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Provincial pathways to carbon-neutral energy systems in China considering interprovincial electricity transmission development[☆]

Qiang Zhang[a,b], Shu Zhang[a,b], Wenying Chen[a,b,*]

[a] Research Center for Contemporary Management, Tsinghua University, Beijing 100084, China
[b] Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- Present the provincial carbon emission pathways towards carbon neutrality targets.
- Provincial load curves are introduced in China TIMES-30PE model.
- Large renewable power deployment increases the interprovincial power transmission.
- The power transmission pattern is shifting towards long-distance and large-capacity.
- Capacity of long-distance UHV lines grow rapidly under carbon neutrality targets.

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ABSTRACT

Achieving China's ambitious carbon neutrality goal requires tangible action by the provinces. Significant heterogeneities between provinces make for divergent transition paths and different contributions to climate goals. To portray the dynamics of the energy transition at the provincial level, this study develops a China's provincial energy-environment-economic model (China TIMES-30PE) with special consideration of the interprovincial electricity transmission. To achieve carbon peaking, it is necessary to raise the carbon intensity reduction target on the basis of the 13th Five-Year Plan and enable rapid emission reductions through non-fossil energy expansion, end-use electrification, and the hydrogen boom to achieve carbon neutrality. Renewable energy and energy storage growth is concentrated in West, but electricity demand is growing rapidly in the East, creating a clear mismatch and making inter-provincial transmission and grid needs steeper. The central provinces shift from electricity exporters to electricity importers in future energy system landscape. By 2060, China is expected to form several major inter-regional power transmission routes from Northwest China to the Yangtze River Delta and Central China, from Inner Mongolia to Shandong, Beijing-Tianjin-Hebei and Henan, from Sichuan to the Yangtze River Delta, and from Yunnan to Guangdong. Driven by large-scale long-distance transmission, the capacity of ultra-high voltage lines is expected to increase rapidly.

1. Introduction

Carbon dioxide (CO_2) occupies a central position in greenhouse gas emissions, playing a pivotal role of utmost importance. Governments around the world must collaborate in concerted efforts aimed at mitigating carbon emissions as a proactive response to the challenges posed by climate change. The Paris Agreement emphasizes the necessity of limiting global temperature rise to within 2 °C compared to the pre-industrial era by 2100, with an aspirational goal of striving for 1.5 °C [1]. As a responsible nation with substantial carbon emissions, China is actively addressing the challenges of climate change and has announced to the world its commitment to strengthen emission reductions based on nationally determined contributions, aiming to achieve carbon peaking by 2030 and strive for carbon neutrality by 2060 [2].

China has more than 30 provincial-level administrative regions with significant differences. The study of low-carbon development pathways across different provinces is of paramount importance. Given the significant differences in socioeconomic development levels and resource

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[*] Corresponding author at: Research Center for Contemporary Management, Tsinghua University, Beijing 100084, China
E-mail address: chenwy@mail.tsinghua.edu.cn (W. Chen).

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endowments among regions, it is essential to formulate and implement effective low-carbon policies for each province. The quantitative emission reduction policy targets for each province in the 14th Five-Year Plan [3] have not been clearly defined. The emission pathways and energy transition simulations for different provinces under China's carbon neutrality target serve as crucial references for the current national policy formulation process. The report of the 20th National Congress of the Communist Party of China highlights the need for China to build a new energy system [4]. While some provinces have put forward specific plans for the near and medium-term development of renewable energy, many others still lack a clear developmental direction. Achieving the carbon neutrality target and promoting the development of renewable energy requires each province to coordinate their efforts from the 14th Five-Year Plan to the 15th Five-Year Plan and even beyond 2060. Infrastructure construction relevant to this goal needs to be considered comprehensively. As shown in Fig. 1, there is a mismatch between renewable resources and the distribution of population and economic centers, and the mismatch will become increasingly pronounced under low carbon transition [5]. Therefore, there is an urgent and necessary need to analyze the electricity transmission patterns and the construction of transmission facilities among provinces under the carbon neutrality objective.

(c) Provincial GDP in 2020 (billion dollars); (d) Provincial population in 2020 (million people)

A comprehensive literature review was conducted to analyze the key issues in the carbon neutrality transition. To obtain a whole energy system perspective, many studies utilize energy-environment-economic models to investigate the energy, environmental, and economic changes associated with decarbonization (Table 1). Additionally, several models

Table 1

Multi-regional energy-environment-economy models in China.

Model Name	Model Horizon	regions
AIM-China [6]	2030	provincial
C-REM [7]	2030	provincial
China TIMES-30P [8]	2050	provincial
MESEIC [9]	2050	6-regions
REACH [10]	2030	provincial
REPO [11,12]	2050	provincial

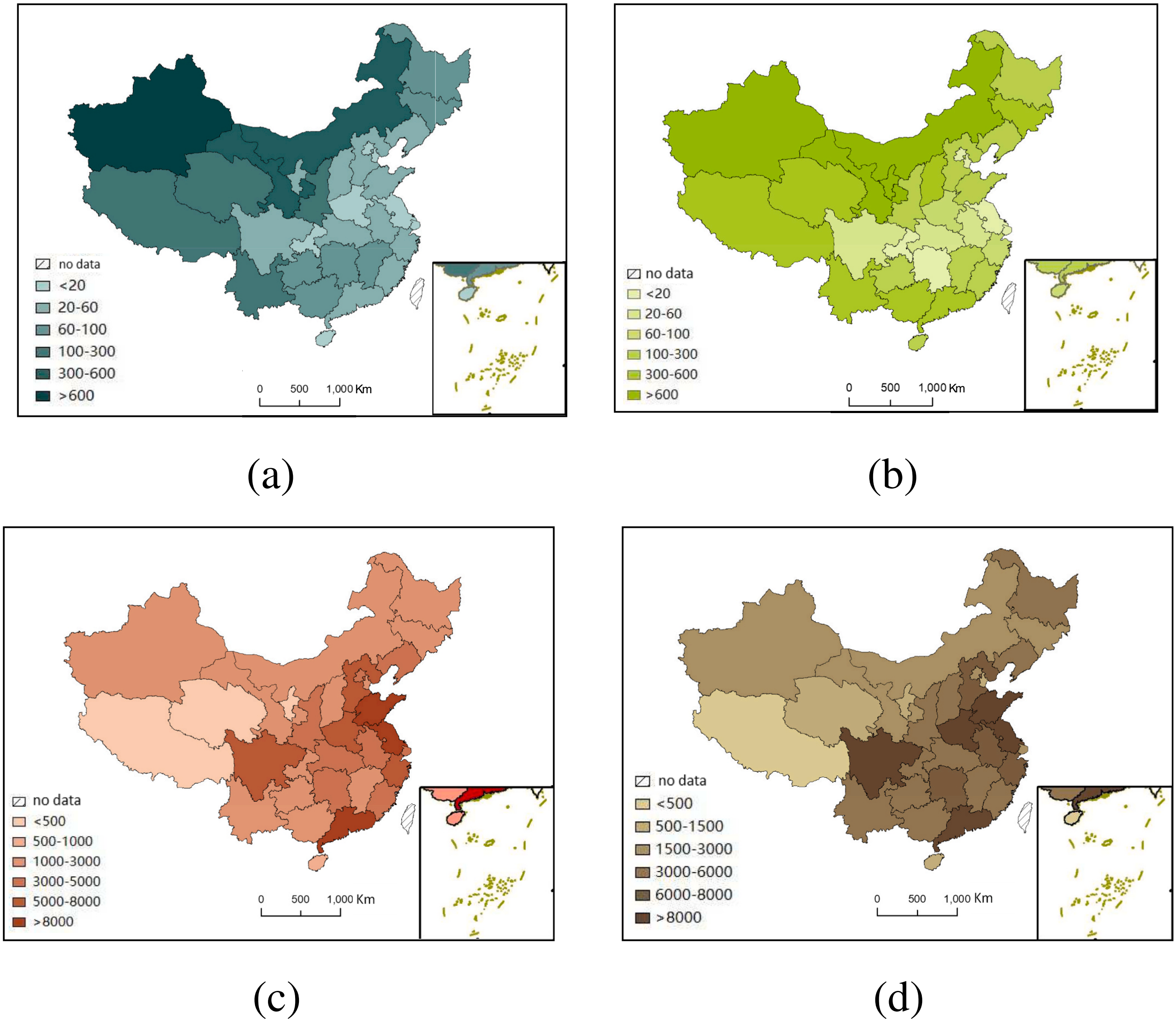


Fig. 1. (a) Potential wind capacity (GW); (b) Potential solar capacity (GW);

specifically focus on employing multi-regional energy system models to analyze the low-carbon transition among different provinces in China.

The existing multi-regional energy-environment-economy models in China cover periods up to 2030 or 2050, which cannot meet the research needs of China's 2060 carbon neutrality goal. Furthermore, there is a lack of detailed characterization of many deep decarbonization technologies under peak carbon emissions and carbon neutrality policy goals. Therefore, it is both necessary and feasible to construct a multi-sector, provincial-level energy-environment-economy model that covers the entire period of China's carbon neutrality policy.

To analyze provincial low carbon transition under carbon neutrality goals more accurately within the model, this study researched how to incorporate the volatility of renewable energy generation and electricity demand into energy system models, adapting to the development of large-scale wind, solar, and energy storage technologies. There are currently several energy system models worldwide that consider the detailed electricity sector. Kannan [13] constructed the TIMES model for the Swiss electricity sector, which analyzes the development of wind, solar, and energy storage technologies and assesses the variations in power supply output. Xiong [11] developed the REPO model based on hourly load data for different provinces in China, creating a multi-regional and multi-temporal system to analyze the development of the electricity sector during China's low-carbon transition. The National Renewable Energy Laboratory (NREL) in the United States created the ReEDS model [14] to analyze the deployment of renewable energy in the U.S.-Canada electricity system. The ReEDS model can assess renewable energy development in the US electricity sector while satisfying various electricity system constraints, emission constraints, and other policy constraints. The REMix model [15] developed by the German Aerospace Center analyzes the energy transition in the European electricity sector using a linear optimization approach. Among the models that consider electricity demand, there are ones like the REPO model [13] and the ReEDS model [14], which focus on a single electricity sector, as well as comprehensive energy system models like the TIMES model and the REMix model [15], which cover multiple sectors. Different modeling approaches have their advantages and disadvantages. Kannan [16] compared the simulation results of a building sector model and a comprehensive sector model, MARKAL, for the UK. They found that the complete sector model had the advantage of a holistic perspective on the energy system but appeared to be less detailed regarding the results concerning the building sector. However, it can comprehensively characterize the pathways of energy transformation across sectors.

