forced to abandon wind and light to prevent the unit from shutdown. Although it can be avoided through policy orders such as full consumption of renewables, it can lead to economic losses.

3.4. CO_2 emission and temperature impact

China's CO_2 emission from 1970 to 2060 is shown in Fig. 9. Without considering CCUS, the CO_2 emission will peak at 5.84 billion tons of CO_2 before 2030, and about 2.85 billion tons in 2060. With the development of renewables, the equivalent CO_2 emission in its life cycle is also gradually increasing. The equivalent CO_2 emission of renewables in 2060 is 576 million tons accounting for 20.24% of the total CO_2 emission in 2060. Although CO_2 emission peaks in 2025, the temperature impact caused by CO_2 emission will show a growing trend in the next 40 years. In 2060, CO_2 emission may lead to a global warming of 0.21 °C.

Table 2
Costs of thermal power units from year 2020–2060.

	2020	2025	2030	2045	2060	AAGR*
Fuel (billion$)	166.3	178.3	181.1	126.5	85.5	−2.78%
Start-stop (million$)	9.39	48.41	1906	9263	17,920	18.41%

*The Annual Average Growth Rate (AAGR) measures the average growth rate from 2025 to 2060, as 2025 has the peak fuel cost and nearly-zero startup cost.

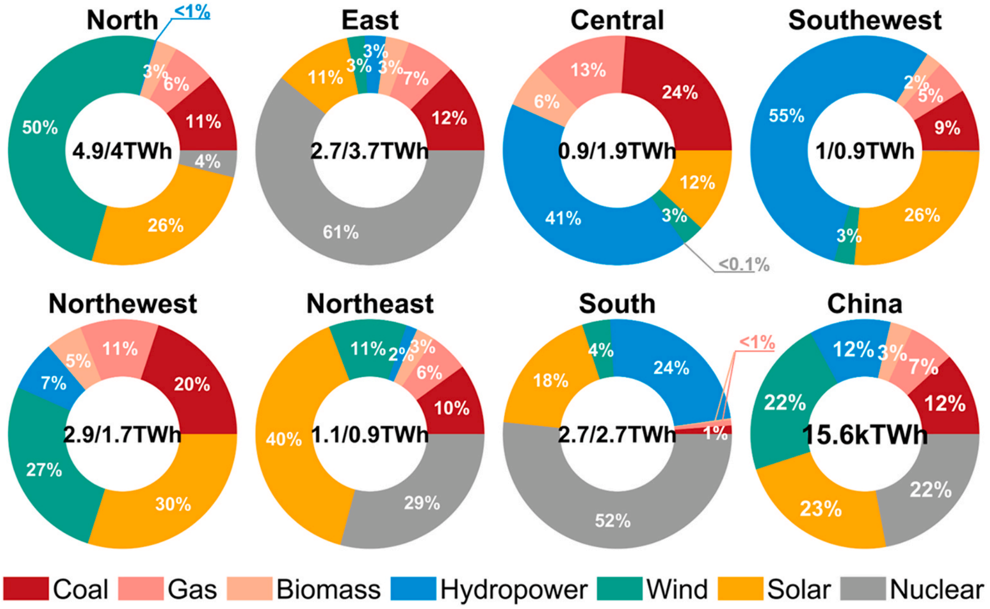


Fig. 5. Sources of power generation by type of power source in 2060.

