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Energy demand and supply planning of China through 2060

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ABSTRACT

At the General Debate of the 75th session of the United Nations General Assembly, a new objective that China will stop adding to the global warming problem by 2060 was proposed. However, the energy demand of China is increasing with the fast-growing economy and China relies heavily for its electricity on coal, which will make it difficult to achieve carbon neutrality. Therefore, the energy demand and supply planning in the future for China should be optimized. In this work, the Long-range Energy Alternatives Planning System was used to forecast the end-use energy demand of China. A new mixed-integer linear programming model was developed to optimize the energy structure, infrastructure projects and exploitation schemes under the constraint of greenhouse gas emissions. Furthermore, an economic, feasible and sustainable energy planning was also obtained. Results show that the electrification rate, green hydrogen demand and other energy demand of China will increase substantially. The coal production capacity will be concentrated, the integration of oil production and refining will be gradually realized, and the production of non-fossil power will increase considerably. The total greenhouse gas emissions of the energy consumption in China between 2017 and 2060 will be approximately 262,783 million tons of CO_2 equivalents.

1. Introduction

In response to the global warming crisis, a consensus has been that reducing greenhouse gas emissions is the best method to alleviate the human climate crisis. In accordance with the Kyoto Protocol and the Copenhagen Climate Conference, all countries should take action to limit greenhouse gas emissions. Among them, China promised to reduce carbon emissions per unit of GDP by 40%–45% in 2020 compared with those in 2005 at the Copenhagen Climate Conference in 2009. In September 2020, with the intensification of the greenhouse effect, China proposed that “We aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060”.

At present, China has not defined “carbon neutrality” in detail. As the greenhouse gas emissions from non-energy sector are difficult to reduce and the contribution of carbon sink and carbon capture and storage (CCS) is also uncertain, the energy consumption should achieve zero carbon emission in 2060 due to the emission reduction measures of energy sector are relatively clear.

However, it is difficult for China to achieve zero carbon emission in the energy sector. On the one hand, as a rapidly developing country with a vast territory and a large population, the energy demand of China is increasing yearly [1]. On the other hand, the proportion of fossil energy in the primary energy of China is relatively high due to the resource condition and production mode, which is one of the important sources of greenhouse gas emissions. Related literature has shown that coal accounted for 58% of the total energy consumption in 2018 [2], while oil and gas accounted for 28%. On the basis of the characteristics of various energy and the current situation of China, it is necessary to explore an economic, sustainable and feasible energy planning scheme for carbon neutrality.

Several studies have been performed on the research of energy planning for China. Table 1 presents the contribution of these research. Some of the studies simulated the energy demand and carbon emissions under different scenarios on the basis of social, economic, population, technology and other parameters [3–9]. For example, Shan B et al. applied the LEAP model to project primary energy, electrification level and final energy demand of China in 2030 under different scenarios [3–6]. Wang Y et al. provided insights into the latest development of energy production, energy consumption and energy strategic planning and policies in China

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Table 1
Relevant research review.

Authors	Year	Approach	Research objects				Projected variables			Optimization variables					Contributions
			Multi-region for China	Multi-energy	100% non-fossil energy	Multi-sector	Final energy demand	Primary energy demand	Carbon emissions	Final energy structure	Power structure	Primary energy structure	Dispatch scheme	Infrastructure program	
Shan B [3–5]	2012	LEAP		✓		✓	✓	✓	✓						Comparative analysis of energy demand and carbon emissions under three economic growth scenarios
Li N [8]	2020	China TIMES-30P		✓		✓	✓	✓	✓						Discuss carbon emissions from a bottom-up perspective
Teske S [9]	2018	Mesap/PlaNet	✓			✓	✓	✓	✓						Compare deep-decarbonization scenarios reveals large differences in final energy demand projections
Li N [10]	2018	China TIMES-30P	✓			✓		✓					✓	✓	Provide a new method to analyze interprovincial coal transportation and the corresponding emissions
Zhang Q [11]	2020	China TIMES-30PE	✓			✓	✓						✓	✓	Develop a new version of the China TIMES-30P with multi-voltage level electricity transmission model
Jie D [12]	2021	MESSAGEix		✓			✓	✓	✓		✓		✓	✓	Build an integrated assessment of China's coal industry towards 2050
Pan X [13]	2020	GCAM		✓		✓				✓		✓			Analyze China's oil and gas consumption using an integrated modeling
Chen J [15]	2017	China's energy supply-and-demand model		✓		✓	✓				✓	✓			Optimize the power structure and primary energy structure
Li T [19]	2020	CRESOM	✓	✓		✓	✓	✓			✓	✓	✓	✓	Develop a mathematical modeling framework describing a national scale low carbon transition and optimizing energy system deployment
Jacobson M Z [21,22]	2018	LOADMATCH, GATOR-GCMOM			✓	✓				✓	✓	✓		✓	Model supplying all-sector load with 100% wind-water-solar
Breyer C [23–25]	2021	LUT model	✓		✓	✓				✓	✓	✓		✓	Enable a more decentralized, cost-driven energy transition optimization across 145 sub-regions of the world
This work	2021	The mixed-integer linear programming model	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	Explore an economic, sustainable and feasible energy planning scheme for carbon neutrality

using the LEAP model [7]. The China TIMES-30P model developed by Li N et al. with detailed characterization of China's provincial energy system also has been used for low carbon scenarios analysis [8]. Teske S et al. compared deep-decarbonization scenarios to reveal large differences in final energy demand projections [9]. However, these simulations mainly used to compare the energy demand and greenhouse gas emissions under different scenarios to analyze the effect of policies.

Besides, there are also a lot of studies that focus on the optimization of energy planning [10–27]. On the basis of the China TIMES-30P model, coal transportation and emissions are explored under the NDC and 2° targets by Li N et al. [10]. Meanwhile, Zhang Q et al. developed an interprovincial electricity transmission model to simulate the reference scenario and three low carbon scenarios from a whole energy system perspective [11]. Jie D et al. established a multi-regional coal supply model with four types of raw coal, which was used to optimize China's coal supply system [12]. Based on the Global Change Assessment Model (GCAM), Pan X et al. analyzed the China's oil and gas consumption under five representative scenarios toward 2050 [13]. However, the above optimization studies focused on one type of energy [10–14]. For all types of energy [15–27], Chen J et al. developed China's energy supply-and-demand model and analyzed China's energy supply and demand under two scenarios [15]. Liu G et al. proposed a linked MARKAL-CGE-EIA model system to conduct the energy supply chain projective analysis and security evaluation [16]. Pan X explored how China's transportation might be decarbonized and transformed in long-term to keep in step with national decarbonization scenarios [17]. Pietzcker RC et al. projected the final energy demand and CO_2 emissions of transport for China, USA and the world until 2100 by 5 energy-economy-models [18]. Li T et al. developed a bottom-up mathematical modeling and optimization framework addressing a national scale energy planning and low carbon transition [19]. Considering the objective of carbon neutrality, in order to reach full sustainability, research in design of 100% non-fossil energy should be conducted [20–27]. On the basis of LOADMATCH grid integration model and global weather-climate-air-pollution Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale and Ocean Model (GATOR-GCMOM), Jacobson M Z et al. modeled supplying all-sector load with 100% wind-water-solar in 20 world regions under three scenarios to explore whether low-cost mixes using 100% WWS can match energy demand with intermittent supply [21]. According to the LUT Energy System Transition model, Breyer C et al. provided an energy transition pathway that could lead from the current fossil-based system to an affordable, efficient, sustainable and secure energy future for the world [23]. Most of these research focused on the power sector and performed hourly energy modelling as a core methodology in the light of large-scale integration of variable renewable resources such as supplied by wind and PV generation. Nevertheless, the detailed supply planning of fossil energy were not considered in these research. The proportion of fossil energy in total energy demand of China will still be high in several decades, which needs to be considered in detail for a comprehensive optimization. Hence, it is necessary to conduct a multi-regional optimization planning for all type of energy to achieve zero carbon emission in energy consumption in 2060 for China.

