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An Empirical Study on China's Energy Supply-and-Demand Model Considering Carbon Emission Peak Constraints in 2030

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ABSTRACT

China's energy supply-and-demand model and two related carbon emission scenarios, including a planned peak scenario and an advanced peak scenario, are designed taking into consideration China's economic development, technological progress, policies, resources, environmental capacity, and other factors. The analysis of the defined scenarios provides the following conclusions: Primary energy and power demand will continue to grow leading up to 2030, and the growth rate of power demand will be much higher than that of primary energy demand. Moreover, low carbonization will be a basic feature of energy supply-and-demand structural changes, and non-fossil energy will replace oil as the second largest energy source. Finally, energy-related carbon emissions could peak in 2025 through the application of more efficient energy consumption patterns and more low-carbon energy supply modes. The push toward decarbonization of the power industry is essential for reducing the peak value of carbon emissions.

1. Introduction

In the 2015 United Nations Climate Change Conference (COP21), all Parties unanimously adopted the Paris Agreement and proposed to keep the global average temperature rise within 2 °C and to control it within 1.5 °C. The Chinese government proposed to have China's carbon dioxide emissions peak by 2030, and strives to achieve that goal as soon as possible. As carbon dioxide emissions mainly come from fossil energy consumption, total carbon dioxide emissions as a new hard constraint will have a significant impact on total energy supply and demand, growth rate, and the structure of China's economy from now to 2030. The quantitative analysis of these effects has important theoretical and practical significance for the development of medium- and long-term energy planning and policies.

Existing carbon emission peak research primarily focuses on the carbon emission growth momentum, peak time, and peak level, as well as on the peak path of regions and sectors. Wang et al. [1] pointed out that GDP growth is the biggest driver of China's carbon emissions growth, and Chai [2] further suggested that industrialization is the primary factor determining whether carbon emissions will peak ahead of time. According to studies by Qu and Guo [3], Jiang et al. [4], and Ma and Chen [5], if the energy-saving and low-carbon mode is adopted for economic and social development, then energy-related carbon dioxide emissions will peak around 2030, with the emission peak coming as early as 2025. Yang et al. [6] and Liu et al. [7] have predicted the carbon emissions peak in Beijing, Chongqing, and other places. Cheng and Xing [8] and Guo [9] have studied the path toward peak carbon emissions in the fields of electric power and industry.

The existing research highlights the role of the energy industry in defining the peak impact and the path toward realization of a lower carbon path. However, the focus mainly lies on the total primary energy consumption. There is a lack of overall systematic optimization analysis regarding the primary energy supply structure, terminal energy consumption structure, power generation and power source structure, energy processing and conversion, and other major energy issues. As a result, it is difficult to answer questions regarding

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the energy supply-and-demand structure, carbon flow, and other important issues that are necessary for determining different peak scenarios. Bearing this in mind, this paper attempts to construct a model of China's energy supply and demand by considering constraints such as the carbon emission peak from the perspective of "energy-economy-environment" (3E) system simulation and to analyze the total energy supply and demand, growth rate, system structure, and detailed carbon emissions for different peak scenarios.

2. Model

Based on classical research methods and models such as MARKAL (Market Allocation Modeling Framework)/TIMES (The Integrated MARKAL-EFOM System) [10], NEMS (National Energy Modeling System) [11], MAED (Model for Analysis of the Energy Demand) [12], AIM (Asia-Pacific Integrated Model) [13], and LEAP (Long-Range Energy Alternatives Planning System) [14], the modeling ideas of "bottom up," "top down," and a 3E system are adopted. These ideas allow the design of China's energy supply-and-demand model to be based on a comprehensive consideration of economic development, technological progress, policies, resources, environmental capacity, and other factors. The model framework is shown in Fig. 1.