After comprehensive research on the status of energy system models considering electricity demand, it is found that models incorporating electricity demand can better characterize the fluctuations of renewable energy, electric vehicles, and energy storage technologies and provide more accurate cost assessments for energy system transitions. Kannan [13] considered the temporal partitioning of the TIMES model in Switzerland into four seasons, three typical days, and further divided it into 24 timeslices and two timeslices (daytime and nighttime) per day when comparing the results of the hourly-based TIMES model with the two-time-period model. They discovered significant differences in describing the peak and valley values of wind and solar generation output between the 24-time-period model and the 2-time-period model within TIMES. Subsequently, Kannan [21] further analyzed the description of electric vehicle charging and pumped storage in energy system models considering electricity demand, providing load/output curves for electric vehicles and energy storage in the Swiss electricity sector. Compared to models with an annual time scale, models considering electricity demand have significant advantages in characterizing technologies such as electric vehicles and energy storage. Lehtveer [17] developed the Global Energy Transition (GET) model for the global energy system and compared the results between models considering electricity demand and those without considering. They found that the models that did not consider electricity demand underestimated the total system cost by 15% to 20%.

Research on multi-sector energy system modeling considering the electricity load curve, as shown in Table 2, primarily focuses on the energy systems in Europe, while relevant studies on China's multi-sector energy system modeling considering electricity demand are still lacking. As shown in Table 2, the number of timeslices in existing multi-sector energy system models considering electricity demand generally ranges from a few to tens. Kannan [22] constructed a UK energy system model based on the MARKAL model with 20 timeslices. Kannan [21] pointed out that the number and length of timeslices can be determined based on the research questions, emphasizing capturing the intervals of peaks and valleys. Ringkjøb [18] developed a European TIMES model considering electricity demand. To compare the computational speed of models with different numbers of timeslices, the authors designed TIMES models with 12 to 2016 timeslices for comparison. The results showed that excessive timeslices would significantly increase the computation time required within the TIMES model, thereby reducing the efficiency of model analysis. Lehtveer [17] constructed the GET model using different numbers of timeslices ranging from 1 × 1 to 8 × 8. By clustering different timeslices to build the model, the authors compared the results of models with 1 to 64 timeslices, revealing differences between models with fewer and more timeslices. However, models with 9 to 16 timeslices already provided a good fit with the results of models with a larger number of timeslices.

The low-carbon transition of China's power sector will increase the demand for interprovincial electricity transmission. To analyze the future interprovincial electricity transmission patterns in China, some studies have utilized energy system models specific to the power sector [9,23]. Other models have employed input-output analysis [24] or electricity dispatch models [25] to simulate future interprovincial electricity transmission in China. However, these studies often isolate the power sector or transmission system from the entire energy system, which may limit their ability to reflect the interactions between different provinces and sectors in low-carbon scenarios. In this study, a module for interprovincial electricity transmission was constructed within the China TIMES-30PE model [5], enabling a comprehensive examination of interprovincial electricity transmission from the perspective of the entire energy system.

This study has constructed a new comprehensive analysis framework for China's provincial carbon neutrality covering the carbon neutrality policy lifecycle. This study developed the China TIMES-30PE model, which considers energy, environment, and economy at the provincial level. By designing different carbon neutrality scenarios with varying timelines and pathways, this study analyzes the deep decarbonization pathways of each province under the carbon peak and carbon neutrality goals. Furthermore, this study observes the development of key energy technologies such as wind power, solar power, and ultra-high-voltage transmission, as well as the interprovincial electricity transmission pattern.

2. Methodology

2.1. China TIMES-30PE model

The International Energy Agency Energy Technology Systems Analysis Program (IEA-ETSAP) developed and maintains the TIMES model, which combines the MARKet ALlocation (MARKAL) model and the

Table 2
Exist multi-timeslice energy system model.

Model Name	Timeslice	Target region	regions
MARKAL(UK) [16]	20	UK	Single
GET(Global) [17]	1 ~ 64	Global	multiple
TIMES(EU) [18]	12 ~ 2016	Europe	Single
LIMES [19]	4 ~ 96	Europe	Single
TIMES(Denmark) [20]	48	Denmark	Single

energy flow optimization model (EFOM). The China TIMES-30PE model was developed based on the China TIMES [26–30] and China MARKAL models [31–33]. As shown in Fig. 2, the 30-province model encompasses energy supply, conversion, transmission, and end-use technologies. The model encompasses a modeling horizon spanning from 2015 to 2060, with a reporting period of 5 years. The flow of various energy carriers in the optimal technology mix is described. Historical data calibration is based on statistics, reports, and official announcements. This study introduces more advanced carbon mitigation technologies such as hydrogen, energy storage, etc. into the model and updates parameters for renewable energy and CCS. To analyze the provincial BECCS development, biomass resource potential is analyzed to better simulate the role of BECCS for deep decarbonization.

2.2. Modeling electricity load and capacity factor curve in China TIMES-30PE

2.2.1. Timeslice in China TIMES-30PE model

This paper distinguished different timeframes based on seasons and daytime periods. Two main considerations drove the temporal partitioning of the model. Firstly, to capture the variability of energy supply, specifically by describing the fluctuations of generation technologies. Secondly, to capture the variability of energy demand, represented by load curves. Seasonal partitioning into four seasons—spring (R), summer (S), autumn (F), and winter(W)—naturally and effectively captures the seasonal changes in both generation and load. This study differentiated the seasons into the following five periods: Night (valley), Morning, Daytime peak, Afternoon, and Evening (night peak). Thus, a total of 20 timeslices were designed for the model, represented as RN, RM, RD, RA, RE, SN, SM, SD, SA, SE, FN, FM, FD, FA, FE, WN, WM, WD, WA, and WE, as determined by combining the seasonal and daytime divisions in Table 3.

The overall timeslice structure of the model is shown in Fig. 3. The model covers the period from 2020 to 2060, with a planning cycle of 5 years. Within the annual time scale, 20 timeslices are delineated to capture the temporal variations in the power sector.

2.2.2. Electricity load curve linearization in China TIMES-30PE model

The TIMES model is a linear optimization model. The activity of the electricity generation process in the TIMES model can be defined by eq. 1. In the equation, r, t, y, s, and p represents region, model period, year, timeslice, and process, respectively.

$$ACT(r,t,y,s,p) = AF(r,t,y,s,p) \times CAPUNT(r,p) \times FR(r,s) \times CAP(r,t,y,s,p) \tag{1}$$

Where:

$ACT(r,t,y,s,p)$: the activity of the electricity generation process.

$AF(r,t,y,s,p)$: the activity factor of the electricity generation process.

$CAPUNT(r,t,y,s,p)$: The activity of unit installed capacity.

$FR(r,t,y,s,p)$: The fraction of the annual demand occurring in timeslices. This parameter describes the shape of the load curve.

$CAP(r,t,y,s,p)$: The capacity of the electricity generation process.

As shown in eq. 1, the model incorporates load curves by describing the electricity demand proportions for each timeslice and including them in the model. Load curve linearization is required because the load curves cannot be directly put into the model. The linearization is shown in eq. 2, where P_L represents the linearized load level, which represents the average load during the specific timeslice. (t) represents the load curve function, and t_1 and t_2 represent the start and end times of the period, respectively.

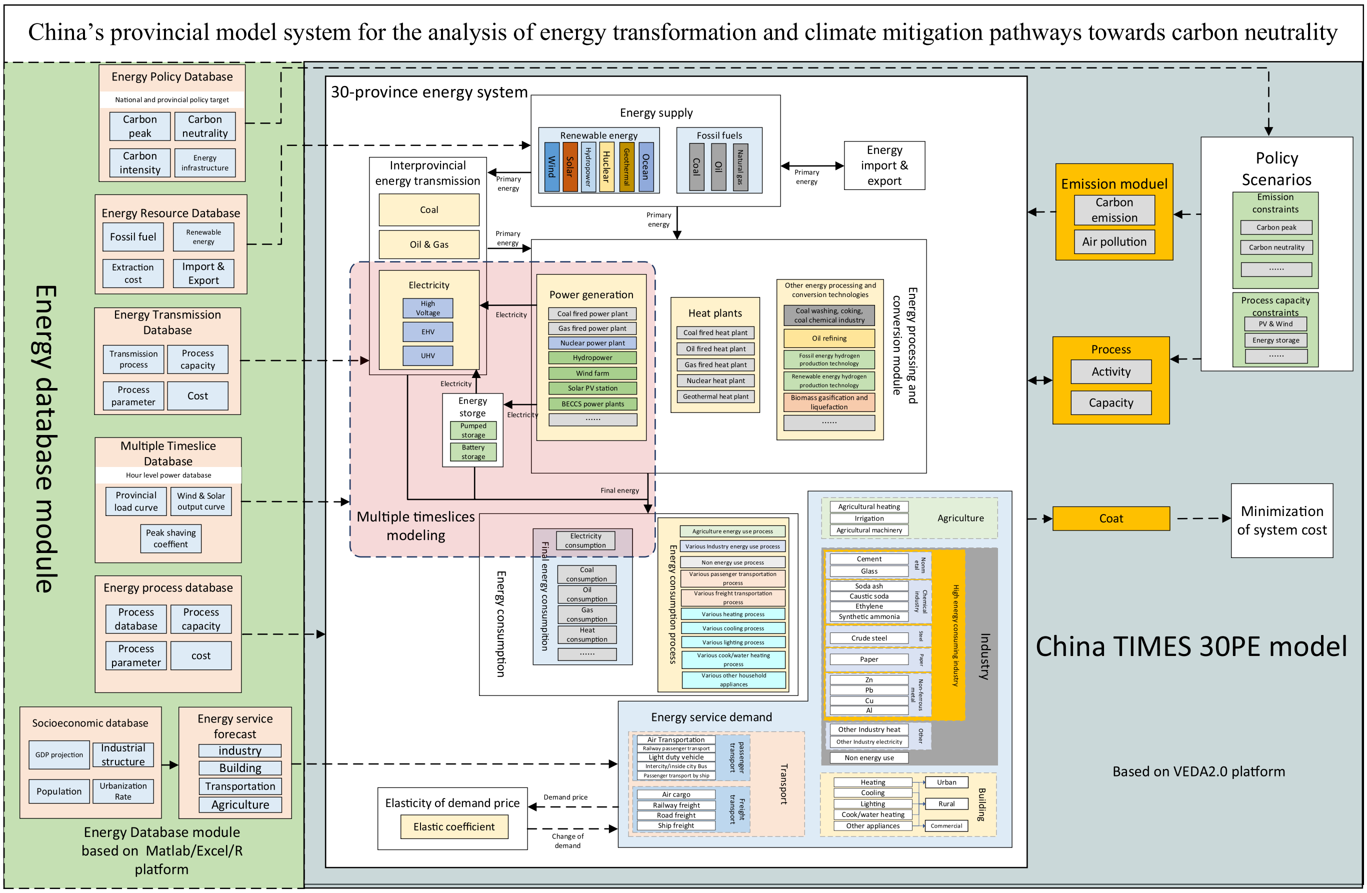


Fig. 2. Model structure of China TIMES-30PE model.

Table 3
Description of timeslice China TIMES-30PE.