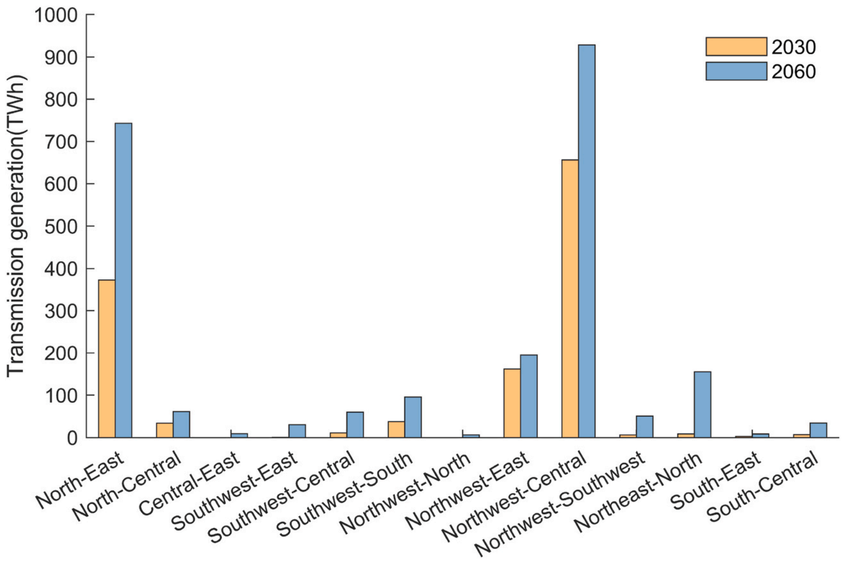


Fig. 6. Change in annual net power transmission of cross-regional liaison lines.

3.5. *Sensitivity Analysis*

Compared to the case where meteorological factors and load feedbacks are not considered, the wind power installed capacity density penalty factor, PV potential correction factor and load correction factor are added, and the comparison is shown in Fig. 10. Considering the increase in installed wind power capacity density, the actual wind power generation in 2060 is reduced by 25.33% compared to the benchmark scenario. In contrast, the actual solar power generation increases by 12.69% as the air pollution level decreases. From the perspective of the power structure, the countervailing influence of the environment on renewables sources will lead to a slight reduction in future renewables generation; from the perspective of power system operation, different generation characteristics between wind and solar will have different degrees of influence on the system operation status in a typical day, for example, the increase in solar power generation will further increase the peak-to-valley difference in solar power generation, which requires deep peak regulation and energy storage. For example, the increase in solar power generation will further increase the peak-to-valley difference in solar power output, which requires deep peaking, energy storage and other means to promote consumption and

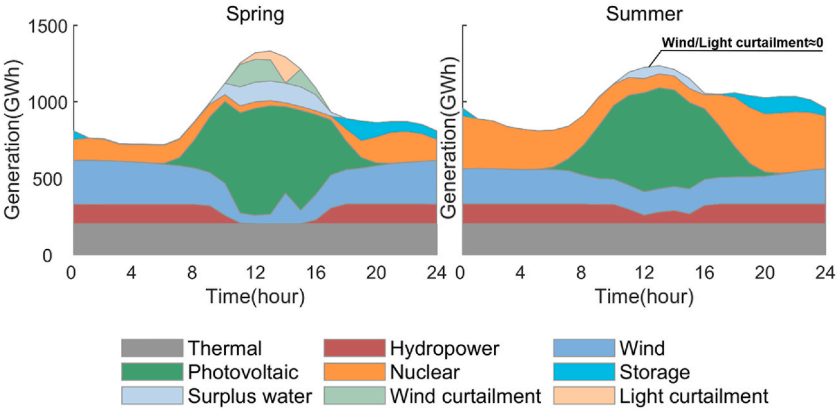


Fig. 7. Output arrangements for the typical day in year 2060.

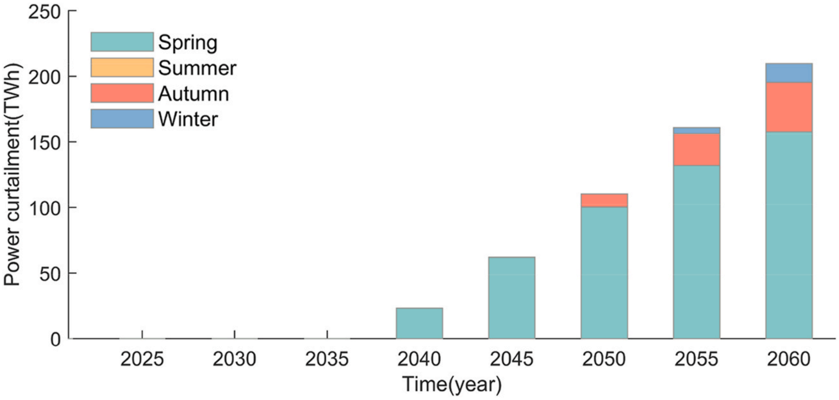


Fig. 8. Annual power curtailment from year 2025–2060.

