Modelling and discussion on emission reduction transformation path of China's electric power industry under "double carbon" goal

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ABSTRACT

China has promised to peak carbon emission before 2030 and to achieve carbon neutrality before 2060 (i.e., “double carbon” goal). Under this background, the emission reduction transformation path of China’s electric power industry is studied in this paper. First, several boundary conditions (i.e., assumptions) of electric power structure transformation (i.e., the costs of power generations, the costs of energy storage systems, the developments of carbon sinks, the emission factors, and the quotas of carbon sinks) are given considering the whole society electricity consumption in the future. Second, a transformation path optimization model is established aiming to minimize the total cost in the electric power industry. Then, according to the optimization results, the transformation predictions for the power industry under the “30⋅60 scenario” (i.e., the scenario that can achieve carbon peak and carbon neutrality before 2030 and 2060) are analyzed in detail, and are compared with the ones of “2 °C scenario” and “1.5 °C scenario” defined by IPCC. Furthermore, the influence of different carbon prices on the transformation path is also analyzed. It can be concluded from the simulation results that the “30⋅60 scenario” is a scenario between “2 °C scenario” and “1.5 °C scenario”, and carbon emission can be reduced rapidly under the guidance of high carbon prices.

1. Introduction

Global warming is one of the most concerning problems in the world, which is related to the survival and sustainable development of all human beings. If countries around the world continue to follow the current development pattern, the global temperature rise will directly threaten the survival of human beings by the middle of this century [1]. Therefore, as early as 1992, the UNFCCC [2] was adopted, in which the emission reduction obligations of developing and developed countries were briefly divided. In 1997, the United Nations adopted the Kyoto Protocol [3]. Since then, countries around the world have been conducting consultations on climate change and related topics. Later in 2015, the Paris Agreement [4] was adopted, which proposed that all countries in the world should uphold the principle of common but differentiated responsibilities. Nationally Determined Contributions (NDCs) have been proposed by the agreement to limit temperature rise of the earth to 2 °C or 1.5 °C by the end of the 21st century [5].

Reducing greenhouse gas emission contribute to combating climate change of the earth, while CO2 emissions account for 75% and more than 80% of greenhouse gas emissions in the world and of China respectively. Therefore, the core of China’s greenhouse gas emission reduction is to reduce CO2 emissions. At the 75th Session of the General Assembly of United Nations held in 2020, China sincerely promised that she would increase the NDC, adopt more powerful policies and measures, and strive to reach the peak and neutrality of CO2 emissions by 2030 and 2060 [6], which is also referred to as “double carbon” goal. (“double carbon” means carbon peaking and carbon neutrality). In December of the same year, at the Climate Ambition Summit, it is further proposed that, before 2030, China’s carbon intensity would fall by more than 65% from the level in 2005 [7]. Therefore, three typical scenarios for reducing the carbon dioxide emissions are utilized to study the carbon dioxide reduction path of China, i.e., (1) “30⋅60 scenario” which aims to peak CO2 emissions by 2030 and neutralize it by 2060; (2) “2 °C scenario” which aims to reduce the net CO2 emissions of the whole society to 2 billion tons; and (3) “1.5 °C scenario” which aims to peak CO2 emissions by 2025...
and neutralize it by 2050. All three carbon dioxide emission reduction scenarios would have socio-economic impacts and slow down the economic development of China in the short term. However, the technical progress during carbon dioxide emission reduction will stimulate economic development in the long term as well. Generally speaking, the socio-economic impacts of the "1.5 °C scenario" are more intense than the "30-60 scenario", and further more intense than the "2 °C scenario". Therefore, a trade-off between CO2 emission reduction and economic development should be considered comprehensively.

According to Refs. [8] and [9], most of China’s CO2 emissions are caused by energy and industrial production activities, and the emissions from the electric power industry accounted for 40.5% of the total CO2 emissions in 2020. According to national statistics, China’s annual per capita electricity consumption in 2020 was 5,200 kWh, compared with 8,000 kWh in the OECD, and 12,800 kWh for the United States. With the further implementation of the "double substitution" strategy (i.e., "electricity substitution" and "clean substitution") in the future, it can be predicted that the proportion of electricity in the terminal energy consumption will be greatly increased, a higher proportion of fossil energy will also be in a more efficient way to use electricity, thus reducing energy activities of the overall carbon emissions. However, it will transfer some carbon emissions originally belonging to primary energy to the electric power industry, and further increase the emission proportion of electric power industry in the future. In fact, as the hub of energy conversion and power replacement [10], the carbon emissions of the power industry will directly determine the CO2 emissions of the energy industry in the future and have a profound impact on the total emissions of the whole society in China. Therefore, the power industry is the core hub of energy transformation and the central link to carbon emission reduction in China.