In this work, the LEAP model was selected to forecast the energy demand. A new multi-regional and multi-energy supply model was developed to optimize the energy supply planning, which considered all types of energy infrastructure in detail. In this model, coal, crude oil, refined oil, six types of power, green hydrogen, heat pump and solar thermal heating were all involved, and the processes of energy production, import, transformation, transportation and storage were considered. Furthermore, from the demand side, combined with the development of society, economy and technology, the total end-use energy demand of different regions was calculated using the LEAP model. From the supply side, the energy structure, exploration schemes and infrastructure planning were optimized by the new energy supply model under the constraints of greenhouse gas emissions. Finally, an economic, feasible and sustainable energy supply scheme for carbon neutrality was obtained.

2. End-use energy demand forecast

In this work, the total end-use energy demand of different regions in China was forecasted using the LEAP model to meet the needs of the economy and society development. The results were related to the summation of all types of energy, rather than a specific type of energy.

2.1. Structure of the LEAP model

In accordance with the energy consumption characteristics and statistical data of China, the end-use energy demand of each region was divided into eight sectors: agriculture, industry, construction, transportation, commerce, urban residents' life, rural residents' life and others. The base year was set to be the year of 2017. The chosen period was from 2017 to 2060. The geographical areas studied included 30 provincial regions (except Hong Kong, Macao, Taiwan and Tibet) of China.

The end-use energy demand of each sector can be calculated using activity level and energy intensity, as shown in the following formula:

$$TED_{i,j} = \sum_{k=1}^{8} \left(EIN_{i,j,k} \times AC_{i,j,k} \right) \quad (1)$$

where subscript i, j and k represent the specific year, region and end-use sector, respectively. TED is the amount of end-use energy demand, AC is the activity level, and EIN is the energy intensity.

Fig. 1 shows the structure of the LEAP model used in this work. The activity levels of industry and life were set as industry value-added and population, respectively. Therefore, the population, urban rate, GDP, industrial structure and energy intensities of each region should be projected firstly to forecast the end-use energy demand.

2.2. Socioeconomic and technical parameters

For population, "The National Population Development Plan (2016–2030)" [28] indicated that the population of China will peak around 2030 and then continue to decline due to the aging population. The plan estimated that the population and urbanization rate of China will reach 1420 million and 60%, respectively, in 2020, and 1450 million and 70%, respectively, in 2030. The population of each region was forecasted in accordance with this plan and related policies, such as "The Belt and Road Initiative" (shown in Fig. 2). The urbanization rate of each region will overall show an upward trend. The urbanization rate in the northeast, central and southeast

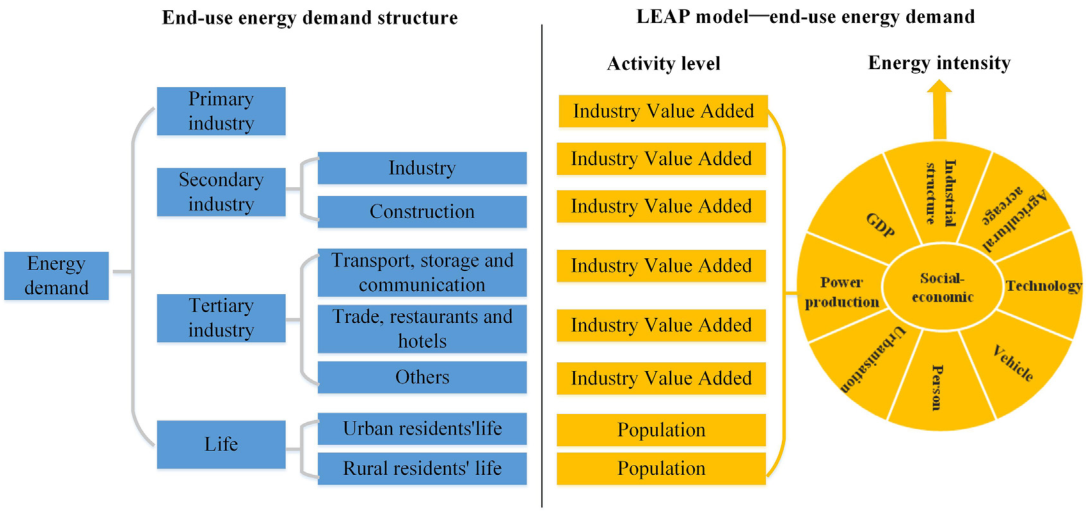


Fig. 1. The structure of the LEAP model.

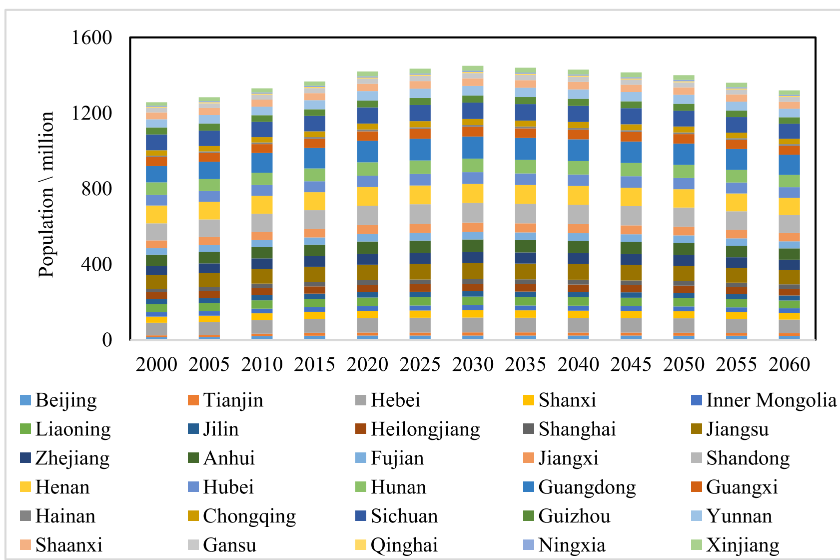


Fig. 2. Population forecast results of each region in China.

coastal areas will increase remarkably. However, the increase of urbanization rate in economically developed areas, such as Beijing, Tianjin and Shanghai, will be small in the future.

From the perspective of GDP, the research results of the Chinese Academy of Social Sciences and the State Council [29] indicated that the average GDP growth rate will be approximately 6.5% from 2016 to 2020, 5.5% from 2020 to 2030, 4.5% from 2030 to 2040 and 3.4% from 2040 to 2050. On this basis, the per capita GDP of various regions in China was projected. It is forecasted that the real GDP of China will reach 96,714 billion Yuan (based on 1978) in 2060.

In terms of industrial structure, the proportion of the industry sector in total GDP will keep decreasing from 2017 to 2060. According to the strategic goal, China will reach the standard of medium-developed countries in 2050. It was estimated that the proportion of the industry sector in total GDP will decrease to 20% in 2060. Meanwhile, the proportion of the tertiary industry will increase to 77%.

In the process of energy intensity projection, the current status of technological development, the historical development trend and the development law of other countries were all considered [30]. Firstly, it can be found that the development trend of energy intensity is basically the same, which will decrease with the increase in per capita GDP [31,32]. In the industry sector, according to the investigation of the energy intensity of industrial products at home and abroad [33], the energy efficiency was projected. Besides, the logistic model [34] was used to project the energy intensity of the transportation sector in each region, and the ARIMA [35] model was used to project the energy intensity of other end-use sectors. In these models, the time was set as the independent variable and energy intensity was set as the dependent variable. On the basis of

Table 2
Comparison of projected and actual value.