The model calculation is divided into two stages. In the first stage, a scenario designed for economic and social development and technological progress is conducted in order to estimate the GDP, population, urbanization rate, and other basic parameters of economic and social development. Econometrics, elastic coefficient, and other methods are then applied to predict the energy service demands required by residential areas and by various industries, including construction, transportation, commerce, and other sectors. Next, the unit consumption method of output value, the unit consumption method of product, the turnover analysis method, and other methods are used to determine the terminal energy demand of different sectors. On this basis, the time series, energy price ratio, and other methods are used to predict the variety of fuel sources used to meet the required energy demand. Varieties include coal, oil, natural gas, electric power, heating power, and other energy sources. In the second stage, by considering power generation, heating, oil refining, coking, gasification, and other processing and conversion links, the total amount and structure of the primary energy supply are obtained through an energy system simulation calculation. This allows proper attention to be paid to both the total carbon emissions (as the main constraint) and the energy supply-and-demand balance, taking into consideration energy resources, processing, conversion capacity, proportion of non-fossil energy, and other constraints (balance). The energy-related carbon dioxide emissions are calculated based on the input-output relations and related physical energy efficiencies of primary energy sources, terminal energies within various links of the supply side, several sectors of the demand side, and the Intergovernmental Panel on Climate Change (IPCC) carbon emission factor.

The main constraints (balance) involved in the second stage of the energy system simulation are as follows.

(1) Constraints of carbon emission peak:

$$Ca_t \le Ca_{\mathrm{T}} \tag{1}$$

where t is the year in the planning period (t = 1, ..., 15 represent 2016, ..., 2030, respectively), T represents the peak year of the planning period, and Ca_t represents the energy-related carbon dioxide emissions in the tth year.

$$\begin{aligned} Ca_t = \sum_{i=1}^{3} \Big(& \left(EP_{it} + IM_{it} - EM_{it}\right) \times RLO_{it} + \left(EP_{it} + IM_{it} - EM_{it}\right) \\ & \times \left(1 - RLO_{it}\right) \times RTP_{it} + TG_{it} \times EG_{it} + TH_{it} \times EH_{it} + FD_{it} \Big) \times Emi_i \end{aligned} \tag{2}$$

where i is the type of fossil energy (i = 1, 2, and 3 represent coal, oil, and natural gas, respectively); EP_{it}, IM_{it}, EM_{it}, RLO_{it}, RTP_{it}, and FD_{it}