Seasonal timeslice					Daily timeslice				
describe	name	start	end	days	describe	name	start	end	hours
spring	R	Mar. 1	May 31	91	Night	N	-3:00	06:00	9
summer	S	Jun.1	Aug. 31	90	Morning	M	06:00	09:00	3
autumn	F	Sep. 1	Nov. 30	92	Daytime peak	D	09:00	12:00	3
winter	W	Dec. 1	Feb. 28	92	Afternoon	A	12:00	18:00	6
					Evening	E	18:00	21:00	3

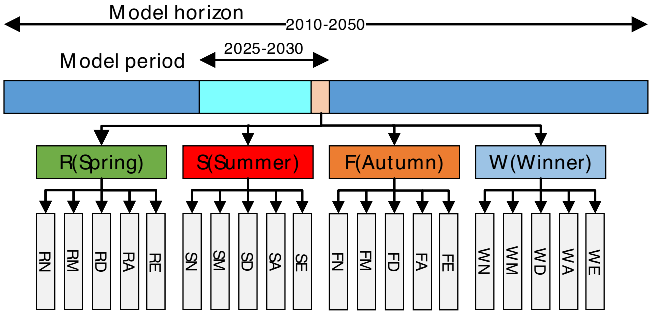


Fig. 3. Timeslice structure in China TIMES-30PE model.

$$P_L = \frac{\int_{t_1}^{t_2} P(t)}{t_2 - t_1} \tag{2}$$

Fig. 4 shows the linearization process of the daytime load curve using the example of Tianjin's daily load curve [34], and a similar approach is applied to annual load curves.

3. Assumptions and scenarios

3.1. Assumptions and data

3.1.1. Energy data in China TIMES 30PE model

The modeling period for China TIMES-30PE spans from 2020 to 2060, with the base year set as 2020. The model was calibrated based on China's 2020 provincial energy balance sheet [35], and the energy system and technology parameters were updated using various data sources such as statistical data, literature, reports, and standards from the year 2020. For example, the capacity and cost of power generation technologies can be found in reports according to the China Electricity Council [36,37] and the distribution and cost of interprovincial electricity transmission technologies can be found in the announcements by the National Energy Administration [38–40]. The electricity technology investment cost projections in the China-TIMES-30PE model can be found in the appendix(Table A). The supply of fossil fuels is referenced from the China Mineral Resources Report [41] and the energy balance sheet. The resource potential of renewable energy sources such as wind power, photovoltaic (PV) power, and biomass is determined based on existing provincial-level resource studies conducted in China. The interprovincial energy transmission situation is determined based on existing government documents and statistical data.

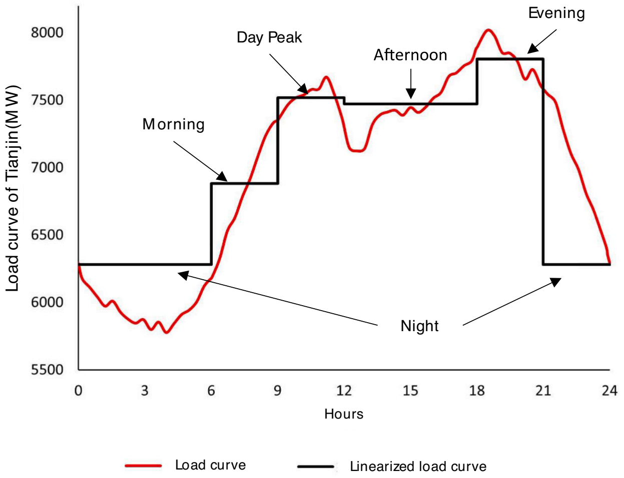


Fig. 4. Load curve linearization in the China TIMES-30PE model.

3.1.2. Load curves and capacity factor curves linearization in China TIMES-30PE

In this study, the fluctuation of the load was characterized by linearizing the load curves obtained from statistical data and extracting the electricity demand proportions for each timeslice. The National Development and Reform Commission provided typical load curves for provincial-level power grids in the "Notice on the Long-term Power Contract Signing Work for 2020" [42], as mentioned in the report [34]. The annual load curve was derived by averaging the maximum and minimum load curves from the document. In contrast, the daytime load curve was obtained by calculating the weighted average of the typical workday load curve and the load curve during holidays based on the actual number of days. According to the method of linearization in section 2.2.2, the TIMES model used the parameter $FR(r,t,y,s,p)$ to describe the provincial load curves.

The output of wind power and photovoltaic (PV) power exhibits temporal variability. He provided typical provincial annual and daily capacity factor curves for PV power plants [43] and provincial annual capacity factor curves for wind power plants [44]. Furthermore, Zhang [45] gave the typical daily capacity factor curve of wind power plants was also consulted. The capacity factor curves of wind power and PV power plants were linearized using the method described in section 2.2.2. It was observed that PV power plants exhibit the highest capacity factor during the day peak in the summer, while wind power capacity factor is lower during the daytime compared to night. The TIMES model used the parameter $AF(r,t,y,s,p)$ to describe the provincial capacity factor curves.

The range of capacity factors for thermal, nuclear, and hydropower can be described in China TIMES-30PE. In the model, the upper limit of the parameter $AF(r,t,y,s,p)$ for these power generation processes is set based on actual operational conditions, while the lower limit is determined according to their peaking capabilities. After peaking capability retrofitting, the average peaking capability of thermal power units in China can reach 30% of their rated capacity [46]. Gas-steam cogeneration units are commonly used as peak power sources for the grid, with a peak capacity ratio of 50% [47]. Although existing nuclear power units are not currently dispatched for peaking, they still possess peaking capabilities. The peaking capability of existing nuclear power units ranges from 30% to 100% of their rated power [48]. Hydropower units exhibit a peaking depth close to 100% when considering spillage-based peaking, indicating excellent peaking performance. However, they are subject to limitations due to constraints on upstream water availability [49].

3.2. Scenarios

The following three scenarios were designed to explore China's provincial low-carbon transition (see Table 4). Based on the current policies and national carbon peak target, this study has designed the CP30 scenario to simulate China's achievement of the national carbon peak target by 2030, including the provincial carbon reduction targets in the "14th Five-Year Plan" and other policy documents such as targets for non-fossil fuel energy ratio, renewable electricity capacity, and energy storage capacity. Additionally, this study has designed the CN60 and CN50 scenarios based on the CP30 scenario by adding national carbon emission constraints to simulate the carbon neutrality pathways for each province when China reaches its carbon neutrality goal. The China TIMES-30PE model is used to simulate each province's mitigation pathways, aiming to minimize nationwide mitigation costs. Tsinghua University [50] projected China's national carbon emission pathways towards carbon neutrality. To achieve carbon neutrality in 2060, China's carbon emissions will peak at 10.5 billion tons in 2030 and reach zero in 2060. To achieve greenhouse gas neutrality in 2060, China's carbon emissions will peak at 10.5 billion tons in 2030, reach zero in 2050, and reach negative emissions in 2060. The national pathways [50] are used in energy system carbon neutrality and greenhouse gas neutrality scenarios as the upper limits of national emissions. In CN60 and CN50 scenarios, the China TIMES-30PE model simulated the provincial carbon emissions pathways and energy system low carbon transition under the national pathways constraints.

4. Results

4.1. Provincial carbon emission pathways

Fig. 5 shows the emission pathways of different provinces under various scenarios. In the CP30 scenario, Beijing, Tianjin, Hebei, and Shandong provinces achieve carbon emissions peaking before 2025, while the rest peak around 2030. All provinces achieve peak emissions between 2020 and 2030 under the carbon neutrality scenario. Compared to the carbon peaking scenario, most provinces experience an earlier peak and a decrease in emission levels under the carbon neutrality scenario.

Beijing, Tianjin, Hebei, Jiangsu, Zhejiang, Shanghai, Fujian, and Shandong will achieve carbon emission peaking before 2025 in the carbon neutrality scenario. These provinces, including Beijing, Tianjin, and Jiangsu, are economically developed and have advantages in emissions reduction. Reports on these provinces' economic and social development achievements [51] indicate that they have been consistently promoting green development and low-carbon transformation since 2020, resulting in a continuous decrease in energy consumption levels. The energy transition in Hebei province is particularly notable, with a 0.7% decrease in total energy consumption in 2021 compared to 2020 and a 13.5 percentage point decrease in the proportion of coal consumption [52]. Hebei province has also prioritized emission reduction in the power sector and vigorously developed renewable energy in its dual carbon plan, aiming to increase wind and solar installed capacity to over 100GW by 2025.

Table 4
Scenarios in China TIMES-30PE.

Scenario Name	description	National carbon peak target	National carbon neutrality target
CP30	Carbon emission peak in 2030	2030	/
CN60	Carbon neutrality in 2060	2030	2060
CN50	Carbon neutrality in 2050	2030	2050

Estimations based on the statistical data released by provinces suggest that most provinces have experienced continuous growth in carbon emissions since 2020. However, considering the carbon neutrality goals, a comprehensive approach is needed in the development process. Given the significant emissions reduction required for future carbon neutrality goals, the carbon intensity reduction targets during the 14th and 15th Five-Year Plans need further enhancement. In the CN60 scenario, the carbon intensity reduction rates during the 14th and 15th Five-Year Plans are increased on average by 1.9 and 9.6 percentage points, respectively, compared to the targets set during the 13th Five-Year Plan. In the CN50 scenario, the increase is 3 and 14.9 percentage points, respectively. The simulation results of carbon neutrality scenarios with different timelines show a more significant increase in carbon intensity reduction rates during the 15th Five-Year Plan than the 14th Five-Year Plan. It highlights the need for provinces to control the growth of carbon emissions and further reduce carbon emission levels before reaching the peak, thus alleviating emission reduction pressure from 2030 to 2060.

Under the carbon neutrality scenarios, all provinces will continue to reduce emissions after 2030, leading to a rapid decrease in both carbon intensity and emission levels. Taking the CN60 scenario as an example, the carbon intensity of each province in 2050 will decrease by 81% to 99% compared to 2020. The carbon neutrality targets pose significant challenges for all provinces, as their emission spaces will be strictly constrained. On average, the carbon intensity of eastern provinces is expected to decrease by 89%, while that of western provinces is projected to decrease by 93%. The higher reduction in carbon intensity in western provinces can be attributed to two main factors. Firstly, the western provinces had relatively higher carbon intensity in 2020. Secondly, the eastern provinces have higher energy service demands that are difficult to mitigate, such as aviation and waterway transportation, compared to the western provinces.

In the carbon neutrality scenario, extensive deployment of BECCS (Bioenergy with Carbon Capture and Storage) technology will be required by 2060 to generate negative emissions. Under the CN60 scenario, Guangxi, Jilin, and Yunnan are projected to achieve zero or negative emissions by 2055. Chongqing Municipality, Gansu Province, Heilongjiang Province, Liaoning Province, Ningxia Autonomous Region, Qinghai Province, Jiangxi Province, Shaanxi Province, Sichuan Province, and Xinjiang Autonomous Region are expected to achieve negative emissions by 2060. Other provinces will not have achieved carbon neutrality by 2060.