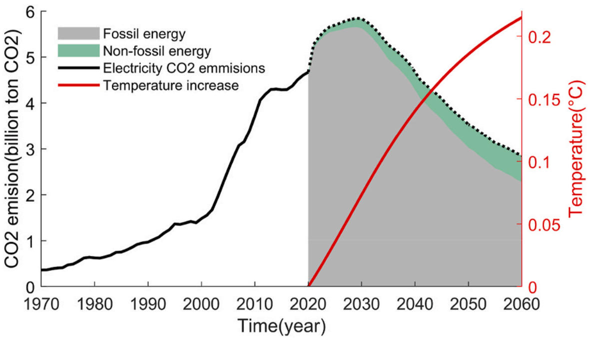


Fig. 9. CO2 emission for the power grid and temperature increase.

avoid abandonment.

Considering the increase in average temperature brought by the greenhouse effect will result in higher summer load, for example, the summer load in 2060 increases about 38.2 TWh. Combined with the analysis in III.C of this paper, the renewables output in summer is already at a lower level in a year, and after considering the impact of global warming on the load, the increase in total and summer peaks in electricity consumption electricity demand will further stress the summer power supply, and renewables cannot meet the new load demand, so additional thermal power output will be needed to achieve a balance between electricity supply and demand, which will lead to an increase in 2060 CO emission in 2060 will increase by about 675 million tons.

Thus, the PMSS suggests that potential meteorological factors have a negative impact on carbon neutrality, implying that relying on the planning pathways to achieve carbon neutrality by 2060 is more difficult than expected and may require additional expenses may

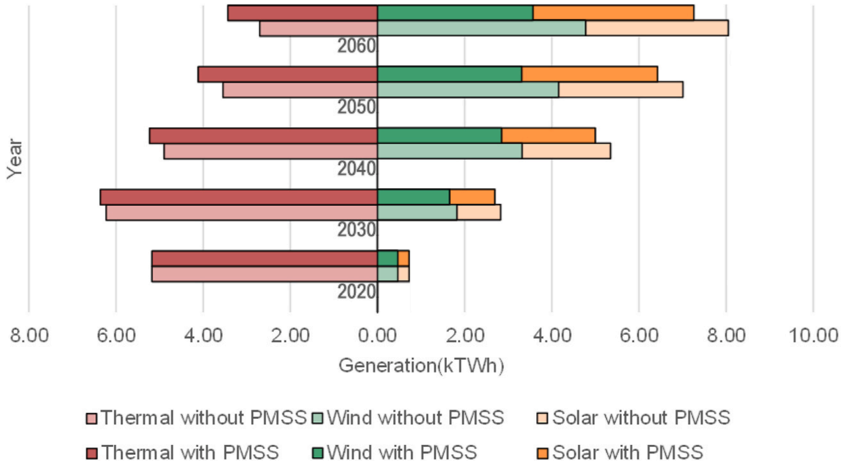


Fig. 10. Power generation mix with and without considering the Power-Meteorological-Society System.

be need to increase the installed renewables capacity, or reduce emissions through other complementary means.

4. Multi-scenario comparison and Analysis

In the process of meeting the "carbon neutral" targets, aside from the capacity of renewables, many other factors can also contribute to the effects. Following the installed capacity of renewables in the base case, we choose deep peak regulation capability of thermal units (DPRC), energy storage capacity and cross-regional power transmission lines as the three representative support facilities to explore their specific effects on system operation and contributions to the "carbon neutral", displayed in Table 3.

With the increase of DPRC, thermal power units can reduce their outputs as much as possible when the system operating reserve constraints are still guaranteed, so as to allow renewables to maximize their outputs and avoid curtailment, also indirectly reduce CO_2 emissions from thermal power. Meanwhile, it also avoids the frequent start and stop of the units. However, it is worth noting that units working at low load rate impacts the life span significantly, which is hardly reflected in the cost.