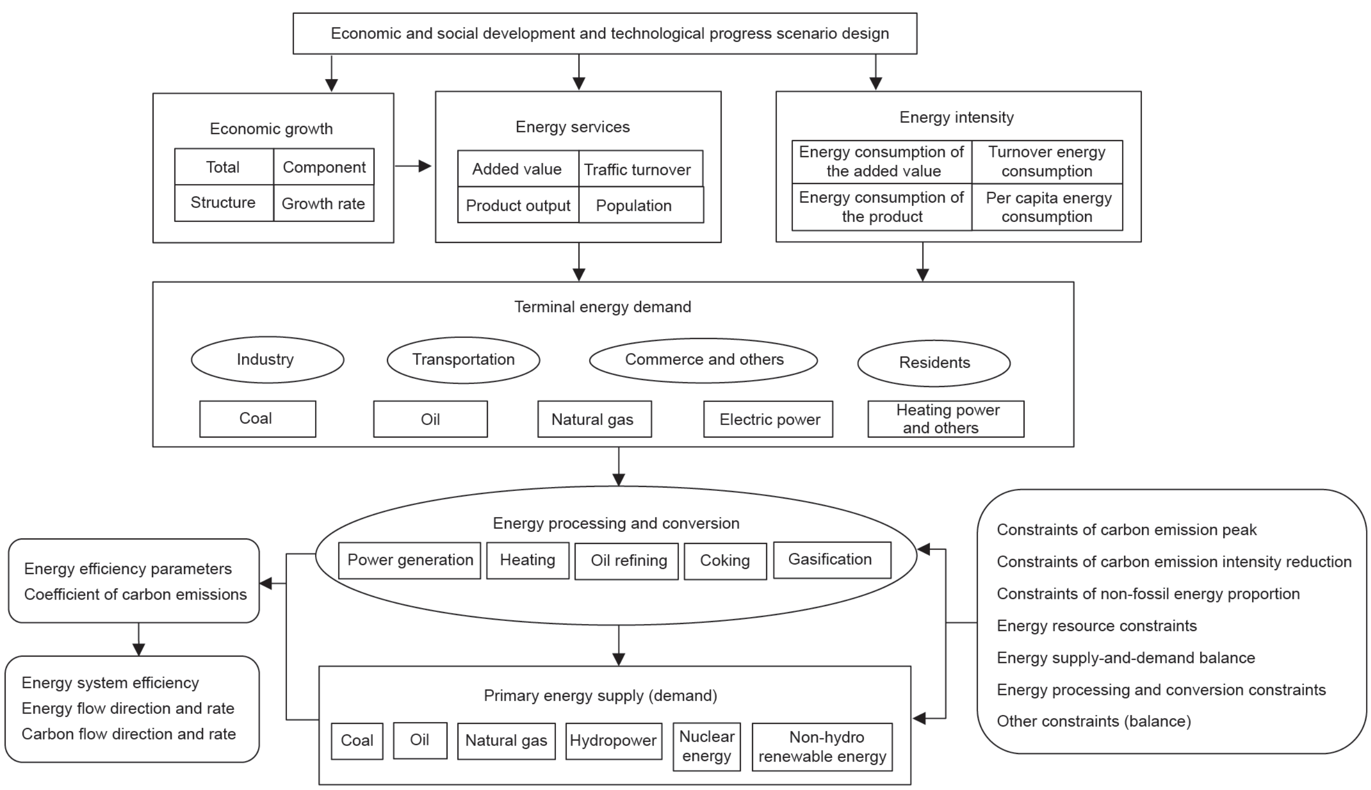

Fig. 1. China's energy supply-and-demand model framework.

represent production, imports, exports, transport and storage loss rate, processing conversion loss rate, and the terminal consumption of the ith fossil energy in the tth year, respectively; TG_{it} and TH_{it} represent the power generation and heat supply in the tth year, respectively, with the ith fossil energy as the input; EG_{it} and EH_{it} represent the corresponding power generation efficiency and heating efficiency, respectively; and Emi_i represents the carbon dioxide emission factor for the ith fossil energy.

(2) The coal supply-and-demand balance is expressed as follows:

$$\begin{aligned}&(EP_{1t}+IM_{1t}-EM_{1t})\times(1-RLO_{1t})\times(1-RTP_{1t})\\&-TG_{1t}\times EG_{1t}-TH_{1t}\times EH_{1t}\geq FD_{1t}\end{aligned} \tag{3}$$

where RLO_{1t} and RTP_{1t} represent the coal transport and storage loss rate and the coal processing and conversion (including washing, coking, and others) loss rate, respectively.

(3) The oil supply-and-demand balance is expressed as follows:

$$\begin{aligned}&(EP_{2t}+IM_{2t}-EM_{2t})\times(1-RLO_{2t})\times(1-RTP_{2t})\\&-TG_{2t}\times EG_{2t}-TH_{2t}\times EH_{2t}\geq FD_{2t}\end{aligned} \tag{4}$$

where RLO_{2t} and RTP_{2t} represent the oil transport and storage loss rate and the oil processing and conversion (refining) loss rate, respectively.

(4) The natural gas supply-and-demand balance is expressed as follows:

$$\begin{aligned}&(EP_{3t}+IM_{3t}-EM_{3t})\times(1-RLO_{3t})\times(1-RTP_{3t})\\&-TG_{3t}\times EG_{3t}-TH_{3t}\times EH_{3t}\geq FD_{3t}\end{aligned} \tag{5}$$

where RLO_{3t} and RTP_{3t} represent the natural gas transport and storage loss rate and the natural gas processing and conversion (liquefaction of natural gas) loss rate, respectively.