Under the carbon neutrality scenarios, China's western, northeastern, and central regions achieve carbon neutrality earlier than the eastern region. The variations in the timing of carbon neutrality among provinces can be attributed to several factors. Firstly, most western provinces have abundant biomass and solar power resources, enabling the power sector to achieve significant emission reductions by utilizing renewable energy and BECCS technology, resulting in substantial negative emissions. Secondly, the energy service demands in western provinces' transportation and industrial sectors are relatively lower than those in eastern provinces, leading to lower emission levels in these sectors when carbon neutrality is achieved.

Compared to the CN60 scenario, some provinces are expected to achieve carbon neutrality earlier, and experience increased negative emissions in the CN50 scenario. In 2060, provinces such as Yunnan, Inner Mongolia, and Heilongjiang in the central and western regions will have further increased negative emissions, primarily through the expanded application of BECCS technology and additional emission reductions in the industrial and transportation sectors. Taking Inner Mongolia as an example, in the CN50 scenario, the region achieves −60 million tons of negative emissions based on its abundant biomass and solar resources. The consumption of biomass and hydrogen energy increases by 25% and 38%, respectively, compared to the CN60 scenario.

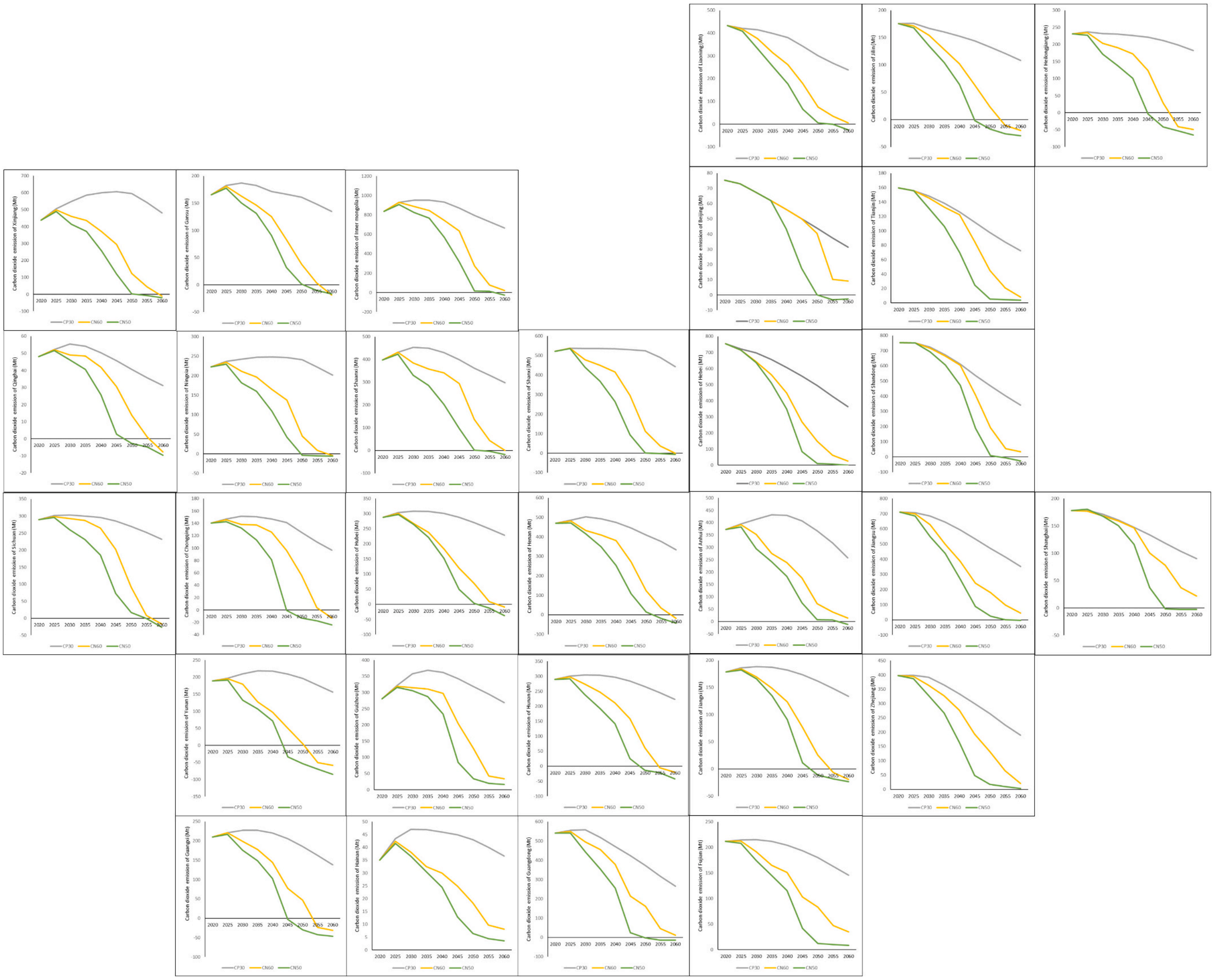
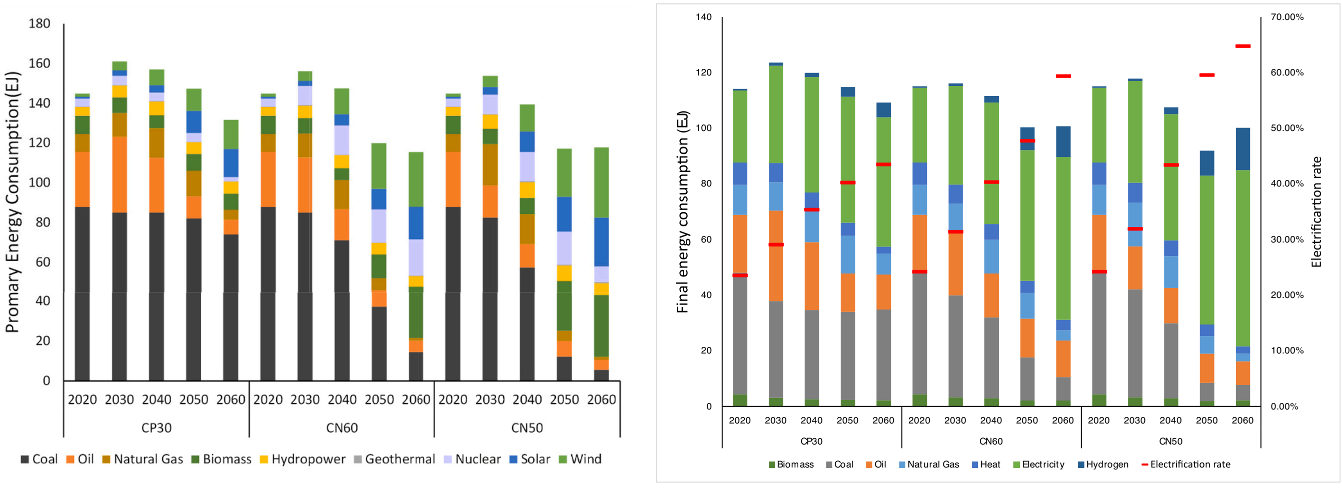


Fig. 5. Provincial carbon emission pathways under carbon neutrality scenarios.



(a)

(b)

Fig. 6. (a)National primary energy consumption under low-carbon scenarios; (b) National final energy consumption and electrification.

4.2. Energy system transition under carbon neutrality scenarios

Under the carbon neutrality scenarios, the proportion of coal consumption in the energy structure rapidly decreases, while non-fossil fuels such as nuclear power, hydropower, wind power, and photovoltaics rapidly increase (Fig. 6(a)). By 2060, the proportion of coal in primary energy consumption in each province will have significantly decreased, with the remaining coal consumption mainly used in industry and coal-fired power plants equipped with carbon capture and storage systems. Under the carbon neutrality scenarios, the electrification rate of end-use sectors continues to increase while coal consumption continues to decrease (Fig. 6(b)). Under CN60 and CN50 scenarios, the proportion of coal in final energy consumption in 2060 decreased to 8.6% and 5.6% respectively, with the electrification rates increasing to 59.4% and 64.7% respectively. Summarizing the carbon neutrality scenarios simulated results from multiple models [53], by the year 2060, China is projected to achieve carbon neutrality with terminal sector electrification rates ranging from 42% to 73%, with a median value of 60%. As fossil fuels are continuously replaced, the consumption of electricity and hydrogen is expected to grow steadily. In the carbon neutrality scenario, by 2060, electricity consumption is projected to increase to 16.3PWh ~ 17.6PWh, and hydrogen consumption to grow to 75 Mt. ~ 99 Mt., accounting for over 10% of the total consumption. In a scenario of carbon neutrality, hydrogen energy will play a significant role in the end-use energy in various provinces, primarily in the industrial and transportation sectors. When viewed from a provincial perspective, the more developed eastern provinces exhibit higher hydrogen consumption. Under the CN60 scenario, by the year 2060, Shandong, Guangdong, Jiangsu, and Hebei provinces are among the top consumers of hydrogen energy nationwide, reaching 5.48 Mt., 4.15 Mt., 4.35 Mt., and 5.21 Mt. respectively. The consumption of hydrogen energy in provinces is primarily influenced by hydrogen costs and the energy consumption demands of industrial or transportation sectors. By 2060, regions such as Inner Mongolia and Xinjiang Autonomous Regions where green hydrogen costs are lower will have a higher demand for hydrogen energy and the consumption of hydrogen energy will reach 4.37 Mt. and 2.76 Mt. respectively. Conversely, Qinghai Province, Ningxia Autonomous Region, and Gansu Province exhibit lower consumption levels, reaching 0.42 Mt., 1.13 Mt., and 1.44 Mt. respectively. Meeting early neutrality targets will further escalate the consumption of hydrogen energy in each province. Similar studies also predict a substantial growth in hydrogen consumption in China. The “China Hydrogen and Fuel Cell White Paper” released by the China Hydrogen Alliance [54] predicts that by 2060, under the carbon neutrality scenario, China's hydrogen consumption is expected to reach 97 Mt.

In contrast, the proportion of non-fossil fuels in primary energy consumption in each province will significantly increase by 2060 (Fig. 7 (a)). Provinces such as Gansu, Inner Mongolia, and Yunnan, which have abundant renewable energy resources, have a higher proportion of non-fossil fuels in their primary energy consumption than other provinces.

The eastern regions have higher electrification levels, while the western provinces have a slower increase in electrification (Fig. 7(b)). By 2060, Guangdong, Shandong, Zhejiang, and Jiangsu have the highest electrification rates in end-use sectors, reaching 74%, 73%, 75%, and 73%, respectively, under the CN50 scenario. In comparison, the electrification rates of Ningxia, Inner Mongolia, Guizhou, and Guangxi reach 53%, 58%, 44%, and 63%, respectively, under the CN50 scenario. Developed provinces have seen a rapid decline in the proportion of coal consumption in end-use sectors, with Beijing, Zhejiang, Jiangsu, and Guangdong all having coal consumption proportions below 10% under the carbon neutrality scenarios. However, underdeveloped provinces still have a certain proportion of coal consumption, with Ningxia, Qinghai, and Shanxi having coal consumption proportions above 10% under the carbon neutrality scenarios.