Although the output of thermal and hydro units is artificially controllable, their output is still subject to the limitations of the units' own characteristics, which means they can only be used as a source of electricity but can't do anything to exceed power. In contrast, energy storage, such as battery and pumped storage, shows the benefits of flexibility. Energy storage devices can store electricity in the form of gravitational potential energy and chemical energy during excess power periods as a load, and release them in the form of electrical energy when needed as a source. This behavior is equivalent to changing the shape of the renewables output curve. Therefore, the growth of energy storage capacity is highly effective for the consumption of the renewables, and has the ability to become one of the main means to consume renewables in the future. Meanwhile, energy storage can also help reduce start-stop costs of thermal power units with more effectiveness.

Renewables with uneven geographical distribution will greatly increase and put a lot of pressure on the power lines. The construction of cross-regional power transmission lines can allow more clean power from the West to be delivered to the East, beneficial to relieve the eastern electricity tension and reduce CO_2 emissions from thermal units. However, these lines only rebalance the distribution of resources on a national scale, and its marginal utility gradually decrease with the increasing capacity. When the transmission lines' capacity grows to 6 times its capacity in 2020, the utility margin is almost reached.

Through the implementation of the CCUS technology, with the assurance of achieving "carbon neutrality" by 2060, we use comprehensive costs to measure the economics of different support facility solutions. The comprehensive costs include constructing and maintaining all the support facilities, using CCUS technology to catch CO_2 and the penalties for CO_2 emissions from 2020 to 2060. By searching for the lowest combined cost, we can find a relatively cost-benefit hybrid solution which balances the economics of different facilities with their contribution to reducing CO_2 emissions, seen in Fig. 11. The x-axis is the energy storage capacity of the whole country whose costs is from Reference [63], the y-axis is the cross-regional power transmission line capacity and the z-axis is the comprehensive costs, while the annual CO_2 emission will be multiplied by a penalty factor and added to the costs. Different surface colors represent three DPRC levels.

5. Conclusion

In this paper, we create a Power-Meteorology-Society Systematic feedback loop to study the impact of meteorological and environmental factors on future power system operation. By introducing different meteorological factors, we find that meteorological do have an impact on the generation of renewables, for wind power −7.1% and solar power 10.5%, respectively. The cumulative effect of CO_2 emission will cause the temperature increase continuously for decades, even the CO_2 emission have peaked in 2030, and in turn increase the electricity load. Such deviations in generation and load may result in higher CO_2 emissions than expected, indicating the

Table 3
Comparison of the power system operation results in different scenarios.

Facility	Scenario*	Renewables generation(kTWh)			Start-stop costs(million$)			CO_2 emission(billion ton)		
		2020	2030	2060	2020	2030	2060	2020	2030	2060
Regulation ability (% minimum load rate)	40	2.22	4.65	9.61	9.39	1905.59	17920.44	4.67	5.83	2.85
	30		4.65	9.68		1491.39	15663.9		5.82	2.76
	20		4.65	9.76		1118.98	13674.39		5.82	2.66
Energy storage capacity (% renewable capacity)	10		4.64	8.92		2881.17	16020.98		5.82	3.36
	20		4.65	9.61		1905.59	17920.44		5.83	2.85
	30		4.65	9.92		525.31	6513.9		5.83	2.68
Transmission line capacity (times than 2020)	2		4.65	9.54		1806.6	23008.5		5.83	2.97
	6		4.65	9.61		1905.59	17920.44		5.83	2.88
	10		4.65	9.65		1445.33	13951.5		5.83	2.85

* Here scenario refers to the construction scale that the facility should achieve in 2060, and the development trend from 2020 to 2060 is adjusted as a whole according to the scale in 2060.