(5) The electric power supply-and-demand balance is expressed as follows:

$$\begin{aligned}&\left(\sum_{k=1}^{10}\left(TCP_{kt}+ACP_{kt}\times UF_{kt}\right)\times CF_{kt}\times\left(1-RLO_{4t}\right)\right.\\&\left.+IM_{4t}-EM_{4t}\right)\times\left(1-RTP_{4t}\right)\geq FD_{4t}\end{aligned} \tag{6}$$

where k represents the type of power source (k = 1, ..., 10 represent coal-fired power, oil-fired power, gas-fired power, hydropower, nuclear power, wind power, solar power, biomass power, geothermal power, and ocean power); TCP_{kt}, ACP_{kt}, UF_{kt}, and CF_{kt} represent installed capacity at the beginning of the period, new installed capacity, new installed equivalent capacity coefficient, and the average equipment utilization hours of the kth power source in the tth year, respectively; and RLO_{4t}, RTP_{4t}, IM_{4t}, EM_{4t}, and FD_{4t} represent the station service hydropower consumption rate, hydropower line loss rate, hydropower imports, hydropower exports, and terminal hydropower consumption in the tth year, respectively.

3. Scenario design

The Chinese government promised to reach the peak point of total carbon dioxide emissions around 2030, while committing to push toward arriving at that peak as soon as possible. Since the energy-related carbon dioxide emissions in China account for approximately 90% of the total national carbon dioxide emissions, energy-related carbon dioxide emissions must also peak around 2030 and must reach that peak point as early as possible. Based on this requirement, two energy-related carbon emission scenarios are designed in this paper: a planned peak scenario and an advanced peak scenario. In the advanced peak scenario, the peak is reached in 2025, whereas in the planned peak scenario, the peak is reached in 2030. Compared with the planned peak scenario, the advanced peak scenario accelerates the low-carbon transformation, transformation of the economic development mode, and pace of industrial restructuring by achieving greater breakthroughs in energy technologies and by significantly enhancing the energy utilization efficiency. Table 1 outlines the assumptions that are made regarding the economic, social, and technical aspects of the two scenarios.

4. Result analysis

4.1. Quantitative analysis of the two scenarios based on the model

The growth rate of total primary energy demand shows a trend of “gradual decline.” A characteristic “decoupling” gradually appears between energy consumption and economic growth. In the advanced peak scenario, from 2015 to 2030, the GDP and population will increase by 139.6% and 4%, respectively, and the urbanization rate will increase by 11.9%. The growth rate of primary energy demand in 2015–2020, 2020–2025, and 2025–2030 will be 1.9%, 1.1%, and 0.6%, respectively. As the GDP growth rate is much higher than that of primary energy demand, the energy consumption elasticity coefficients of the three periods will be 0.3, 0.2, and 0.1, respectively. By 2030, the total primary energy demand will reach 3.6×10^9 tons of oil equivalent (toe), which is an increase of approximately 25% over 2015. The per capita energy consumption will be 2.5 toe, which is an increase of 0.4 toe over 2015. In the planned peak scenario, by 2030, the total primary energy demand will be 2.31×10^8 toe more than in the advanced peak scenario. The per capita energy consumption will be 0.1 toe more than in the advanced peak scenario. The

Table 1
Main assumptions in the two scenarios.