In the past, several studies focused on the low carbon transition path of China. In [11], the authors studied how to peak the CO2 emissions before 2030 and realize a cost-effective transition for the energy economy. It is pointed out that effective policies and programs are required to solve the problem of potential energy emissions. However, Reference [11] did not discuss the specific issues in the power industry. In [12], the scenario analysis and Logarithmic Mean Divisia Index (LMDI) are utilized to predict the impacts and potential reduction of carbon dioxide emissions. In [13], it is pointed out the power industry has the most potential for CO2 emission reduction and it is more important to reduce the carbon intensity of electricity generation. In [14], a long-term power generation expansion planning (LPGWGP) model is proposed considering the integration costs of renewable energy sources (RES), which aims to determine the cost-effective low pathway for the carbon transition of the power industry in China. Although there are many predictions about the future power structure in China in the previous studies, few specific mathematical models and detailed boundary conditions are given.

In this context, this paper studies the emission reduction transformation path of China’s electric power industry, and take the influence of various factors into consideration, such as the economy through mathematical modelling optimization, so as to provide corresponding ideas for the transformation path of China’s power structure. First, several boundary conditions and hypotheses are introduced. Second, a transformation path model is proposed to minimize the total cost of CO2 emission reduction transformation in the power industry under the background of "30-60”. Then, combined with three typical scenarios, the power structure and power generation ratio are analysed in detail. Next, other factors that need to be considered in building the "new type of power system" and in the transition to emission reduction are pointed out. Finally, corresponding conclusions and prospects of this paper are given.

2. Boundary conditions for "double carbon" studies

In order to simulate the emission reduction transformation path of the power industry accurately, it is necessary to assume the boundary conditions including the power consumption of the whole society, wind power, photovoltaic, energy storage, the carbon sink provided by LULUCF, the carbon sink provide by CCUS, emission factors of the power industry, carbon sink quota of the power industry and other factors. For the convenience of formula derivation, WD, PV, NU, HY, CO, GS, BE, ESS, RS and DR respectively represent wind power, photovoltaic, nuclear power, hydropower, coal, gas, biomass energy, energy storage, reserved resources and demand response when no confuse arises. T represents the study period of this paper, and t is the time variable. t = 0 stands for the year 2020 and t = 1 for the year 2021. The rest is presented in a similar manner.

2.1. Forecast of the whole society electricity consumption

Forecasting the whole society electricity consumption can help to reasonably plan the generation capacity to be installed for each year. Generally speaking, the growth of electricity consumption in a country has a strong relationship with the growth of Gross Domestic Product (GDP). Table 1 shows the changes of GDP and electricity consumption of China in whole society from 2016 to 2020. It can be seen that the electricity growth is slightly lower than that of GDP. However, with the continuous promotion of the "electricity substitution" strategy [15], more energy will be utilized in the form of electricity and the increment of this part needs additional consideration.

Therefore, the medium- and long-term forecast of China’s total social electricity from 2020 to 2060 is decomposed into two parts: GDP electricity $E_{GDP}(t)$ and energy replacement $E_{rel}(t)$. Based on the assumption that the GDP growth rate is about 5.0% per year during the 14th “Five-year Plan” period, 4.5% per year from 2026 to 2030, 4.0% per year from 2031 to 2035 and 3% per year after 2035, the average growth rate of electricity related to GDP in the corresponding period is predicted to be 4.0%, 3.0%, 2.0% and 1.1% respectively. It should be noted that several studies are focusing on predicting the GDP and electricity growths of China [16, 17, 18], however, most of them only gave short-term predictions. Therefore, the GDP and electricity growth after 2030 are assumed by the authors according to our experience indeed. The corresponding expression is given as equation (1).

$$E_{GDP}(t) = \begin{cases} 7.51 \times (1 + 4.0\% \cdot t) & 1 \leq t \leq 5 \\ 9.01 \times \{1 + 3.0\% \cdot (t - 5)\} & 5 < t \leq 10 \\ 10.36 \times \{1 + 2.0\% \cdot (t - 10)\} & 10 < t \leq 15 \\ 11.40 \times \{1 + 1.1\% \cdot (t - 15)\} & 15 < t \leq 50 \end{cases} \quad (1)$$

where t is the time variable, and t = 0 for the base year 2020 and it is noted that the coefficient 7.51 is the electricity consumption in 2020, which is the actual historical value. The coefficients 9.01, 10.36, and 11.40 are respectively the electricity consumption in 2025, 2030, and 2035, which are the predicted values. Similarly, the actual electricity substitution of China is trillion 0.14 trillion kWh [19], and it is assumed that the average growth rate of electricity substitution in China is 40% according to the compromise between two scenarios mentioned in Ref. [15], therefore, the corresponding expression can be determined as equation (2).