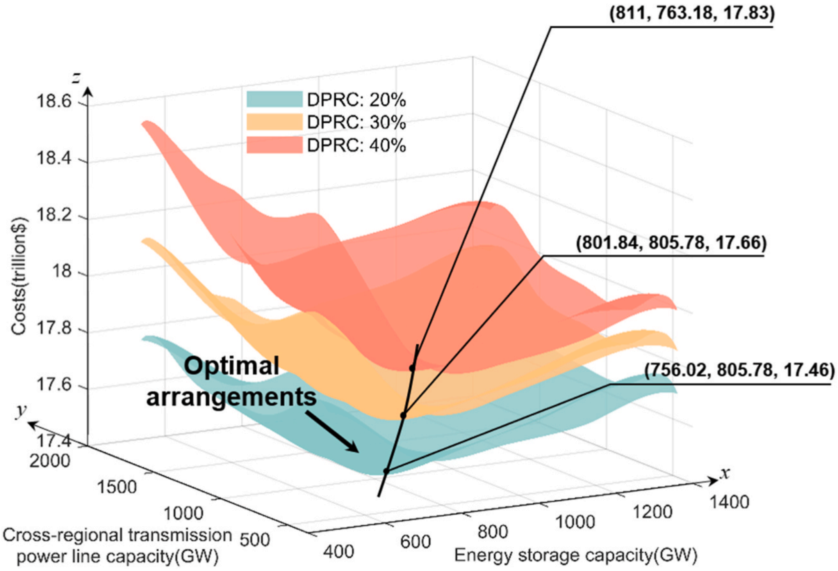


Fig. 11. Comprehensive costs for achieving "carbon neutrality" by 2060 in different scenarios.

negative impact on carbon neutrality.

Based on this, we compare the different paths to achieve carbon neutrality by 2060 and recommend the most economical one. By changing the three corresponding support facilities of DPRC of thermal power units, energy storage capacity and cross-regional power transmission line capacity, our analysis indicates that constructing energy storage is a relatively efficient idea for the consumption of renewables, on the contrary the role of transmission lines is less. After comparing different options, we identify the most effective one in order to achieve 2060 carbon neutrality.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Hao Ming: Writing – original draft, Software, Methodology, Conceptualization. **Mingyi Lin:** Writing – original draft, Software, Methodology. **Ciwei Gao:** Writing – review & editing, Conceptualization. **Ning Zhang:** Writing – review & editing, Methodology. **Le Xie:** Writing – review & editing, Methodology. **Yuting Mou:** Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e27970.