Factors	Advanced peak scenario	Planned peak scenario
GDP	The average annual GDP growth rate will be 6.5%, 6.0%, and 5.5% for the periods of 2015–2020, 2020–2025, and 2025–2030, respectively	Same as the advanced peak scenario
Industrial structure	The ratio between primary, secondary, and tertiary industries will be 8:36:56 in 2020 and 6:29:65 in 2030. Major energy-intensive products will reach their peak around 2020	The proportion of the secondary industry in 2020 and 2030 will be respectively 0.25% and 1% higher than for the advanced peak scenario. The opposite is the case for the tertiary industry. Major energy-intensive products will reach their peak around 2025
Population	The population will be 1.41 billion in 2020 and 1.43 billion in 2030	Same as the advanced peak scenario
Urbanization rate	The urbanization rate will reach 60% in 2020 and 68% in 2030	Same as the advanced peak scenario
Energy technology progress	The average annual energy consumption of primary energy-intensive products, the general industrial and commercial output value, and the traffic turnover will decrease by 1%–3%	The energy consumption of primary energy-intensive products, the general industrial and commercial output value, and the traffic turnover will be 1%–3% higher than for the advanced peak scenario
Non-fossil energy development	The proportion of non-fossil energy consumption relative to primary energy consumption will be not less than 15.2% and 20.5% in 2020 and 2030, respectively	The proportion of non-fossil energy consumption relative to primary energy consumption will be not less than 15% and 20% in 2020 and 2030, respectively

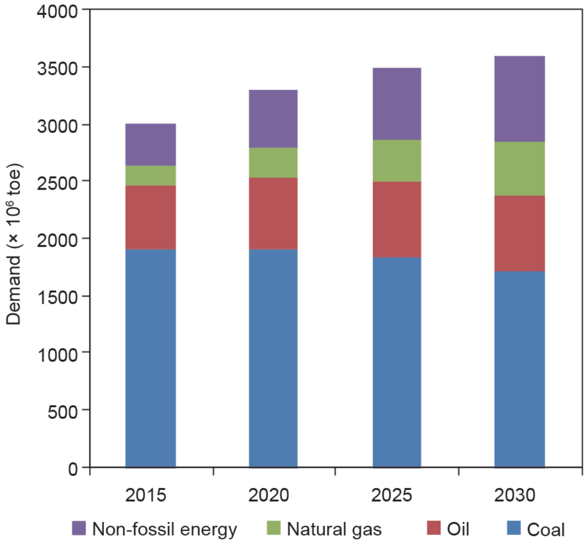

Fig. 2. Primary energy demand in the advanced peak scenario.

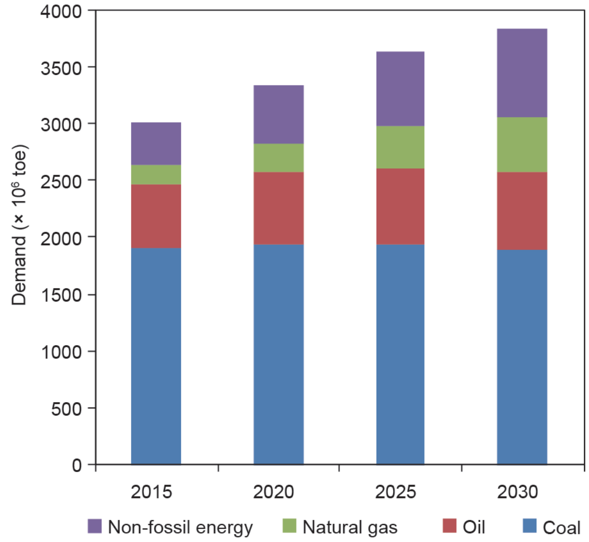

Fig. 3. Primary energy demand in the planned peak scenario.