4.3. Electricity sector low carbon transition towards carbon neutrality

4.3.1. Deep decarbonization in the power sector

In the carbon neutrality scenarios, both electricity capacity and electricity generation are projected to experience rapid growth. Fig. 8 shows the structural changes in national electricity capacity and electricity generation under different scenarios. In the CP30 scenario, national electricity generation is expected to reach 10.6 PWh in 2030 and increase to 14.8 PWh by 2060. By 2030, the total installed electricity capacity will reach 3486 GW, with wind power and solar power accounting for over 1200 GW, and the share of coal-fired power installations dropping to 40.5%. By 2050 and 2060, the total electricity capacity is projected to further increase to 4861 GW and 4962 GW, respectively. Electricity demand will gradually rise with a significant increase in the electrification rate under the carbon neutrality target. By 2030, national electricity generation is projected to reach 10.8 PWh to 11.5 PWh in the carbon neutrality scenarios and increase to 18.0 PWh to 19.4 PWh by 2060. Due to the higher electricity demand in the carbon neutrality scenario, the total electricity capacity is expected to reach 6382 GW to 7539 GW by 2060.

The carbon peak and neutrality targets promote the accelerated development of clean electricity and further growth of renewable energy installations. By 2030, clean electricity (including fossil fuel power

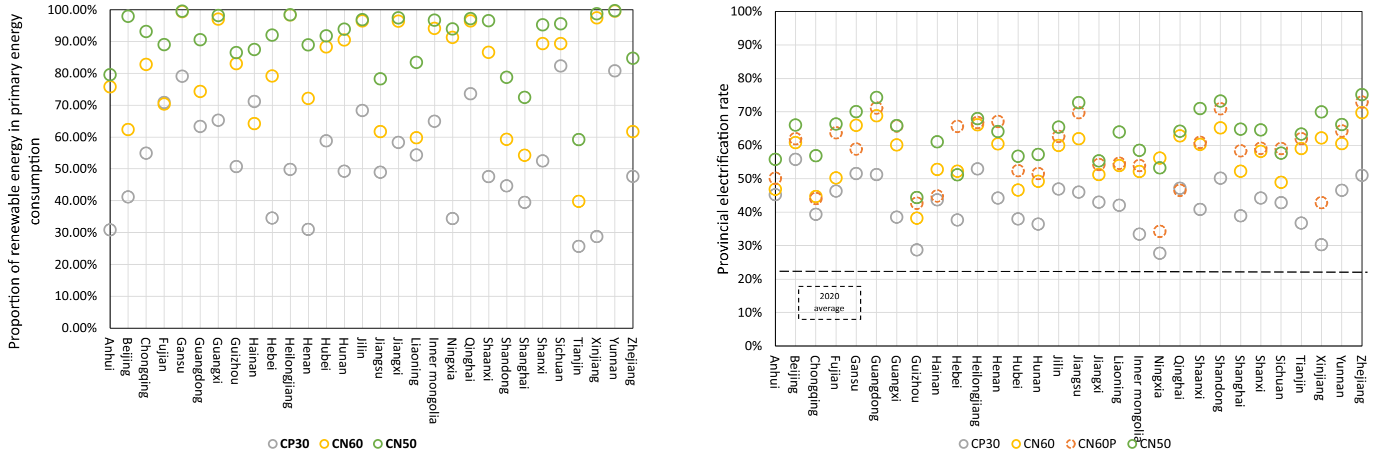


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Fig. 7. (a) Proportion of renewable energy in primary energy consumption in 2060; (b) Provincial electrification rate in 2060.

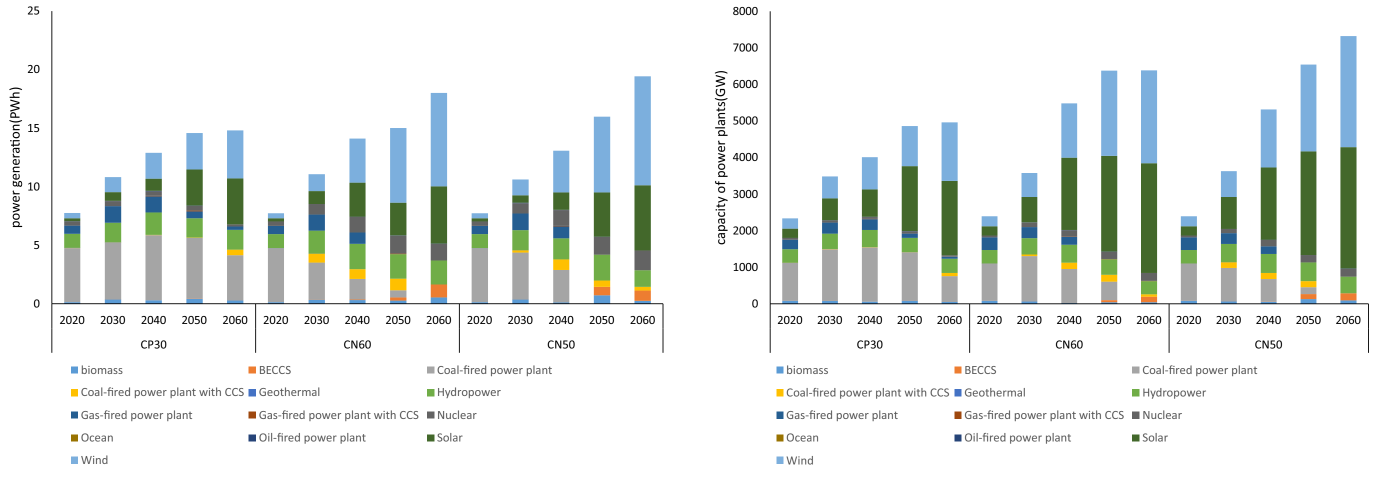

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Fig. 8. (a) National electricity generation under low-carbon scenarios; (b) National electricity capacity under low-carbon scenarios.

generation with Carbon Capture and Storage (CCS) facilities) is projected to account for 48.7% to 58.7% of total electricity generation in the carbon neutrality scenario, compared to 41.6% in the CP30 scenario. In 2060, the share of clean electricity generation is expected to surpass 95%, up from 72.1% in the CP30 scenario. By 2030, wind power and solar power capacity in the CP30 scenario could reach the policy planning targets. Under the CN60 and CN50 scenarios, the capacity will increase to 1351 GW and 1575 GW, exceeding the policy planning objectives. By 2060, wind power and solar power installations will dominate, accounting for over 85% of the total installed capacity in the carbon neutrality scenario. Wind and solar capacity in the CN60 and CN50 scenarios is projected to increase to 5535 GW and 6356 GW, respectively. Similar studies have also projected rapid electricity capacity and generation growth under the carbon neutrality target. According to research [55], using the GTEP model, electricity capacity is estimated to increase to 5822 GW (in the 2-degree scenario) and 6463 GW (in the 2050 carbon neutrality scenario), with electricity generation reaching 14.3 PWh and 16.3 PWh, respectively. Relevant research [56] found that the total electricity capacity under carbon neutrality will reach 7008 GW in 2050, and electricity generation will increase to 15.2

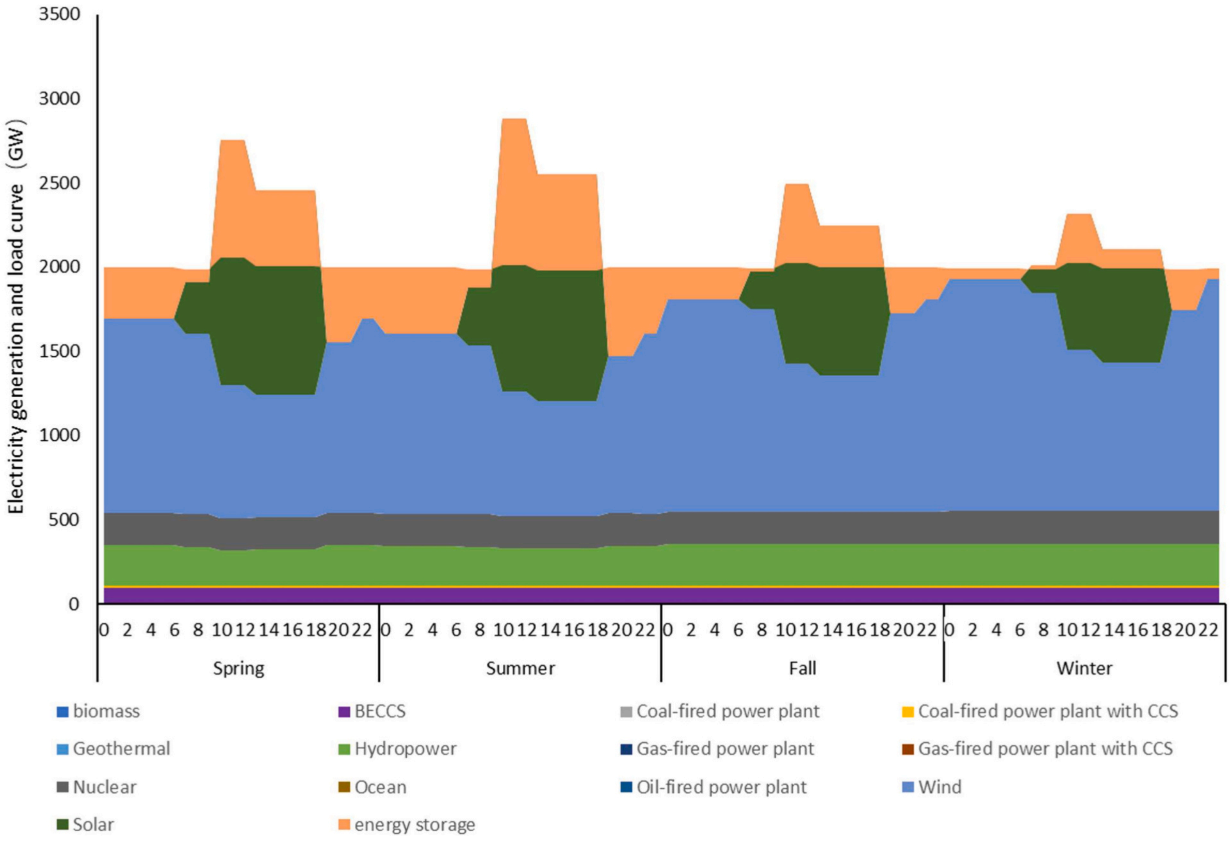

Fig. 9. Electricity generation and load curve under CN60 scenario in 2060.

PWh.

Taking the CN60 scenario as an example, Fig. 9 shows the electricity supply and load curve in 2060. Under the CN60 scenario, the national electricity generation in 2060 amounts to a staggering 18.0 PWh. Nuclear power, BECCS (Bioenergy with Carbon Capture and Storage) plants, and hydropower demonstrate relatively stable electricity output. Wind power and solar photovoltaics (PV) exhibit complementary seasonality and diurnal pattern characteristics. Taking the spring season as an example, the average maximum power for charging during the daytime peak and the average maximum power for discharging during the night peak. In scenarios where wind and solar power contribute significantly, energy storage plays a crucial role in “peak shaving” or balancing the disparity between power generation and demand. In 2060, the capacity of the energy storage process will reach 935 GW and 1147 GW under CN60 and CN50 scenarios, respectively.