Region		China				Shaanxi			
Parameters		Population	Urbanization rate	GDP	Proportion of industrial GDP	Population	Urbanization rate	GDP	Proportion of industrial GDP
Unit		Million person	%	Billion yuan	%	Million person	%	Billion yuan	%
2018	Projected value	1393.1	59.3	91322.9	32.7	38.64	57.8	2443.8	39.6
	Actual value	1395.4	59.6	91928.1	32.8	38.64	58.1	2394.2	40.2
	Relative difference	0.16%	0.50%	0.66%	0.30%	0%	0.52%	2.07%	1.49%
2019	Projected value	1412.4	59.8	95625.6	32.4	39.11	58.9	2554.0	39.5
	Actual value	1400.1	60.6	99086.5	32.0	38.76	59.4	2579.3	39.3
	Relative difference	0.88%	1.32%	3.49%	1.25%	0.90%	0.84%	0.98%	0.51%

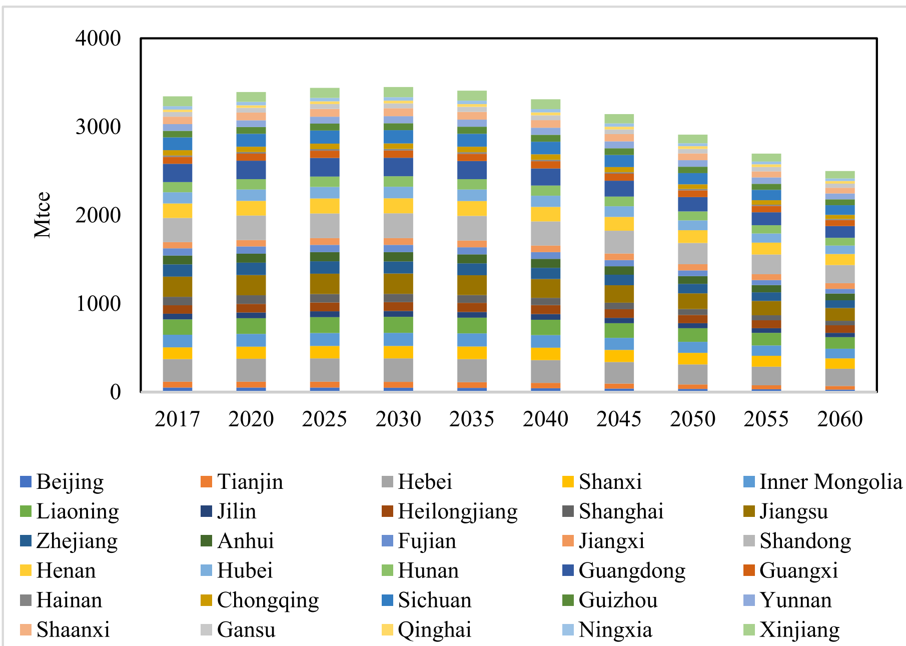


Fig. 3. The end-use energy demand of each province from 2017 to 2060.

the historical data of 2000–2017 in the statistical yearbook, the parameters of all models can be calculated by SPSS software.

The year 2017 was selected as the base year in this work, given that the energy statistics have been updated to 2017 only. Data of population, urbanization rate, GDP and industrial structure in 2018 and 2019 can be used for verification. The relative difference, which is the ratio of the difference between the actual value and projected value and actual value, can be used to measure the forecast accuracy. As shown in Table 2, the relative differences between the projected and actual value of most parameters are within 2%.

2.3. End-use energy demand of each region

The results of the end-use energy demand of each province through 2060 can be obtained as shown in Fig. 3. With the improvement in energy efficiency, the total end-use energy demand of China will firstly increase and then decrease in the future, reaching a peak at around 2030 with 3449 million tons of coal equivalents (Mtce). The total end-use energy demand will reach 2498 Mtce in 2060.

3. Development of an energy supply model

On the basis of the forecasting results of total end-use energy demand, a new mixed-integer linear programming model was developed for China to optimize the energy structure, infrastructure construction plans and energy production schemes. Fig. 4 shows the structure of the energy supply optimization model. In this model, all the processes of the energy supply system, including the production, importation, transportation, storage and transformation were considered. The capital and variable costs of the infrastructures were also included. Besides, considering the uncertainty of carbon capture and storage, and the other carbon emission from the non-energy sector, blue hydrogen and grey hydrogen were not included in this work, but green hydrogen. In addition, heat pumps and solar thermal heating were put into others for calculation.

3.1. Input parameters

In this model, the input parameters are shown as the following:

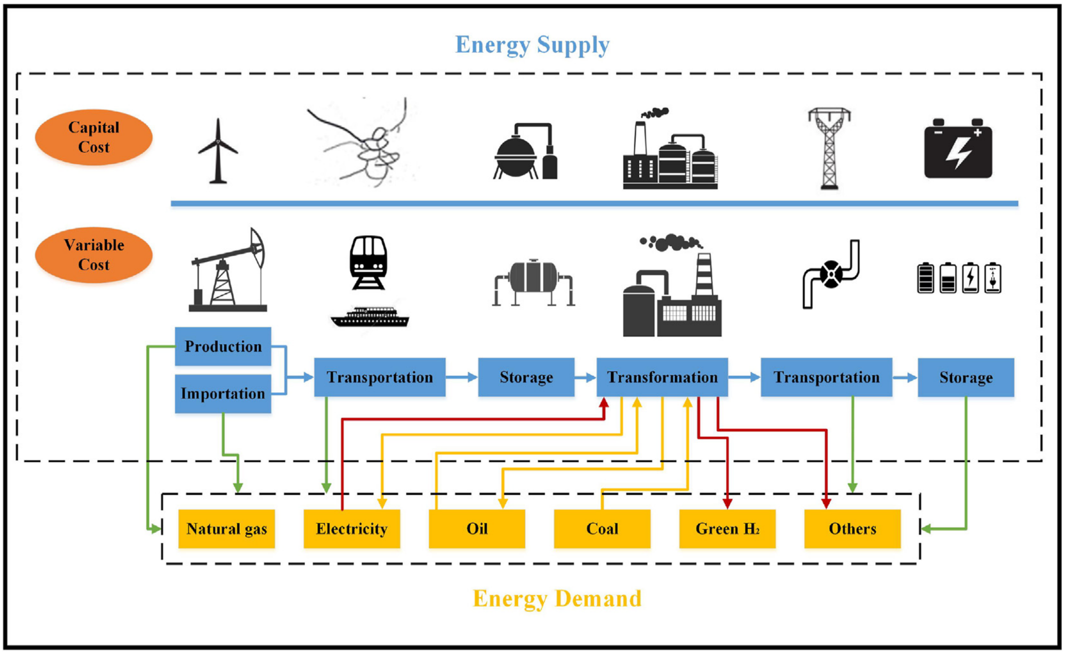


Fig. 4. Energy supply optimization model.

① Geographical situation of the 30 regions in China, including the adjacent regions information and the distance matrices by land and sea.
② The forecast results of the total end-use energy demand and the power demand of each hour in a typical day [36].
③ Energy conditions, including the reserves of different types of fossil energy in the base year, the available hours of wind power, solar power and hydropower, and the wind energy and solar energy of each hour in the typical day in all regions.
④ Infrastructure condition in the base year, which contains existing energy production capacity, pipeline, power grids, battery and LNG terminal condition of each region.
⑤ The capital costs, operating costs and life of all types of infrastructures mentioned above at present and future.

In this work, the distance matrices by land and sea for all regions can be obtained on the basis of geographic information. For the end-use energy demand, the results were calculated in Section 2. Other input parameters were discussed in detail below.

3.1.1. Resource condition

Fig. 5 shows the details of the distribution of energy reserves in China. For coal resources, the remaining technically recoverable reserves in China were approximately 1666.7 billion tons in 2017 [37]. For crude oil, the remaining technically recoverable reserves in China were approximately 3.54 billion tons at the end of 2017 [38]. Most of them are distributed in eight basins of China, which account for approximately 80% of the total. For natural gas, the remaining technically recoverable reserves were 5.52 trillion cubic