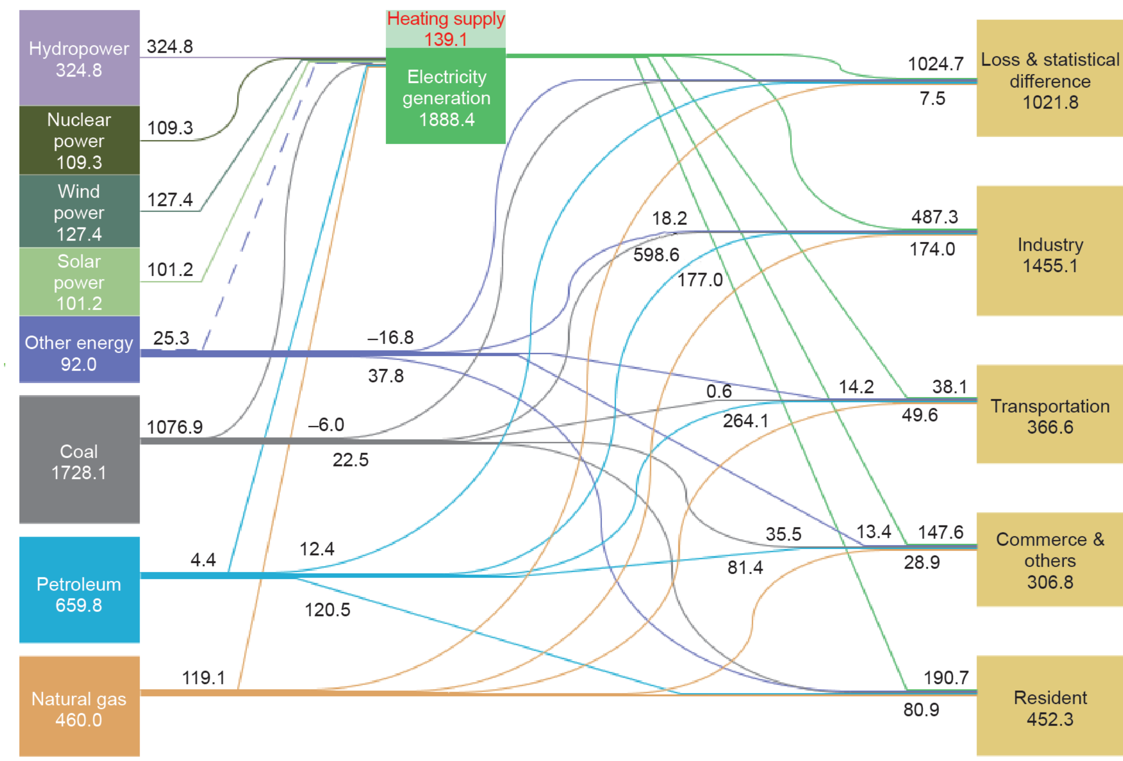

Fig. 4. Energy flow in 2030 in the advanced peak scenario. The unit is 1×10^6 toe. Hydropower, nuclear power, and other power generated from non-hydro renewable energy are converted into primary energy by the fossil fuel replacement method. The energy consumption for electricity generation includes the energy consumption for heating. Losses include the net input, recovery energy, and energy transport and storage loss in the processing and conversion process such as electricity generation, heating, coal washing and separation, coking, oil refining, gasification, and natural gas liquefaction. Due to rounding, the energy supply-and-demand balance may be slightly different for different varieties and sectors.

total amount and structure of the primary energy demand in both scenarios are shown in Fig. 2 and Fig. 3. The energy supply-and-demand situation in the advanced peak scenario is shown in Fig. 4.

4.2. Proportion of coal consumption will be reduced to below 50%

In the advanced peak scenario, subject to resource bottlenecks and environmental capacity constraints, negative growth will be seen for the demand of coal during the 13th Five-Year Plan, and the proportion of coal consumption in the total primary energy consumption will experience a sustained drop. In 2030, coal demand will be 1.73×10^9 toe and its proportion in the total primary energy demand will be reduced from 63.7% in 2015 to 48%. In the planned peak scenario, the coal demand in 2030 will be 1.68×10^8 toe higher than for the advanced peak scenario, and its proportion in the total primary energy demand will be 1.4% higher than for the advanced peak scenario.