References

[1] J. Li, Evaluation of dynamic growth trend of renewable energy based on mathematical model, Energy Rep. 9 (2023) 48–56, https://doi.org/10.1016/j.egyr.2022.11.139. https://www.sciencedirect.com/science/article/pii/S2352484722025264. URL.
[2] World Energy Outlook 2019, 2019. https://www.iea.org/reports/world-energy-outlook-2019. URL.
[3] Global Energy Review 2020, 2020. https://www.iea.org/reports/global-energy-review-2020. URL.
[4] K. Kimon, V. Diaz, W. Matthias, V. Toon, T. Marie, T.M. Stephane, S.R. Antonio, K. Jette, V.D. Rita, S.C. Qimin, Global Energy and Climate Outlook 2019: Electrification for the Low-Carbon Transition, JRC Working Papers, 2020.
[5] Guangyue Xu, Lanmei Zang, Peter Schwarz, Hualiu Yang, Achieving China's carbon neutrality goal by economic growth rate adjustment and low-carbon energy structure, Energy Pol. 183 (2023) 113817, https://doi.org/10.1016/j.enpol.2023.113817. ISSN 0301-4215.
[6] Guangyue Xu, Haoyun Dong, Zhenci Xu, Nishan Bhattarai, China can reach carbon neutrality before 2050 by improving economic development quality, Energy 243 (2022) 123087, https://doi.org/10.1016/j.energy.2021.123087. ISSN 0360-5442.
[7] Guangyue Xu, Yunting Wang, Hafizur Rehman, The future trajectory of carbon emissions in the process of carbon neutrality in South Korea, J. Environ. Manag. 345 (2023) 118588, https://doi.org/10.1016/j.jenvman.2023.118588. ISSN 0301-4797.
[8] Mavis Adjei, Huaming Song, Xiang Cai, Emmanuel Nketiah, Bright Obuobi, Gibbson Adu-Gyamfi, Globalization and economic complexity in the implementation of carbon neutrality in Africa's largest economies, Sustain. Energy Technol. Assessments 52 (2022) 102347, https://doi.org/10.1016/j.seta.2022.102347. ISSN 2213-1388.
[9] Kun Yuan, Tingting Zhang, Xiaomin Xie, Sha Du, Xingyu Xue, F. Amir, N. Abdul-Manan, Zhen Huang, Exploration of low-cost green transition opportunities for China's power system under dual carbon goals, J. Clean. Prod. 414 (2023) 137590, https://doi.org/10.1016/j.jclepro.2023.137590. ISSN 0959-6526.
[10] Yiling Ouyang, Jian Guo, Carbon capture and storage investment strategy towards the dual carbon goals, J. Asian Econ. 82 (2022) 101527, https://doi.org/10.1016/j.asieco.2022.101527. ISSN 1049-0078.
[11] Lei Wen, Peixin Diao, Simulation study on carbon emission of China's electricity supply and demand under the dual-carbon target, J. Clean. Prod. 379 (2) (2022) 134654, https://doi.org/10.1016/j.jclepro.2022.134654. ISSN 0959-6526.
[12] IEA renewables, URL, https://www.iea.org/fuels-and-technologies/renewables, 2022.
[13] Y. Shu, L. Zhang, Y. Zhang, Y. Wang, G. Lu, B. Yuan, P. Xia, Carbon peak and carbon neutrality path for China's power industry (Chinese), Strategic Study of CAE 23 (2021) 1–14, 006.
[14] J. He, Z. Xie, Z. Li, X. Zhang, Synthesis report on China's long-term low carbon development strategy and transition pathway study (Chinese), China Population, Resour. Environ. 30 (11) (2020) 25.
[15] Z. Li, S. Chen, W. Dong, P. Liu, E. Du, L. Ma, J. He, Low carbon transition pathway of power sector under carbon emission constraints (Chinese), Proceedings of the CSEE 41 (12) (2021) 14.
[16] N. Zhang, L. Xing, G. Lu, Chinese medium and long-term energy and power transition development outlook and challenges (Chinese), China Power Enterprise Management 13 (2018) 6.
[17] N. Zhang, L. Xing, G. Lu, Outlook for China power development for 2050 (Chinese), Energy of China 40 (3) (2018) 6.
[18] Y. Zhang, N. Zhang, H. Dai, S. Zhang, X. Wu, M. Xue, Model con-struction and pathways of low-carbon transition of China's power system (Chinese), Electr. power 54 (3) (2021) 11.
[19] X. Zheng, L. Xie, K. Lee, D. Fu, J. Wu and P. Chang, "Impact of climate simulation resolutions on future energy system reliability assessment: a Texas case study," in iEnergy, doi: 10.23919/IEN.2023.0014.
[20] A.T.D. Perera, V.M. Nik, D. Chen, et al., Quantifying the impacts of climate change and extreme climate events on energy systems, Nat. Energy 5 (2020) 150–159, https://doi.org/10.1038/s41560-020-0558-0.
[21] S.G. Yalew, M.T.H. van Vliet, D.E.H.J. Gernaat, et al., Impacts of climate change on energy systems in global and regional scenarios, Nat. Energy 5 (2020) 794–802, https://doi.org/10.1038/s41560-020-0664-z.
[22] R.A. Harris, L. Zhou, G. Xia, Satellite observations of wind farm im-pacts on nocturnal land surface temperature in Iowa, Rem. Sens. 6 (12) (2014) 12234–12246.
[23] L.M. Slawsky, L. Zhou, S. Baidya Roy, G. Xia, M. Vuille, R.A. Harris, Observed thermal impacts of wind farms over northern Illinois, Sensors 15 (7) (2015) 14981–15005.
[24] V. Fthenakis, Y. Yu, Analysis of the Potential for a Heat Island Effect in Large Solar Farms, 2013, pp. 3362–3366.
[25] G.A. Barron-Gafford, R.L. Minor, N.A. Allen, A.D. Cronin, A.E. Brooks, M.A. Pavao-Zuckerman, The photovoltaic heat island effect: Larger solar power plants increase local temperatures, Sci. Rep. 6 (1) (2016) 35070, 35070.
[26] L.M. Miller, D.W. Keith, Climatic impacts of wind power, Joule 2 (12) (2018) 2618–2632, https://doi.org/10.1016/j.joule.2018.09.009. https://www.sciencedirect.com/science/article/pii/S254243511830446X. URL.
[27] D. Millstein, S. Menon, Regional climate consequences of large-scale cool roof and photovoltaic array deployment, Environ. Res. Lett. 6 (3) (2011) 034001–9.
[28] H. Chen, H. Yan, K. Gong, X.-C. Yuan, How will climate change affect the peak electricity load? evidence from China, J. Clean. Prod. 322 (2021) 129080, https://doi.org/10.1016/j.jclepro.2021.129080. https://www.sciencedirect.com/science/article/pii/S0959652621032698. URL.
[29] J.-L. Fan, J.-W. Hu, X. Zhang, Impacts of climate change on electricity demand in China: an empirical estimation based on panel data, Energy 170 (2019) 880–888, https://doi.org/10.1016/j.energy.2018.12.044. https://www.sciencedirect.com/science/article/pii/S0360544218324101. URL.
[30] H. He, Q. Liu, Measurement and analysis of seasonal index of power load (Chinese), Power Demand Side Management 1 (2010) 4.
[31] Notice of the National Development and Reform Commission and Na-Tional Energy Administration on the Signing of Medium and Long-Term Contracts for Electricity in 2021, 2020. URL, http://www.gov.cn/zhengce/zhengceku/2020-12/03/content_5566580.htm.
[32] X. Zhou, S. Chen, Z. Lu, Y. Huang, S. Ma, Q. Zhao, Technology features of the new generation power system in China (Chinese), Proceedings of the CSEE 38 (7) (2018) 12.
[33] S.G. C. of China, State Grid Corporation 2020 Social Responsibility Report (Chinese), Tech. rep., State Grid Corporation of China, 2021.
[34] Jelle Meus, Kris Poncelet, Erik Delarue, Applicability of a clustered unit commitment model in power system modeling, IEEE Trans. Power Syst. 99 (2017) 1.
[35] B.S. Palmintier, M.D. Webster, Heterogeneous unit clustering for effi-cient operational flexibility modeling, IEEE Trans. Power Syst. 29 (3) (2014) 1089–1098.
[36] B. Han, J. Shu, H. Sun, Regional power system production simulation based on clustered unit commitment (Chinese), Modern Electric Power, Mod. Electr. Power 37 (5) (2020) 6.
[37] A.S. Adams, D.W. Keith, Are global wind power resource estimates overstated? Environ. Res. Lett. 8 (1) (2013) 015021.
[38] M.Z. Jacobson, C.L. Archer, Saturation wind power potential and its implications for wind energy, Proceedings of the National Academy of Sciences - PNAS 109 (39) (2012) 15679–15684.
[39] Air pollution reduces China's solar potential (Chinese), Sino-Global, Energy 23 (2) (2018) 103–104.
[40] Shiwei Yu, H. Gui, J. Yang, China's provincial wind power potential assessment and its potential contributions to the "dual carbon" targets, Environ. Sci. Pollut. Control Ser. 30 (5) (2023) 13094–13117.