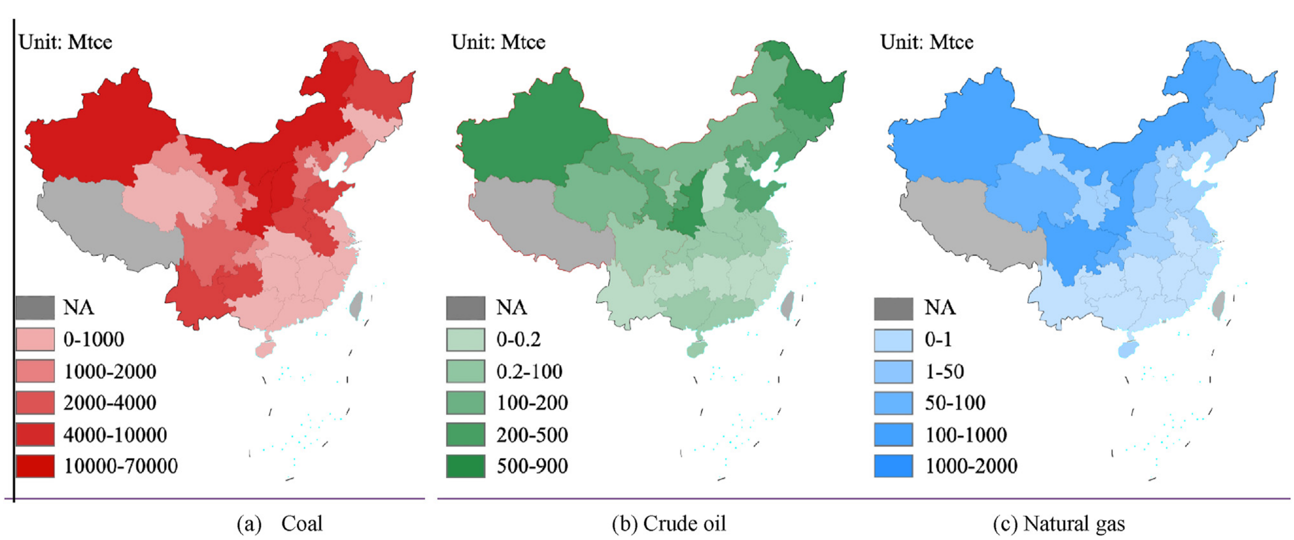


Fig. 5. Distribution of energy reserves.

Table 3
Details of energy transportation projects [39–41].

Energy type	Projects	Origin	Destination	Length	Capacity
Refined oil	Lan–Cheng–Yu pipeline	Lanzhou	Chongqing	1251/km	7/(million tons/year)
	Jinzhou–Zhengzhou pipeline	Jinzhou	Zhengzhou	1285/km	10/(million tons/year)
	Lan–Zheng–Chang pipeline	Lanzhou	Changsha	2148/km	15/(million tons/year)
Crude oil	Wu–Lan pipeline	Urumqi	Lanzhou	1800/km	20/(million tons/year)
	Ruili–Chongqing pipeline	Ruili	Chongqing	1631/km	22/(million tons/year)
	Qing–Fu pipeline	Daqing	Fushun	596/km	20/(million tons/year)
Natural gas	West–east gas pipeline I	Lunnan	Shanghai	3836/km	17/(billion cubic meters/year)
	West–east gas pipeline II	Huoerguos	Guangzhou	9242/km	30/(billion cubic meters/year)
	Shaanxi–Beijing gas pipeline IV	Jingbian	Beijing	1066/km	30/(billion cubic meters/year)
Electricity	Haminan–Zhengzhou line	Hami	Zhengzhou	2210/km	16/GW
	Jindongnan–Nanyang–Jinmen line	Changzhi	Jinmen	640/km	24/GW
	Huainan–Zhebei–Shanghai line	Huainan	Shanghai	649/km	21/GW

Table 4
Details of energy import paths in 2017 [39].

Import path	Oil		Natural gas	
	Destination	Annual capacity	Destination	Annual capacity
Sino-Kazakhstan pipeline	Xinjiang	20 million tons	Xinjiang	85 billion cubic meters
Sino-Russian pipeline	Heilongjiang	30 million tons	Heilongjiang	38 billion cubic meters
Sino-Burmese pipeline	Yunnan	22 million tons	Yunnan	12 billion cubic meters
Sea passage	Southeast coastal cities	600 million tons	Southeast coastal cities	56.4 million tons of LNG

meters [38].

3.1.2. Infrastructure condition in the base year

The infrastructure considered in this model includes the energy production, transportation, import and transformation infrastructure. For the energy production infrastructure, the total production capacities of coal, crude oil and natural gas in China were 2382, 434 and 211 Mtce, respectively, in 2017.

For the energy transportation infrastructure, many long-distance oil and gas pipelines and ultra high voltage (UHV) lines have been established in China. These projects enable the transfer of energy from the production place to the consumption place. The main typical projects were listed in Table 3.

For the energy import infrastructure, the external dependence of oil and natural gas is relatively high. Both of them are imported through four major paths. The details of these paths were shown in Table 4.

In terms of the energy transformation infrastructure, the total power generation capacity of China in 2017 was 1777 GW, including 344 GW of hydropower, 36 GW of nuclear power, 163 GW of wind power, 129 GW of solar power, and 1105 GW of thermal power [42]. The total refining capacity of China was 757 Mtce in 2017.

3.1.3. Capital and operating costs of infrastructure

The diversity of the energy resource condition of each region in China directly leads to the difference in energy exploitation costs. For example, in such provinces as Shaanxi and Xinjiang, which have rich coal resources, the mining costs are low due to the excellent mining conditions. Contrarily, for the provinces in eastern China, the mining costs are relatively high. In this work, the capital and operating costs of coal, oil, gas, power, green hydrogen and others in production, transportation and storage processes in different regions were investigated. The current costs of these energy infrastructures were shown in Table 5. For wind power, solar PV power and battery, with the development of related technologies, the costs may fluctuate considerably in the future. The forecast data were shown in Table 6.

3.2. Optimization variables and objectives

The optimization variables of this model include design and operation variables. The design variables are the construction plan of energy infrastructure. The operation variables refer to the energy structure and the quantities of energy production, transportation, import, transformation and storage. For the design variables of large projects, such as power grid, gas pipeline, oil pipeline and LNG terminals, the minimum count unit should be limited. Accordingly, integer variables were used to realize the constraint.

The optimization objective of this work is to minimize the total costs of energy supply, including coal, oil, natural gas, power, green hydrogen and others.

$$T = T_{coa} + T_{oil} + T_{gas} + T_{ele} + T_{gre} + T_{oth} \tag{2}$$

where T is the total cost of energy supply for all regions from 2017 to 2060. T_{coa}, T_{oil}, T_{gas}, T_{ele}, T_{gre} and T_{oth} are the costs for coal, oil, natural gas, green hydrogen and other energy supply, which can be calculated as below.

$$T_{coa} = C_{cp} + O_{cp} + T_{cs} + T_{ct} + I_{cs} + I_{ct} \tag{3}$$

$$\begin{aligned} T_{oil} = {} & C_{op} + C_{rp} + C_{oip} + C_{rip} + C_{otp} + C_{rtp} + O_{op} + O_{rp} \\ & + O_{oip} + O_{rip} + O_{otp} + O_{rtp} \\ & + T_{os} + T_{rs} + T_{ot} + T_{rt} + I_{os} \\ & + I_{rs} + I_{op} + I_{rp} \end{aligned} \tag{4}$$

$$\begin{aligned} T_{gas} = {} & C_{gp} + C_{gjp} + C_{gjl} + C_{gtp} + C_{gs} + O_{gp} + O_{gip} + O_{gil} + O_{gtp} \\ & + O_{gs} + I_{gp} + I_{gl} \end{aligned} \tag{5}$$

$$T_{ele} = C_{ep} + C_{es} + C_{et} + O_{ep} + O_{es} + O_{et} \tag{6}$$

$$T_{gre} = C_{hpr} + C_{hpe} + C_{htp} + O_{hp} + O_{htp} + T_{htt} + T_{hts} \tag{7}$$

Table 5
Construction and operating costs of energy infrastructure ($).