After reaching the peak, the carbon neutrality target requires each province to continue promoting deep decarbonization in the power sector based on their energy resource endowments. Fig. 10 presents the electricity capacity in different scenarios for each province. In the carbon neutrality scenario, provinces in the northwest region will rely on abundant wind and solar resources to achieve deep decarbonization in the power sector through wind and solar power generation. Eastern provinces will rely on wind, solar, and nuclear power to achieve low-carbon transformation in the power sector. Coastal provinces with favorable conditions for nuclear power are actively constructing nuclear power plants. Guangdong, Zhejiang, and Jiangsu provinces have higher electricity capacities, reaching 61 GW to 74 GW, 53 GW to 55 GW, and 25 GW to 30 GW by 2060, accounting for over 60% of the national nuclear electricity capacity. Southwestern provinces will rely on sufficient hydropower, wind and solar resources to achieve deep decarbonization in the power sector. The low carbon transition in Yunnan and Sichuan's electricity sector mainly relies on hydropower, wind, and solar capacity. By 2060, Yunnan province is expected to have 85 GW to 106 GW of hydropower capacity and 236 GW to 274 GW of wind and solar capacity. Sichuan province is estimated to have 103 GW to 155 GW of hydropower capacity and 69 GW to 97 GW of wind and solar capacity. With abundant renewable wind and solar resources, Northeastern provinces will develop wind and solar power to achieve low-carbon transformation in the power sector. By 2060, the total wind and solar capacity in Heilongjiang, Jilin, and Liaoning provinces are projected to increase from 181 GW to 212 GW, 147 GW to 173 GW, and 111 GW to 196 GW, respectively. Central provinces will rely on wind, solar, and hydropower to achieve deep decarbonization in the power sector. Shanxi province is expected to reach 234 GW to 270 GW of wind and solar capacity by 2060, with solar power accounting for over 60%. Hubei province is actively developing integrated renewable energy from wind, solar, and hydropower, with hydropower installations reaching 38 GW to 42 GW and wind and solar capacity surpassing 87 GW by 2060.

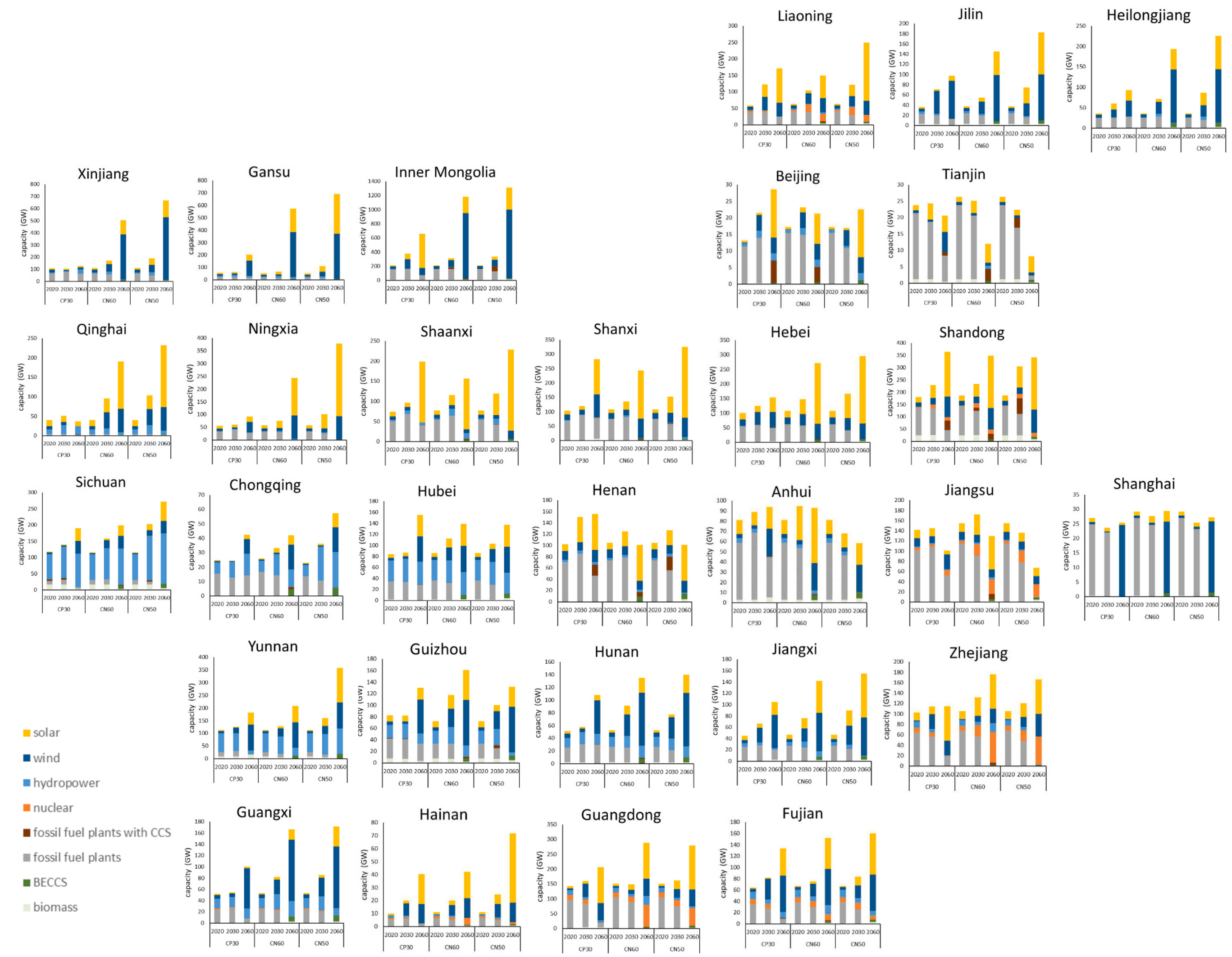

Fig. 10. Provincial electricity capacity under different scenarios.

Hunan is projected to have 92 GW to 103 GW of wind electricity capacity by 2060.

4.3.2. Interprovincial electricity transmission pattern

In the scenario of carbon neutrality, provincial-level electricity transmission needs to be optimized to match the distribution of renewable energy resources with electricity demand. The interprovincial electricity transmission and capacity of interprovincial power transmission lines continue to increase. By 2060, under the carbon neutrality scenario, the interprovincial electricity transmission is expected to grow from 6747TWh to 7057TWh, accounting for 36% to 39% of the total electricity generation (Fig. 11(a)). The early achievement of carbon neutrality will further enhance interprovincial electricity transmission. Relevant studies conducted using the GTEP model by the Department of Electrical Engineering at Tsinghua University [55] also suggest a significant increase in interprovincial electricity transmission in China, with a simulated transmission volume of 6052.73TWh in 2050 under the carbon neutrality scenario.

Under the carbon neutrality target, the capacity of interprovincial transmission lines will overgrow. Fig. 11(b) shows the capacity of interprovincial transmission lines. Advancing the carbon neutrality timeline and strengthening emission constraints in eastern provinces will further drive the construction of interprovincial transmission lines. By 2060, the interprovincial transmission capacity is expected to reach 1637GW and 1768GW under the CN60 and CN50 scenarios, respectively. Other studies predict a substantial increase in interprovincial power transmission capacity in China. Relevant research [64] indicates that between 2020 and 2050, under the carbon neutrality scenario, the capacity of newly constructed interprovincial transmission lines would reach 788 GW. In this study, the capacity of newly constructed interprovincial transmission lines ranges from 704GW to 870GW in 2050.

Under the carbon neutrality scenario, significant changes will occur in the pattern of interprovincial power transmission compared to the current framework. Fig. 12 shows the interprovincial power transmission pattern in the CN60 scenario in 2060. Electricity exports from the northwestern provinces continue to grow. By 2060, Gansu Province will have established multiple large-scale wind and solar power generation bases, becoming the province with the highest power exports in the northwest region. The electricity transmitted externally from Gansu in the CN60 scenario will reach 1167TWh. Gansu supplies electricity to provinces in central, eastern, and northwestern regions, such as Shaanxi and Ningxia, thus becoming an important energy base and hub in the northwest region. Under the CN60 scenario, the electricity transmission from Gansu to the Yangtze River Delta region will reach 360TWh, and the electricity delivered to Hunan will reach 170TWh. Under the CN60 scenario, power exports from Xinjiang will rise to 1051TWh in 2060. The main transmission channels for Xinjiang's electricity transmission include routes to Anhui, Zhejiang, Jiangsu, and Henan. The electricity exports from Ningxia and Qinghai continue to grow, reaching 192TWh and 111TWh, respectively, by 2060. As a result of the declining coal-fired electricity capacity and increasing power demand during the low-carbon transition, Shaanxi will be a net power importer in the CN60 scenario, with power imports increasing to 301TWh in 2060.

In the Northern, Inner Mongolia, which is planned to be an energy base, sends electricity to Shandong, Shanxi, and the Beijing-Tianjin-Hebei region. By 2060, with its vast land area and abundant renewable resources, Inner Mongolia will have become China's largest electricity-exporting province. In the CN60 scenario, power exports from Inner Mongolia in 2060 will increase to 2436TWh, accounting for over one-third of the interprovincial electricity transmission in the country. Shanxi will transition from an electricity exporter to an electricity importer by 2030. The power imports in the North China region, including Shandong Province and the Beijing-Tianjin-Hebei region, continue to increase, reaching 1093TWh and 931TWh in 2060 under the CN60 scenario.

Under the carbon neutrality scenarios, electricity will be transmitted from the Northeast region to the Beijing-Tianjin-Hebei region. Jilin will mainly deliver electricity to Liaoning, which will be a power-importing province.

In 2060, the Central region primarily relies on Sichuan Province as a net power-exporting province, while other provinces become net power-importing provinces. From 2030 to 2060, Sichuan will continuously increase its power exports, reaching 230TWh in 2060 under the CN60 scenario, with 151TWh delivered to the Yangtze River Delta region. As the power sector undergoes deep decarbonization, Hubei transitions to a power-importing province due to its higher power demand than production. From 2030 to 2060, Henan, Hunan, and Jiangxi will experience continuous growth in power imports.

From 2030 to 2060, electricity imports in East China provinces further increase. In the southern region, Yunnan, an energy-exporting base, continues to increase its electricity exports, while Guangdong, a load center, sees a rise in power imports. The primary power transmission channel in the southern region will remain between Yunnan and Guangdong.