4.3. Oil demand growth will gradually approach zero growth

In the advanced peak scenario, the growth rate of oil demand continues to fall due to factors such as the slowdown in automobile consumption growth. In particular, after 2020, as the electric car enters the stage of large-scale commercial application, oil consumption will tend to zero growth. By 2030, oil demand will be 6.58×10^8 toe, with an increase of 1.05×10^8 toe over 2015. In the planned peak scenario, the average annual growth rate of oil demand is 0.3% higher than in the advanced peak scenario, and the oil demand in 2030 will be 2.8×10^7 toe higher than in the advanced peak scenario.

4.4. Natural gas demand will continue to grow rapidly

In the advanced peak scenario, as the domestic natural gas production capacity, gas pipeline transmission capacity of imported natural gas, and coastal liquefied natural gas receiving capacity improve, the natural gas supply capacity increases significantly. The annual demand growth of natural gas will be 6.6% for the period of 2015–2030. By 2030, the total natural gas demand will reach 4.62×10^8 toe. In the planned peak scenario, the growth rate of natural gas demand is slightly higher than in the advanced peak scenario, and the natural gas demand in 2030 will be approximately 5% higher than in the advanced peak scenario.

4.5. Non-fossil energy will replace oil as the second largest energy source

In the advanced peak scenario, a continuous rapid growth is seen in non-fossil energy consumption due to the large-scale operation of newly installed hydropower units and to an increase in the installed capacity of wind power, solar power, and nuclear power. However, as the base continues to rise, the growth rate will exhibit a downward trend. By 2030, non-fossil energy demand will be 8×10^8 toe, which accounts for 20.9% of the total primary energy demand. In the planned peak scenario, non-fossil energy demand achieves a rapid growth, and will account for 20.1% of the total primary energy demand in 2030.

4.6. More than 50% of new power supply comes from non-fossil energy

In the advanced peak scenario, the level of electrification for the entire society will continue to improve; the proportion of electric power consumption within the total terminal energy consumption will increase from 21.3% in 2015 to 29.3% in 2030; the total electric power consumption of the entire society will increase by an annual average of 3.2%, and will reach 9200 TW·h in 2030, with an increase of 58.2% over 2015; and more than 50% of the increment will be supplied from non-fossil energy. In the planned peak scenario, the average annual growth rate of total electric power consumption is 0.4% higher than in the advanced peak scenario for the period of 2015–2030, and the total electric power consumption by 2030 will be 500 TW·h higher than in the advanced peak scenario.

4.7. Carbon emissions peak time and value depend on growth of non-fossil energy

In the advanced peak scenario, the energy-related carbon dioxide emission growth will be reduced from 2.6% for the period of 2010–2015 to 0.8% for the period of 2015–2020 due to the rapid development and utilization of hydropower, nuclear power, and non-hydro renewable energy. A further decline will occur after 2020, and carbon dioxide emissions will reach a peak of 1.02×10^{10} t in 2025. By 2030, carbon dioxide emissions will be reduced to 1×10^{10} t, of which the emissions of the electricity sector will account for nearly 50%. The emissions of different sectors and different varieties are shown in Fig. 5. In the planned peak scenario, energy-related carbon