Item	Capital cost	Fixed operating cost	Variable operating cost	Life/year
Coal-fired power	450/kW	8/(kW·year)	1.68/(MW·h)	30
Gas combined cycle power plant [43]	999/kW	11.33/(kW·year)	3.61/(MW·h)	30
Conventional hydropower [43]	2948/kW	40.85/(kW·year)	1.36/(MW·h)	100
Advance nuclear power [43]	6034/kW	103.31/(kW·year)	2.37/(MW·h)	35
Wind power [43]	1250/kW	48.42/(kW·year)	0/(MW·h)	30
Solar PV power [43]	1900/kW	22.46/(kW·year)	0/(MW·h)	25
Battery [43]	1950/kW	36.32/(kW·year)	7.26/(MW·h)	6
Electricity transmission	2000/MW·km	–	–	35
Coal mining	45/t-90/t	44.62333/t - 70/t		50
Coal transportation by ship	–	–	0.00857/(t·km)	–
Coal transportation by train	–	–	0.00714/(t·km)	–
Oil exploitation	145.255/t - 300/t	72.993/t - 150/t		40
Oil refinery [44]	243/t	11/(t·year)	12.25/t	30
Oil transportation by ship	–	–	0.01286/(t·km)	–
Oil transportation by train	–	–	0.04286/(t·km)	–
Oil pipeline [45]	(102,425.2/bt+754754.5)/km	(4877.4/bt+26786.8)/km		35
Natural gas exploitation	2.056/m^3 - 5/m^3	0.06795/m^3 - 0.1/m^3		10
Gas storage	0.4238/m^3	0.1059/(m^3·year)	0.0001035/m^3	50
LNG terminal	187/t	3.65/(t·year)	48.76/bcm	20
Gas pipeline [45]	(92,182.7/bcm+754754.5)/km	(4389.7/bcm+26786.8)/km		35
Electrolyzer	800/kW	10/(kW·year)	–	10
H_2 transportation by ship	–	–		–
H_2 transportation by train	–	–	3.5/(t·km)	–
H_2 pipeline	(230457/bcm+1886886)/km	(4389.7/bcm+26786.8)/km		35
Others	6071/tce	1/(tce·year)	–	20

Table 6
Construction and operating costs of energy infrastructure in 2060 ($).

	Capital cost	Fixed operating cost	Variable operating cost
Wind power [46]	668/kW	46.74/(kW·year)	0/(MW·h)
Solar PV power [46]	542/kW	21.05/(kW·year)	0/(MW·h)
Battery [47]	487/kW	34.21/(kW·year)	6.95/(MW·h)

$$T_{oth} = C_{rp} + O_{rp} \tag{8}$$

where C_{cp} and O_{cp} are the capital and operating costs of coal production, respectively. T_{cs} and I_{cs} are the transportation and import costs of coal by ship, respectively. T_{ct} and I_{ct} are the transportation and import costs of coal by train, respectively. C_{op}, C_{oip}, C_{otp} and C_{rp}, C_{rip}, C_{rtp} are the capital costs of production equipment, import pipelines and transportation pipelines for crude oil and refined oil, respectively. O_{op}, O_{oip}, O_{otp} and O_{rp}, O_{rip}, O_{rtp} are the operating costs generated from the processes of production, import by pipeline and transportation by pipeline for crude and refined oil, respectively. T_{os}, T_{rs} and T_{ot}, T_{rt} are the transportation costs of crude oil and refined oil by ship and train, respectively. I_{os}, I_{rs} and I_{op}, I_{rp} are the import costs of crude oil and refined oil by ship and pipeline, respectively. C_{gp}, C_{gip}, C_{gtp}, C_{gs} and C_{gil} are the capital costs of natural gas production equipment, import pipelines, transportation pipelines, storage facilities and LNG terminals, respectively. O_{gp}, O_{gtp}, O_{gtp}, O_{gs} and O_{gil} are the operating costs generated from the processes of natural gas production, import by pipeline, transportation by pipeline, storage and receiving LNG. C_{ep} is the total capital costs of power generation equipment for coal, gas, hydro, nuclear, wind and solar power generation. C_{es} and C_{et} are the capital costs of electricity storage facilities and UHV lines. O_{ep}, O_{es} and O_{et} are the operating costs generated from the processes of power generation, storage and transportation. C_{hpr}, C_{hpe} and C_{htp} are the capital costs of renewable power production equipment, electrolyzer and pipeline. O_{hp} and O_{htp} are the operating costs generated from the processes of green hydrogen generation and transportation by pipeline. T_{htt} and T_{hts} are the transportation costs by ship and train. C_{rp} and O_{rp} are the capital costs and operation costs of other energy production.

The capital, operating, transportation and import costs mentioned in the above equations can be further calculated using unit price and activity level. For example,

$$C_{gtp} = \sum_{i=2017}^{2060} \sum_{j=1}^{30} \sum_{e=1}^{30} \left(GTPZP_{i,j,e} \times LP \times a \right) \tag{9}$$

$$O_{gtp} = \left(\sum_{i=2017}^{2060} \sum_{j=1}^{30} \sum_{e=1}^{30} (GTP_{i,j,e} \times GTPP_i \times L_{j,e}) \right) \Big/ 2 \tag{10}$$

$$I_{gl} = \sum_{i=2017}^{2060} \sum_{j=1}^{30} (GL_{i,j} \times GLP_i) \tag{11}$$

where subscript e represents a specific region, $GTPZP$ is the unit capital cost of natural gas pipeline, LP is the minimum unit of pipeline capacity, a is an integer variable, GTP is the amount of natural gas transported between j and e regions by pipeline, $GTPP$ is the unit operating cost of natural gas transportation by pipeline, L is the distance between j region and e region, GL is the amount of natural gas imported by LNG terminal (this value was set to zero when j region is an inland region), and GLP is the unit import cost of natural gas. A special case is the power storage system, as the battery cost accounts for approximately 67% of the total cost of power storage [48], the total cost of power storage was estimated on the basis of the battery cost.

3.3. Constraints

Constraints in this work are summarized as follows:

① The total end-use energy demand is equal to the sum of all types of energy demand.

$$TED_{i,j} = \sum_{p} TPD_{i,j,p} + \sum_{s} TSD_{i,j,s} \tag{12}$$

where subscripts p and s represent a specific type of primary and secondary energy, respectively. TPD and TSP are the end-use demand for a specific type of primary and secondary energy, respectively.

② All types of secondary energy need to be converted into primary energy to calculate the total primary energy demand [49].

$$TTPD_{i,j,p,m} = TSD_{i,j,s,m} \Big/ \eta_{i,j,s,m} \tag{13}$$

$$TTPD_{i,j,p} = \sum_{m} TTPD_{i,j,p,m} \tag{14}$$

$$TSD_{i,j,s} = \sum_{m} TSD_{i,j,s,m} \tag{15}$$

$$EPD_{i,j,p} = TTPD_{i,j,p} + TPD_{i,j,p} \tag{16}$$

$$ESD_{i,j,s} = TSD_{i,j,s} \tag{17}$$

where subscript m represents a specific energy conversion process, $TTPD$ is a specific type of primary energy demand in the energy conversion process, η is the conversion efficiency, EPD and ESD are the sum of a specific type of primary and secondary energy demand, respectively. It is worth noting that with the development of technology, the efficiency of energy conversion in each region will increase yearly. According to the "National energy saving and low carbon technology promotion catalog" [50] and "The guidance catalog for industrial structure adjustment" [51], which were issued by the state development and reform commission to guide the development of the energy conversion industry, the efficiency of energy conversion in the future was estimated (as shown in supplementary data).

③ The energy supply and consumption in each region should be balanced:

$$EPI_{i,j,p} + EPP_{i,j,p} + EPTI_{i,j,p} = EPTO_{i,j,p} + EPD_{i,j,p} \tag{18}$$

$$ESI_{i,j,s} + ESP_{i,j,s} + ESTI_{i,j,s} = ESTO_{i,j,s} + ESD_{i,j,s} \tag{19}$$

where EPI and ESI are the import amounts of a specific type of primary and secondary energy, respectively. EPP and ESP are the production amounts of a specific type of primary and secondary energy, respectively. $EPTI$ and $ESTI$ are the amounts of a specific type of primary and secondary energy transferred from other regions to j region, respectively. $EPTO$ and $ESTO$ are the amounts of a specific type of primary and secondary energy transferred from j region to other regions, respectively.

④ The energy production is constrained by energy reserves. The power generation from renewable energy is constrained by the available hours of renewable power.

$$\sum_{i=2017}^{2060} EPP_{i,j,p} \leq EC_{i,j,p} \tag{20}$$

$$QP_{i,j,q} \leq QPL_{i,j,q} \times H_{i,j,q} \tag{21}$$

where EC is the amount of energy reserves, subscript q represents the specific type of power generation, QP is the amount of power generation, QPL is the capacity of power generation, and H is the available hours of renewable power (as shown in supplementary data).