Fig. 13 shows the interprovincial power transmission pattern in the CN50 scenario in the year 2060. Comparing the results between the

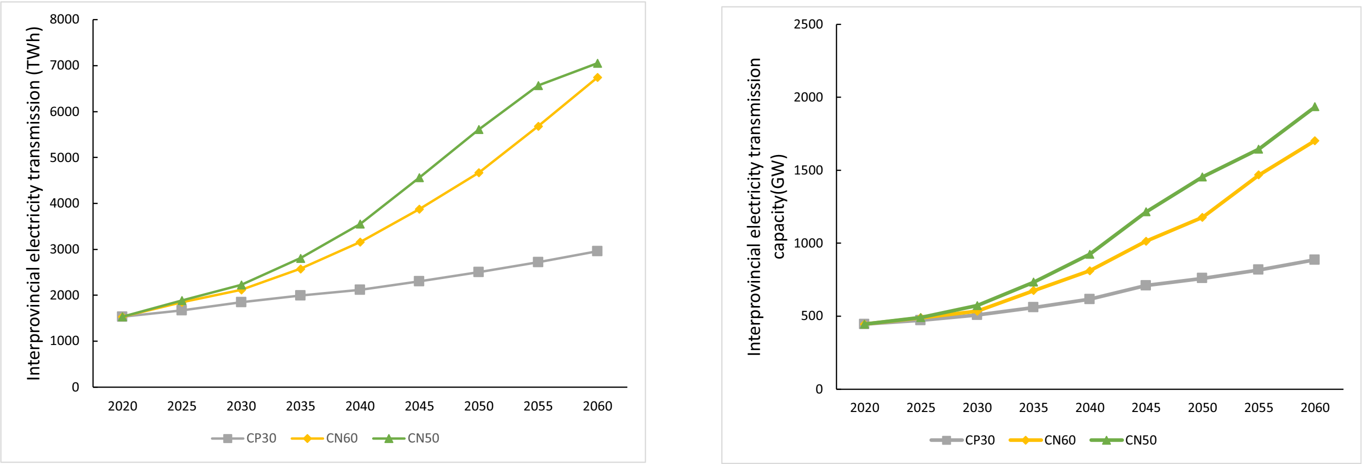

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Fig. 11. (a) Interprovincial electricity transmission under different scenarios (b) The capacity of interprovincial electricity transmission lines under different scenarios.

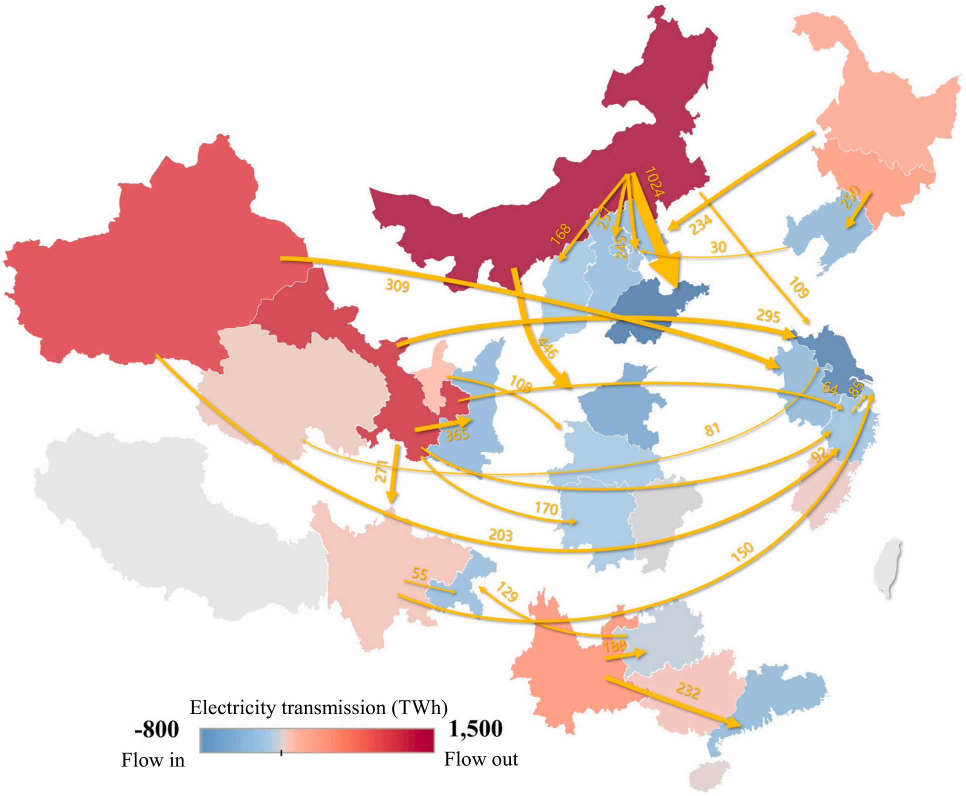


Fig. 12. Interprovincial power transmission pattern under the CN60 scenario.

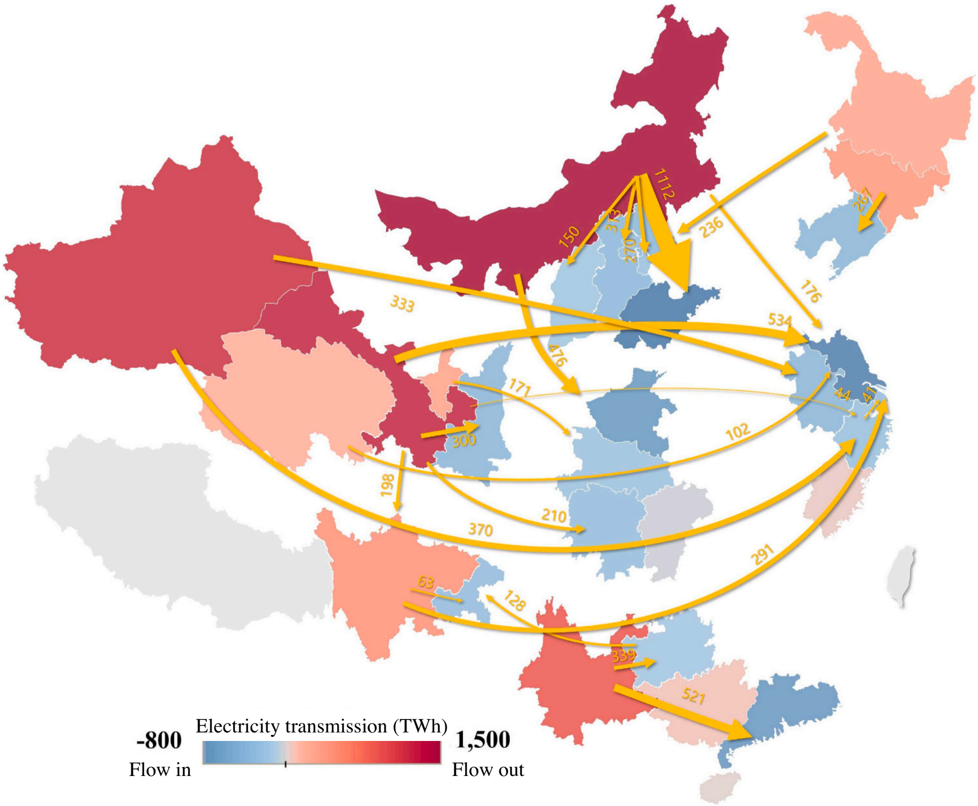


Fig. 13. Interprovincial power transmission pattern under the CN50 scenario.

CN50 and CN60 scenarios, the stricter emission constraints in the early carbon neutrality target lead to further increases in the power dispatch from most power-exporting provinces. With the increasing wind and solar power generation in the Northwest region and the rising electricity demand in the Eastern region under the CN50 scenario, electricity transmission from Inner Mongolia, Xinjiang, Gansu, Qinghai, and Ningxia is projected to grow rapidly. For example, in 2060, the power exports from Inner Mongolia and Gansu will increase to 2586TWh under the CN50 scenario. Due to the growing electricity demand in Sichuan, it needs to import more electricity from the Northwest provinces. Comparing the CN50 and CN60 scenarios results, the stricter emission constraints in the early carbon neutrality target further increase inter-provincial electricity transmission. As the major electricity-importing regions, the Beijing-Tianjin-Hebei region, the Yangtze River Delta region, Shandong, and Guangdong will experience further growth in electricity imports to 933TWh, 2392TWh, 1201TWh, and 725TWh, respectively, under the CN50 scenario.

A relevant study using the GTEP model at the Department of Electrical Engineering of Tsinghua University [55] has also indicated that the interprovincial power transmission pattern in China under the carbon neutrality scenario will become more complex. The simulation results for the year 2050 showed that interprovincial power transmission would exceed 40% of total electricity generation and follow a pattern of “west to east” and “north to south,” with the northern and northwestern regions serving as the main power exporting areas, while the eastern and central regions as the main electricity importing provinces.

4.3.3. *Ultra-high voltage electricity transmission*

Ultra-high voltage transmission technology has played an essential role in inter-provincial power transmission with its advantages of long-distance transmission, high transmission capacity, and low power loss. In the process of deep decarbonization in the power sector, the development of UHV transmission lines continues. By 2060, the UHV transmission line capacity will reach 439GW, 652GW, and 940GW under CP30, CN60, and CN50 scenarios (Fig. 14(a)). Under the CN60 and CN50 scenarios, the transmitted power through UHV transmission lines will reach 2855TWh and 4215TWh (Fig. 14(b)), respectively, accounting for 42.3% and 59.7% of the national interprovincial power transmission.

Fig. 15 shows the capacity of ultra-high voltage (UHV) transmission lines in 2060. UHV transmission lines will be responsible for long-distance and high-capacity power transmission in 2060, and their installed capacity will rapidly increase with the growth of interprovincial power transmission volumes. In the CN60 and CN50 scenarios, the UHV transmission capacity starting from the Northwest reaches 400GW and 563GW, respectively, with major endpoints in the Central and Eastern regions. Due to the long transmission distance, Xinjiang requires UHV transmission to export power. In 2060, the capacity of UHV transmission lines to connect Xinjiang with the Yangtze River Delta region and Henan will further increase. Under the CN60 and CN50 scenarios, Xinjiang's UHV transmission capacity will reach 223GW and 252GW in 2060, respectively. Specifically, the capacity of the UHV lines that connect Xinjiang and the Yangtze River Delta region will increase to 174GW and 211GW, respectively. Other major UHV transmission corridors in the Northwest region include Gansu to Hunan and Qinghai to Guangdong. Recent provincial energy policies align closely with the results of China TIMES-30PE. Gansu government [57] planned to supply electricity to Hunan, and Qinghai government [58] planned to supply electricity to the southern grid in 2021.

In the North China region, UHV installed capacity mainly originates from Inner Mongolia, increasing to 88GW and 105GW under the CN60 and CN50 scenarios, respectively. By 2030, UHV transmission lines starting from Inner Mongolia will cover Hebei, Shandong, Jiangsu, Tianjin, and Beijing, supporting power delivery from Inner Mongolia to the Beijing-Tianjin-Hebei region and the East China region. The UHV transmission capacity from Heilongjiang to North China is 42GW and 48GW, respectively. In 2060, the UHV transmission capacity starting from Sichuan will reach 44GW and 85GW under the CN60 and CN50 scenarios, respectively. In 2060, UHV transmission lines reaching the Yangtze River Delta region account for over half of the national UHV transmission capacity, reaching 350GW and 506GW under the CN60 and CN50 scenarios, respectively. Major UHV power transmission corridors include those from Gansu to Jiangsu, Inner Mongolia to Jiangsu, Qinghai to Jiangsu, Sichuan to Shanghai, Xinjiang to Anhui, Xinjiang to Zhejiang, and Xinjiang to Jiangsu.