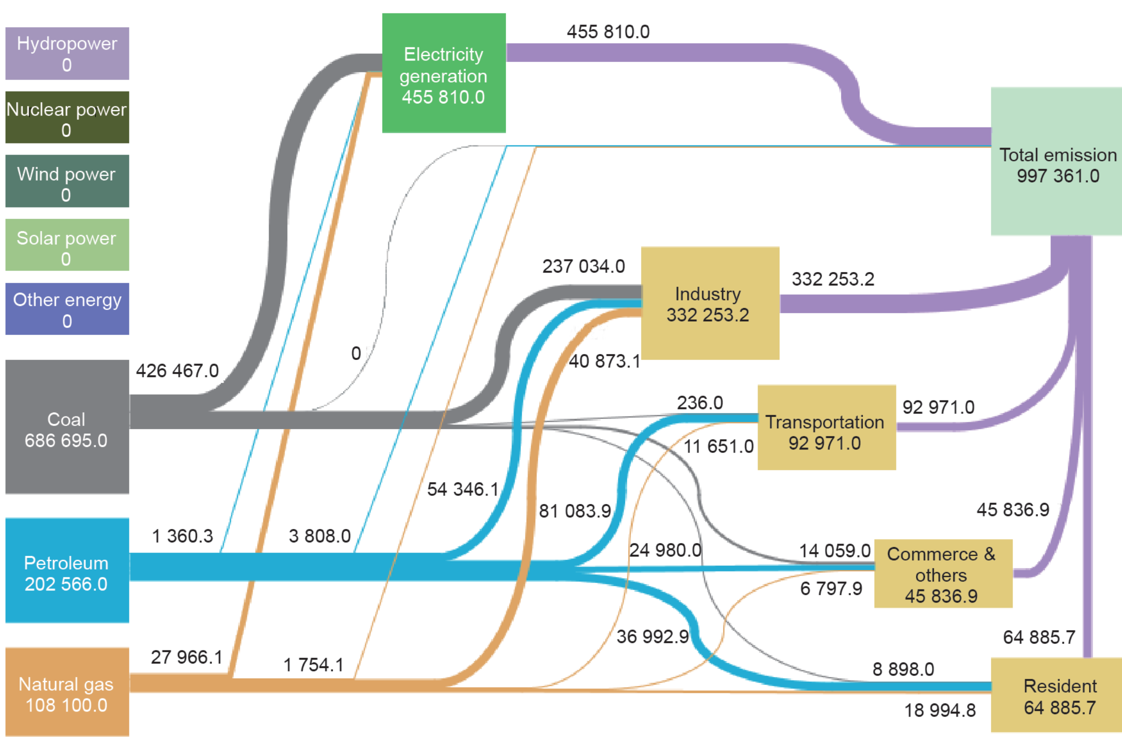

Fig. 5. Carbon flow in 2030 in the advanced peak scenario. The unit is 1×10^4 t of carbon dioxide. Carbon emissions of the power generation sector include the carbon dioxide emissions generated from heating energy consumption. To achieve the total balance, it is assumed that the energy loss and balance of different varieties include the carbon dioxide emissions. The carbon emission coefficients of hydropower, nuclear power, wind power, and other non-fossil energy sources are zero. The carbon emission coefficients of coal, oil, and natural gas are 3.96 $t_{CO_2}\cdot toe^{-1}$, 3.08 $t_{CO_2}\cdot toe^{-1}$, and 2.35 $t_{CO_2}\cdot toe^{-1}$, respectively. Due to rounding, the carbon balance may be slightly different for different varieties and sectors.

dioxide emissions will peak in 2030, and the peak value will be approximately 5×10^8 t higher than in the advanced peak scenario.

5. Conclusions

Through an analysis of energy supply and demand and carbon emission data for a planned peak scenario and an advanced peak scenario, the following conclusions can be drawn.

(1) Primary energy and power demand will continue to grow up to 2030. Since low-carbon transformation promotes the rapid enhancement of the electrification level, the growth rate of the power demand will be significantly larger than that of the primary energy demand.

(2) Decarbonization is the basic characteristic of the structural changes to the energy supply and demand. Non-fossil energy will replace oil as the second largest energy source prior to 2030, but coal will remain the largest energy source.

(3) Energy-related carbon emissions may peak in 2025 due to the application of consumption patterns focusing on higher energy efficiency and more low-carbon energy supply modes.

(4) As the primary method for non-fossil energy development and utilization, power generation produces nearly half of carbon emissions. Therefore, the decarbonization of the power supply system is a key factor in achieving peak carbon emissions as soon as possible and in reducing the peak value of carbon emissions.

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