⑤ The energy production, transportation, import, transformation and storage are restricted by infrastructures, such as production capacity, LNG terminal capacity and pipeline capacity.

$$EPP_{i,j,p} \leq EPPL_{i,j,p} \tag{22}$$

$$NIL_{i,j} \leq NILL_{i,j} \tag{23}$$

$$NPT_{i,j,e} \leq NPTL_{i,j,e} \tag{24}$$

where $EPPL$ is the production capacity, NIL is the amount of natural gas imported by LNG terminal, $NILL$ is the annual receiving capacity of LNG terminal, NPT is the amount of natural gas transported by pipeline from j region to e region, and $NPTL$ is the natural gas pipeline capacity between j region and e region.

Besides, the installed capacity of battery and solar PV power generation facility will substantially decline with the increase in service life. According to reference [52,53], the attenuation rate of the capacity of the battery and solar PV power generation facility in each year were obtained, and considered in the calculation process:

$$\begin{aligned} DL_{i,j} = {} & DLZ_{i,j} + DLZ_{i-1,j} \times l_1 + DLZ_{i-2,j} \times l_2 + DLZ_{i-3,j} \times l_3 \\ & + DLZ_{i-4,j} \times l_4 + DLZ_{i-5,j} \times l_5 \end{aligned} \tag{25}$$

where DL is the battery capacity, DLZ is the capacity of the new battery, and l is the attenuation rate of the specific year.

⑥ In order to describe the capacity constraint of the battery, considering the special of the battery, the charging and discharging process of the battery was all considered. The typical daily data [54], including power load (as shown in supplementary data), solar energy and wind energy of each hour, were chosen to model the operation of the battery by hours.

$$RB_{i,j,1} = RB_{i,j,25} \tag{26}$$

$$0 \leq RBI_{i,j,k} \leq DL_{i,j}\gamma_{ri}, \ \ 0 \leq RBO_{i,j,k} \leq DL_{i,j}\gamma_{ro} \tag{27}$$

$$RB_{i+1,j,k} = RB_{i,j,k}(1-\eta_{rs}) + RBI_{i,j,k}\eta_{ri} - RBO_{i,j,k} \Big/ \eta_{ro} \tag{28}$$

$$\begin{aligned} & RBO_{i,j,k} + RPC_{i,j,k} + RPG_{i,j,k} + RPN_{i,j,k} + RPS_{i,j,k} + RPW_{i,j,k} \\ & \quad + RPH_{i,j,k} + RTI_{i,j,k} \\ & \quad \geq RBI_{i,j,k} + RD_{i,j,k} + RTO_{i,j,k} \end{aligned} \tag{29}$$

where RB is the amount of power in the battery, subscript k represents a specific hour, RBI and RBO are the amounts of power charged and discharged in the hour, respectively. γ_{ri} and γ_{ro} are the maximum charging and discharging rate, respectively. η_{rs} is the self-discharge efficiency, η_{ri} and η_{ro} are the charging and discharging efficiency, respectively. *RPC*, *RPG*, *RPN*, *RPS*, *RPW* and *RPH* are the amounts of power generated using coal, gas, nuclear, solar, wind and hydropower in the hour, respectively. *RD* is the power demand, *RTI* and *RTO* are the amount of power import and export, respectively.

⑦ The greenhouse gas emissions should be limited. According to the objective of achieving carbon neutrality in 2060, greenhouse gas emissions were constrained.

$$\sum_{j=1}^{30}\sum_{p=1}^{3} EPD_{2060,j,p} \times \alpha_p = 0 \tag{30}$$

where α is the greenhouse gas emission coefficient. In this work, CO_2, N_2O and CH_4, the three types of greenhouse gases, were mainly considered. N_2O and CH_4 were converted into CO_2 in accordance with 100-year GWP. The calculation of greenhouse gas emissions from coal, oil and natural gas consumption was simplified, all of which were calculated using the default emission factors for stationary combustion proposed by IPCC [55], and the fugitive emissions were ignored. The greenhouse gas emission coefficients of different types of fossil energy were shown in Table 7.

Besides, the other energy mainly used to supply the cooling and heating demand of the building, the proportion of other energy to total end-use energy should be constrained by 15%.

4. Results

The energy structure, infrastructure construction plans and exploration schemes were optimized on the basis of the total end-use energy demand and the energy supply optimization model. In this section, the future demands for coal, oil, natural gas, power, green hydrogen and other energy were obtained. The supply planning of all kinds of energy was analyzed.

4.1. Energy demand structure

Fig. 6 depicts that the electrification rate of China will gradually increase from 23.9% in 2017 to approximately 75% in 2060. Meanwhile, the proportion of green hydrogen and other energy in end-use energy will increase to approximately 10% and 15% in 2060, respectively. For primary energy, the demand for natural gas and coal will increase first and then decline while the oil demand will decrease from 2017 to 2060. The demand for coal will reach the peak in 2022, and the demand for natural gas will peak in 2041 by 557 Mtce. Considering the constraint of carbon neutrality, the primary energy demand of non-fossil energy (calculated according to the coal consumption of thermal power generation) will gradually increase, and the proportion of non-fossil energy to total primary energy demand will reach 100% in 2060.

4.2. Energy supply planning

To meet the final and primary energy demand of each region, the distributions of production of different types of energy in China were forecasted and the power generation and capacity construction schemes were discussed.

4.2.1. Fossil energy

According to the calculation result, the demand of China for coal can be self-sufficient in the future, while the external dependence of natural gas and oil will still be relatively high. Under the constraint of carbon neutrality, Fig. 7 shows that the production of all types of fossil energy will decrease to 0 Mtce in 2060. For coal, large coal production bases will be gradually formed in Shaanxi, Shanxi, Inner Mongolia and other provinces with abundant coal reserves.

For oil, constrained by the limited crude oil reserves, the annual crude oil production of China will remain lower than 200 million tons in the future to achieve sustainable development. Refineries will be established near the regions where crude oil is produced or imported in the future. The integration of oil production and refining will be gradually realized.

For the production of natural gas in different provinces of China, the production capacity in Shaanxi, Xinjiang and Sichuan provinces will increase substantially in the future. Meanwhile, the total natural gas production in China will firstly increase from 197 Mtce in 2017 to approximately 300 Mtce in 2047 and then decrease to 0 Mtce in 2060.

With regard to other infrastructure, considering the demand for all types of fossil energy will be 0 Mtce in 2060, the calculation results show that there will be no new capacity of the pipeline and LNG terminals in the future.

4.2.2. Power

For power generation, as presented in Fig. 8, the annual total power generation in the 30 regions of China will generally rise from 786 Mtce in the base year to approximately 2207 Mtce (including the power demand of hydrogen production) in 2060. A substantial increase can be observed in Hebei, Beijing, Fujian, Yunnan and Ningxia.

As to the power structure of China, solar and wind power will increase considerably in the future. As illustrated in Fig. 9, the wind power and solar power will increase to 1141 and 840 Mtce in 2060, respectively. Meanwhile, the capacity of wind power and solar power will increase to 3368 and 4699 GW, respectively. Besides, the power generated using coal will firstly increase from 520 Mtce in 2017 to approximately 797 Mtce in 2030, and then gradually decrease to 0 Mtce in 2060, given the constraint of greenhouse gas emissions.

4.2.3. Green hydrogen and other energy

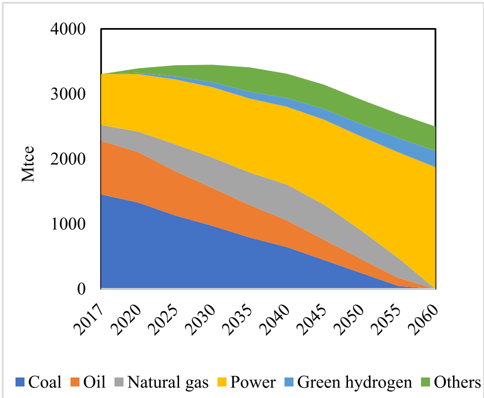
For green hydrogen, the production will gradually increase from 2017 to 2060. As shown in Fig. 10, the production of other energy will increase from 2017 to 2035, and then be steady by 2060. In 2060, the total green hydrogen production of all regions will reach approximately 250 Mtce, while the production of other energy will be approximately 375 Mtce. In this model, due to the regional difference and limitation of green hydrogen production were not considered, the product distribution will be scattered and the transportation pipeline will be not required.