5. Conclusion

A modeling framework for energy transition and carbon neutrality analysis at the provincial level in China, China TIMES-30PE model, with 20 timeslices, is updated to provide an in-depth analysis of energy transformation and interprovincial power transmission towards carbon neutrality.

The results indicate that achieving carbon neutrality will require a profound decarbonization of energy systems across all provinces. By 2060, the energy supply structure is projected to shift dramatically from being coal-dominated to renewable-dominated, with non-fossil energy sources comprising over 90% of the energy mix.

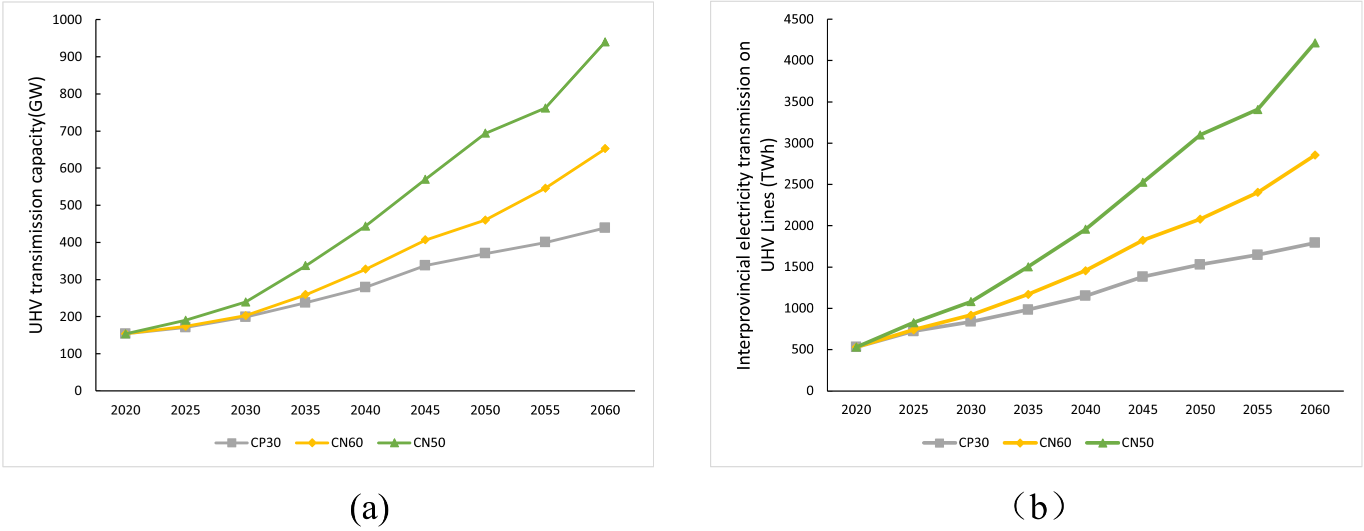
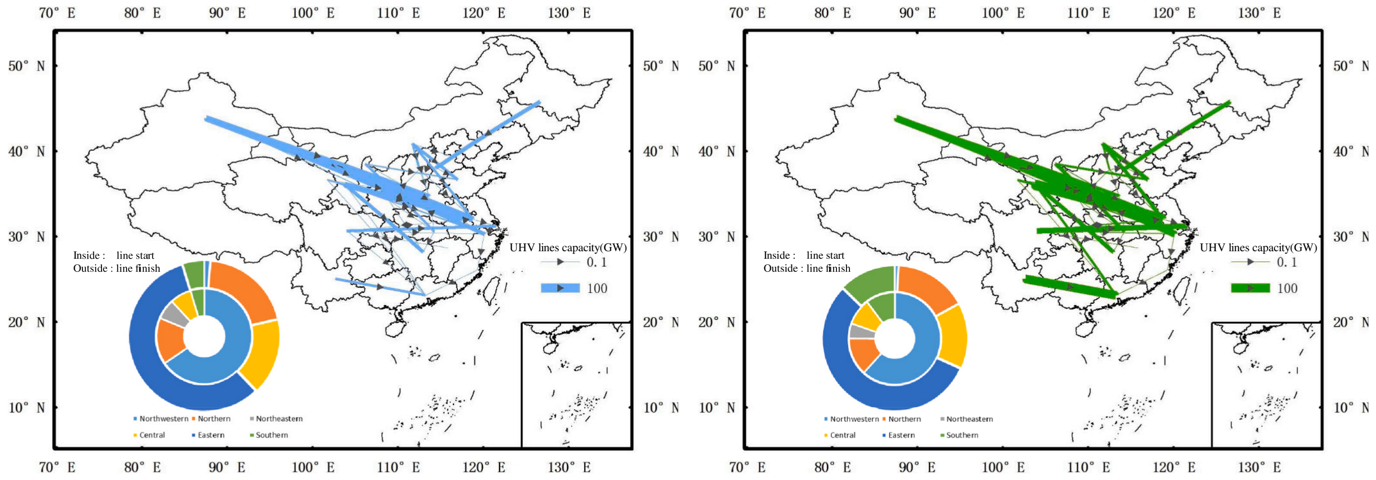


Fig. 14. (a) The capacity of interprovincial UHV lines under different scenarios; (b) Interprovincial electricity transmission on UHV lines under different scenarios.



(a)

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Fig. 15. (a) Interprovincial UHV lines under CN60 scenario; (b) Interprovincial UHV lines under CN50 scenario.

The reduction in carbon intensity is expected to accelerate during the ‘14th Five-Year Plan’ and ‘15th Five-Year Plan’ periods compared to the ‘13th Five-Year Plan.’ Developed provinces like Beijing and Shanghai are anticipated to peak their carbon emissions before 2025, while most other provinces will peak between 2025 and 2030. By 2060, carbon intensity across provinces is projected to decrease by an average of 81% compared to 2020 levels. Provinces such as Shandong, Henan, and Sichuan are expected to achieve carbon neutrality earlier, contributing to negative emissions by 2060.

The transition will involve substantial increases in electricity capacity, predominantly from wind and solar power, which are expected to account for over 86% of total electricity capacity. This shift will necessitate extensive deployment of energy storage solutions to ensure a stable and secure supply of renewable energy. Interprovincial power transmission, especially through ultra-high voltage (UHV) lines, will be critical in balancing regional energy supply and demand. By 2060, key transmission routes will include flows from the Northwest to the Yangtze River Delta and central provinces, from Inner Mongolia to Shandong and the Beijing-Tianjin-Hebei regions, and from Sichuan to the eastern coastal provinces.

These findings underscore the importance of coordinated policy efforts and technological advancements to support the energy transition towards a carbon-neutral future.

6. Discussion

6.1. Policy implications

In the past two years, China's total energy consumption and emissions have continued to increase, with energy intensity in 2022 remaining relatively stable compared to 2021. The growth of emissions before the carbon peak will pose more significant challenges for provinces in reducing emissions between 2030 and 2060. China's carbon emission need to peak before 2030 to reduce the pressure of emissions reduction from 2030 to 2060. While ensuring high-quality green economic development, efforts should be made to control carbon emissions before reaching a carbon peak and reduce the pressure of emissions reduction from peak to carbon neutrality.

In the “13th Five-Year Plan” period, western provinces with abundant renewable resources have exceeded their emission reduction targets. In the “14th Five-Year Plan” period, it would be advisable to strengthen the carbon intensity reduction goals for the western provinces with abundant renewable. Lower carbon intensity reduction goals would drive the green transformation of production and consumption patterns, facilitate renewable energy development, and promote high-quality development in these provinces. At the same time, policies such as carbon markets could be employed to provide financial or technological support to underdeveloped provinces, which would facilitate balanced development among provinces.

As the power system undergoes deep decarbonization, large-scale renewable energy bases need to be constructed in the Northwest, Northeast, and Southwest regions in the future. The substantial interprovincial power transmission requirements necessitate coordinated planning of renewable energy generation, power transmission, and energy storage. To achieve carbon neutrality, the implementation of an extensive network of ultra-high-voltage (UHV) transmission lines is imperative for the transmission of renewable electricity. The current policies that promote UHV lines need to be maintained until 2060 under the carbon neutrality targets.

6.2. Future work

This study aims to simulate greenhouse gas neutrality scenarios by referencing existing research to reduce national carbon emissions and advance the carbon neutrality timeline. In the future, a non-CO2 greenhouse gas emission module could be incorporated into the model to simulate the scenario of achieving greenhouse gas neutrality in China by 2060. As the electrification rate continues to rise in the future, the shape of the load curve may change, and demand-side response will also impact these variations. Future studies should consider how demand-side responses influence changes in electricity demand across different end-use sectors to better account for load variations. Additionally, uncertainties exist in wind and solar power generation. In future research, we aim to utilize the Monte Carlo method to simulate different wind and solar power output curves, enabling an analysis of how large-scale renewable energy influences energy supply stability.

CRediT authorship contribution statement

Qiang Zhang: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shu Zhang:** Writing – review & editing. **Wenying Chen:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Appendix

Table A
Technology investment cost projections in the China-TIMES-30PE model. [5,56,59].

Investment cost (USD/kW)		2020	2025	2030	2035	2040	2045	2050	2055	2060
Thermal power without CCS	Biomass & coal co-combustion	716	698	681	664	664	664	664	664	664
	Ultra-supercritical coal-fired power	550	547	545	542	540	538	535	533	531
	IGCC coal-fired power	1454	1324	1206	1098	1000	911	829	747	665
	Nature gas steam turbine power	550	550	550	550	550	550	550	550	550
Thermal power with CCS	Biomass & coal co-combustion retrofit	1021	947	878	835	794	774	755	736	717
	Biomass combustion	2128	1916	1726	1554	1400	1261	1136	1011	886
	Ultra-supercritical coal-fired power	1062	1031	1000	970	941	913	886	854	825
	IGCC coal-fired power	2107	1868	1655	1467	1300	1152	1021	890	759
	NGCC gas-fired power	921	912	904	897	897	897	897	897	897
Nuclear	Nuclear power	1995	1946	1897	1850	1805	1805	1805	1805	1805
Renewables	PV solar power	754	637	538	454	383	324	324	324	324
	Offshore wind power	1980	1859	1746	1640	1540	1446	1358	1270	1182
	Onshore wind power	1095	1056	1019	983	948	915	882	850	840
	Small hydro power	1312	1312	1312	1312	1312	1312	1312	1312	1312
	Large hydro power	1066	1066	1066	1066	1066	1066	1066	1066	1066
Energy storage	Battery energy storage	5235	4352	2712	2271	1892	1577	1293	1162	987
	Pumped hydro storage	885	821	762	742	723	704	686	668	650
Hydrogen	Water electrolysis	1138	837	691	539	420	327	255	204	167

Notes: CCS = carbon capture and storage; IGCC = integrated gasification combined cycle; NGCC = natural gas combined cycle; PV = photovoltaic.

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