[41] M.R. Davidson, D. Zhang, W. Xiong, X. Zhang, V.J. Karplus, Modelling the potential for wind energy integration on China's coal-heavy electricity grid, Nat. Energy 1 (2016) 1–7, https://doi.org/10.1038/nenergy.2016.86.

[42] R. Tang, J. Zhao, Y. Liu, X. Huang, Y. Zhang, D. Zhou, A. Ding, C.P. Nielsen, H. Wang, Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030, Nat. Commun. 13 (1) (2022) 1008, 1008.

[43] Notice on the Issuance of the Work Plan for the Full Implementation of Ultra-low Emission and Energy Conservation Improvement of Coal-Fired Power Plants (Chinese), 2015. URL, https://www.mee.gov.cn/gkml/hbb/bwj/201512/t20151215_319170.htm.

[44] B. Sweerts, S. Pfenninger, S. Yang, D. Folini, M. Wild, Estimation of losses in solar energy production from air pollution in China since 1960 using surface radiation data, Nat. Energy 4 (8) (2019).

[45] G. Pan, Q. Hu, W. Gu, S. Ding, H. Qiu, Y. Lu, Assessment of plum rain's impact on power system emissions in yangtze-huaihe river basin of China, Nat. Commun. 12 (2021).

[46] J. Leggett, W.J. Pepper, R.J. Swart, J. Edmonds, M. Wang, Emissions scenarios for the ipcc: an update, Clim. Change (1992) 543–556.