4.3. Greenhouse gas emissions

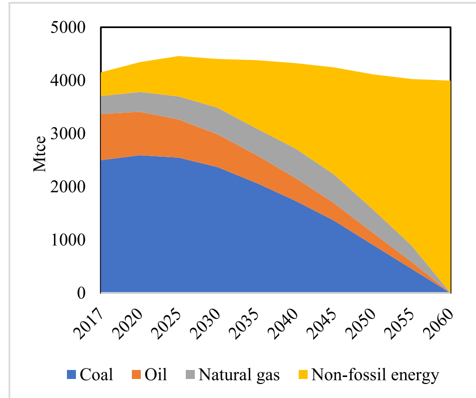
Under the constraint of carbon neutrality, as shown in Fig. 11, the greenhouse gas emissions of energy consumption in China will reach the peak by 9389 million tons of CO_2 equivalents in 2021 and then decline. The total greenhouse gas emissions between 2017 and 2060 will be approximately 262,783 million tons of CO_2

Table 7
Greenhouse gas emission coefficient of different types of fossil energy.

	CO_2/kg·TJ^{-1}	N_2O/kg·TJ^{-1}	CH_4/kg·TJ^{-1}
Coal	94,600	1.5	1
Crude oil	73,300	0.6	3
Natural gas	56,100	0.1	1

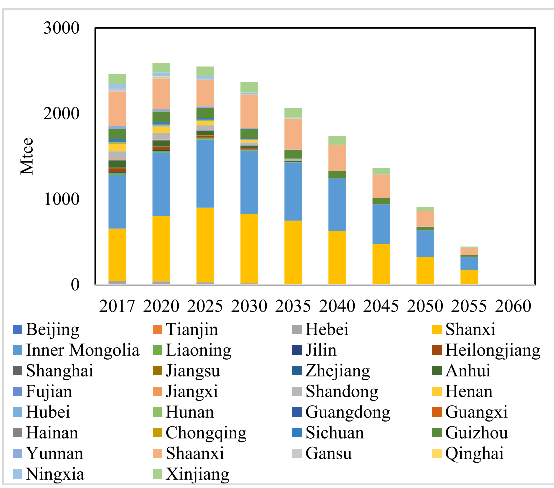


(a) End-use energy demand from 2017 to 2060

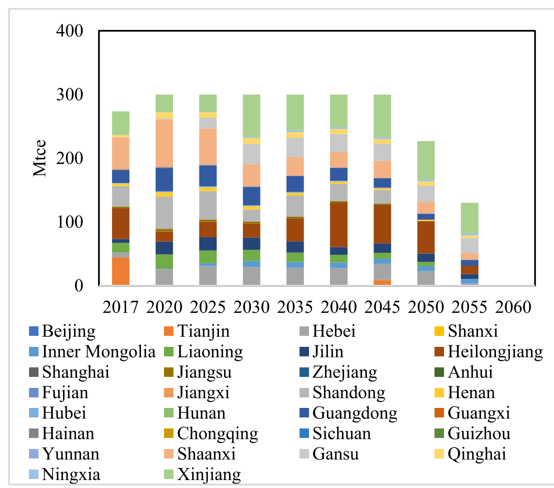


(b) Primary energy demand from 2017 to 2060

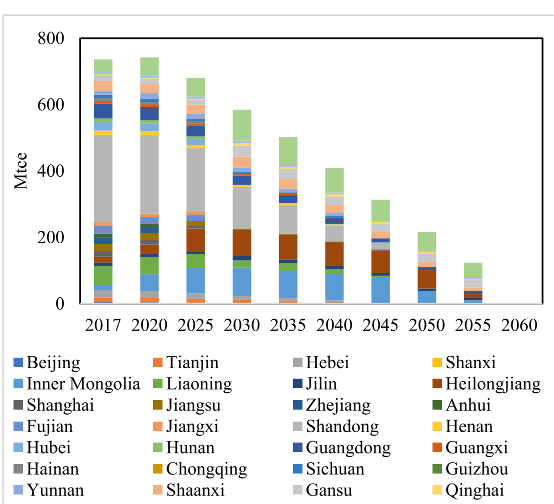
Fig. 6. End-use energy demand and primary energy demand of China.



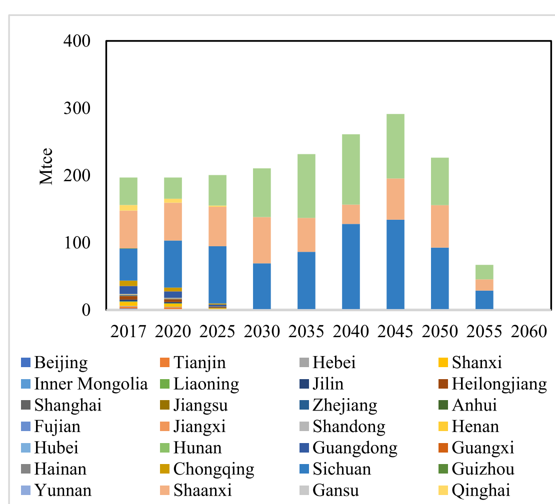
(a) Coal production of each province



(b) Crude oil production of each province

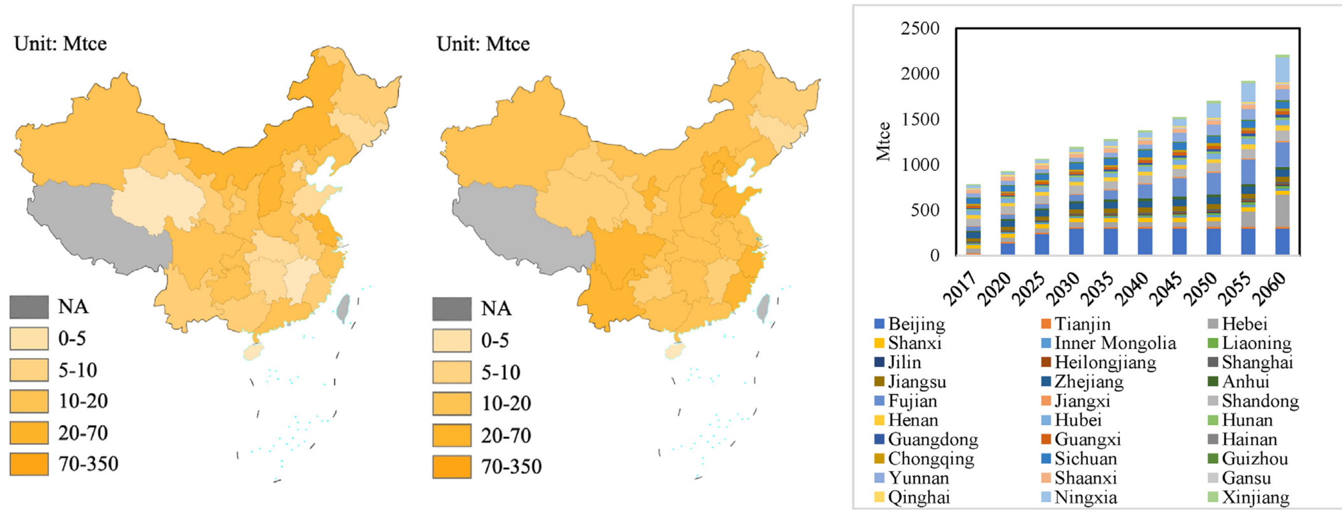


(c) Refined oil production of each province



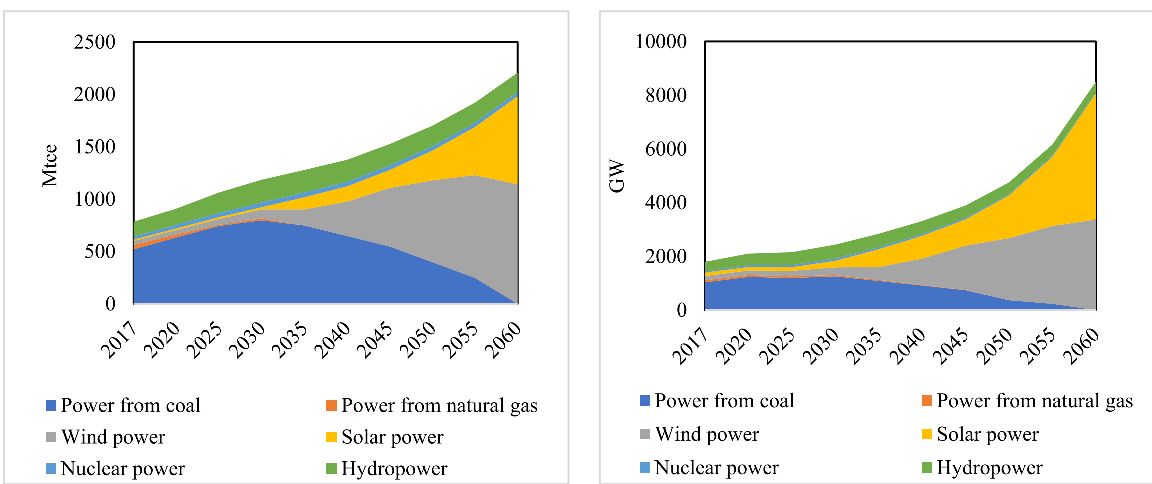
(d) Natural gas production of each province

Fig. 7. The fossil energy production of each province from 2017 to 2060.



(a) Distribution of power generation in 2017 (b) Distribution of power generation in 2060 (c) Power generation of each province from 2017 to 2060

Fig. 8. Power generation of China.



(a) Composition of generated power (b) Composition of power capacity

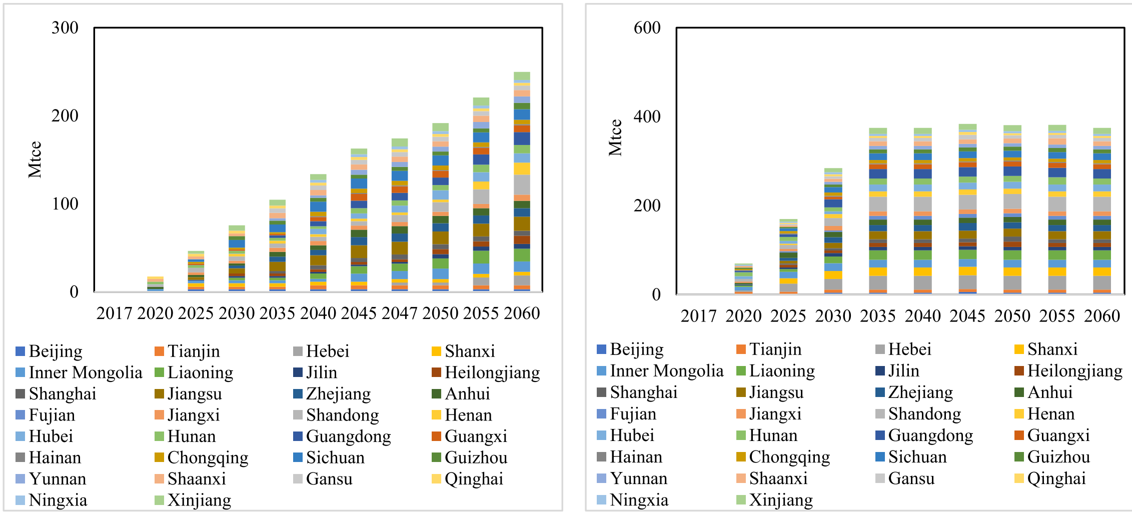
Fig. 9. The power structure of China from 2017 to 2060.

equivalents.

4.4. Discussion

The uncertainty of this work mainly comes from the projection results of the socio-economic parameters. The model results are driven by end-use energy demands, which are calculated based on the socio-economic parameters. In this work, the socio-economic parameters were compared with the existing researches and reports to ensure these parameters are within a reasonable range.

Besides, the results in the carbon neutrality year of this work and other research of 100% non-fossil energy consumption planning, such as the research of Breyer C et al. and Jacobson M Z et al., are showed in Table 8 for comparison. The power demand and the installed capacity of wind power in the carbon neutrality year of this work are between the research of Breyer and Jacobson. As for the installed capacity of PV, the results of this work is less than other research due to the larger power demand in the research of Jacobson and the higher proportion of PV in the research of Breyer. Compared with the research of Breyer C et al. and Jacobson M Z et al., the supply planning of fossil energy was considered in detail for a comprehensive optimization in this work due to the high proportion of fossil energy in the total energy demand of China. In general, all the results showed that the power sector will emerge as the backbone of the entire energy system and wind power and solar energy will dominate the energy supply for China in the future.



(a) Green hydrogen production of each province

(b) Other energy production of each province

Fig. 10. Green hydrogen and other energy production of each province from 2017 to 2060. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

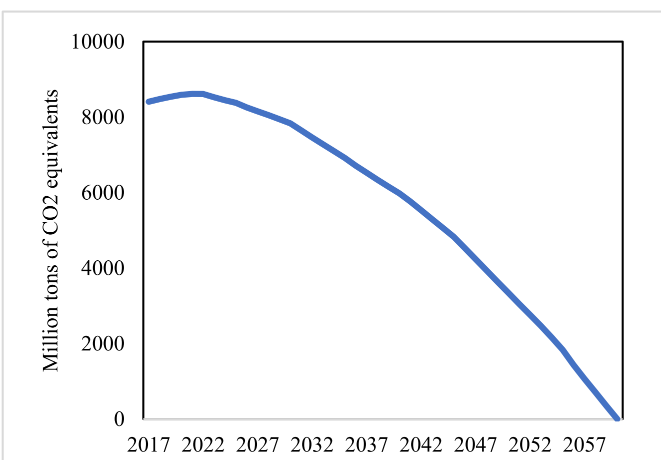


Fig. 11. Greenhouse gas emissions of energy consumption in China from 2017 to 2060.

5. Conclusions

China, a rapidly developing country, has a high demand for energy. Determining how to supply energy under the constraint of carbon neutrality is a priority to meet the requirement of economic development. In this work, the energy structure and supply planning were optimized in consideration of all processes from energy production to consumption.

The optimization results indicate that the electrification rate of China will increase substantially in the future, from 23.9% in the base year to approximately 75% in 2060. Meanwhile, the proportion of green hydrogen and other energy in end-use energy will increase to approximately 10% and 15%, respectively. For primary energy, the demand for natural gas and coal will increase first and then decline while the demand for oil will decrease from 2017 to 2060. The demand for non-fossil energy will increase to 100% in 2060. Overall, the energy structure of China will be optimized gradually.

For the energy supply side, coal production will be greatly reduced, the coal production capacity will be concentrated, forming

Table 8
Comparison of results in the carbon neutrality year.

Authors	Breyer C et al. [25]	Jacobson M Z et al. [21]	This work
Carbon neutrality year	2050	2050	2060
Region	China	China, Democratic Republic of Korea, Mongolia	30 provincial regions (except Hong Kong, Macao, Taiwan and Tibet) of China
End-use energy demand (TWh)	–	22,732–29,337	20,325
Power demand (TWh)	13,216	22,188–29,200	17,958
Total installed capacity of PV (GW)	6345	6043–7018	4699
Total installed capacity of wind power (GW)	1170	4816–5298	3368
Total installed capacity of hydropower (GW)	366	301.3	394

some large coal bases. The refineries will be established near the regions where the crude oil is produced or imported. The integration of oil production and refining will be gradually realized. Natural gas production will increase by 2047 in the future, from 197 Mtce in 2017 to 300 Mtce in 2047, especially in Shaanxi, Xinjiang and Sichuan provinces. In addition, the total power generation capacity will rise with the considerable increase in the generation capacity of wind power and solar power. It is projected that the external dependence of oil and natural gas will be relatively high in the future, and coal, power, green hydrogen and other energy can be self-sufficient.

Furthermore, the greenhouse gas emissions of energy consumption in China will reach the peak in 2021, and the total greenhouse gas emissions between 2017 and 2060 will be approximately 262,783 million tons of CO_2 equivalents.

Declaration of competing interest

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

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Credit author statement

Shuo Qiu: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. Tian Lei: Validation, Investigation, Resources, Data curation. Jiangtao Wu: Writing – review & editing, Supervision, Project administration. Shengshan Bi: Writing – review & editing, Supervision.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121193.

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