[47] F. Ackerman, S.J. DeCanio, R.B. Howarth, K. Sheeran, Limitations of integrated assessment models of climate change, Climatic Change 95 (3–4) (2009) 297–315.

[48] R.H. Moss, J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.V. Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, The next generation of scenarios for climate change research and assessment, Nature 463 (7282) (2010) 747–756.

[49] W. Ofipcc, Climate change 2013: the physical science basis, Contribu-tion of Working 43 (22) (2013) 866–871.

[50] B.W. Ang, H. Wang, X. Ma, Climatic influence on electricity consump-tion: the case of singapore and Hong Kong, Energy 127 (may15) (2017) 534–543.

[51] C.L. Hor, S.J. Watson, S. Majithia, Analyzing the impact of weather variables on monthly electricity demand, IEEE Trans. Power Syst.: A Publication of the Power Engineering Society (4) (2005) 20.

[52] S. Mima, P. Criqui, The costs of climate change for the european energy system, an assessment with the poles model, Environ. Model. Assess. 20 (4) (2015) 1–17.

[53] Mohammad Shourav, Ahmed Sabbir, Shamsuddin Shahid, Bachan Singh, Morteza Mohsenipour, Potential Impact of Climate Change on Residential Energy Consumption in Dhaka City, Environmental Modeling Assessment, 2018.

[54] O. Adeoye, C. Spataru, Modelling and forecasting hourly electricity de-mand in west african countries, Appl. Energy 242 (2019) 311–333.

[55] C. Dingbang, C. Cang, C. Qing, S. Lili, C. Caiyun, Does new energy consumption conducive to controlling fossil energy consumption and carbon emissions?-evidence from China, Resour. Pol. 74 (2021) 102427, https://doi.org/10.1016/j.resourpol.2021.102427. https://www.sciencedirect.com/science/article/pii/S0301420721004360. URL.

[56] L.D. Labzovskii, H.W.L. Mak, S. Takele Kenea, J.-S. Rhee, A. Lashkari, S. Li, T.-Y. Goo, Y.-S. Oh, Y.-H. Byun, What can we learn about effectiveness of carbon reduction poli-cies from interannual variability of fossil fuel co2 emissions in east asia? Environ. Sci. Pol. 96 (2019) 132–140, https://doi.org/10.1016/j.envsci.2019.03.011. https://www.sciencedirect.com/science/article/pii/S1462901118312905. URL.

[57] D. Nugent, B.K. Sovacool, Assessing the lifecycle greenhouse gas emissions from solar pv and wind energy: a critical meta-survey, Energy Pol. 65 (2014) 229–244.

[58] Ipcc updates methodology for greenhouse gas inventories (201). URL https://www.ipcc.ch/2019/05/13/ipcc-2019-refinement/.

[59] K.L. Ricke, K. Caldeira, Maximum warming occurs about one decade after a carbon dioxide emission, Environ. Res. Lett. 9 (12) (2014) 124002.

[60] W. Ym, Y. By, T. Bj, L. Lc, L. H, C. Jm, S. Fh, A. Ry, W. X, T. Jx, Z. Y, Z. Zh, Discussion on contributions of novel power system to achieving carbon emission peak and carbon neutrality of coastal city (Chinese), Trans. Beijing Inst. Technol. 24 (4) (2022) 13–26.

[61] Crippa M., Guizzardi D., Solazzo E., Muntean M., Schaaf E., Monforti-Ferrario F., Banja M., Olivier J., Grassi G., Rossi S., Vi- gnati E., Emissions database for global atmospheric research version v6.0f t2020 (ghgtime-series), European Commission, JRC SCIENCE FOR POLICY REPORT. (1) (2021) 9-14. URL http://data.europa.eu/89h/2f134209-21d9-4b42-871c-58c3bdcfb549.

[62] S. Zheng, G. Huang, X. Zhou, X. Zhu, Climate-change impacts on electricity demands at a metropolitan scale: a case study of guangzhou, China, Appl. Energy 261 (2020) 114295.

[63] X. Fu, F. Li, X. Yang, P. Yang, Cost analysis of energy storage based on life cycle cost, Distributed Energy 5 (3) (2020) 34–38.