Table 1. China’s and GDP total social electricity consumption in 2016-2020.

| Year   | GDP (Billions CNY) | Growth Rate (%) | Electricity Consumption (Trillion kWh) | Growth Rate (%) |
|--------|--------------------|-----------------|---------------------------------------|-----------------|
| 2016   | 74,639.5           | 7.8             | 5.92                                  | 5.0             |
| 2017   | 83,203.6           | 6.9             | 6.30                                  | 6.6             |
| 2018   | 91,928.1           | 6.7             | 6.84                                  | 8.5             |
| 2019   | 98,651.5           | 6.0             | 7.23                                  | 4.5             |
| 2020   | 101,598.6          | 2.3             | 7.51                                  | 3.1             |
| Average| 90,004.3           | 5.9             | 6.76                                  | 5.5             |

Data Source: https://data.stats.gov.cn/english/easyquery.htm?cn=C01.
Based on the above assumptions, the whole society electricity consumption of China in 2030, 2040, 2050 and 2060 can be calculated and obtained as shown in Table 2, reaching 9.71, 13.29, 15.10 and 16.91 trillion kWh respectively, which will be one of the boundary conditions of the model proposed in this paper.

### 2.2. Future development forecast of wind power and photovoltaic

Wind power and photovoltaic are the keys to achieving “clean substitution” and decarbonization of the electric power industry. In recent years, wind power and photovoltaic have been developing rapidly in China. According to Refs [20] and [21], the installed generation capacity of wind power in China has reached 282GW, the corresponding annual average utilization hours are 2097 in 2020. Besides, the capacity cost of wind power in China is about 6,000 CNY/kW, and the average on-grid electricity price of wind power in China is about 0.525 CNY/kWh. Furthermore, the installed photovoltaic capacity has reached 253GW in 2020, generating 260.5 billion kWh. The capacity cost is about 4,500 CNY/kW, and the average on-grid price is 0.41 CNY.

Under the market environment, the main factors affecting the future development of wind power and photovoltaic are their unit capacity cost and power generation cost. Therefore, it is assumed in this paper that the unit capacity cost $c_{\text{CS}}^\text{t}(t)$ and unit power generation operating cost $c_{\text{OP}}^\text{t}(t)$ of wind power are reduced by a compound annual reduction rate of 6.5% and 3.0%, respectively. The unit capacity cost of photovoltaic $c_{\text{PV}}^\text{t}(t)$ and unit power generation operating cost $c_{\text{OP}}^\text{t}(t)$ are reduced at the compound rate of 7.0% and 3.5% per year, respectively, which can be expressed as equations (3)–(6).

\[
c_{\text{OP}}^\text{t} = 0.14 \times (1 + 40\% \cdot t)
\]  
\[
c_{\text{PV}}^\text{t} = 0.525 \times (1 - 3.0\% \cdot t)
\]  
\[
c_{\text{CS}}^\text{t} = 4500 \times (1 - 7.0\% \cdot t)
\]  
\[
c_{\text{OP}}^\text{CS} = 0.410 \times (1 - 3.5\% \cdot t)
\]  

where the unit of installed cost is CNY/kW, and unit of electricity cost is CNY/kWh.

### 2.3. Cost forecast of energy storage systems

Large-scale penetration of intermittent energy would cause great uncertainty to the power system, change the original scheduling pattern and bring great challenges to the security of power system operation [22, 23]. Therefore, in the future, Energy Storage System (ESS) will be quite important in smoothing the fluctuations of both sources and loads. By the end of 2020, the construction cost of ESS has been reduced to about 1, 500 CNY/kWh. Assuming that it still reduces with a compound reduction rate of 6.5% [24, 25, 26], then the following equation can be obtained as equation (7).

\[
c_{\text{ES}}^\text{t} = 1500 \times (1 - 6.5\% \cdot t)^t
\]

where $c_{\text{ES}}^\text{t}(t)$ is the unit capacity construction cost of the ESS in year $t$. Besides, considering the charge, discharge and operation losses, it is assumed that the unit operation cost of the ESS is 0.05CNY/kWh, which can be given as equation (8).

\[
c_{\text{OP}}^\text{ES} = 0.05
\]

### 2.4. Forecast for the development of LULUCF and CCUS

Since it is impossible for human activities to completely avoid carbon dioxide emissions, the ultimate realization of carbon neutrality depends on large-scale emission reduction to “near-zero” emissions. On the other hand, the development of the carbon sinks provided LULUCF [27] and CCUS, and other carbon sinks to absorb the final remaining carbon dioxide to achieve “net-zero” CO₂ emissions. According to the Climate Change Report of the People’s Republic of China [28], China’s LULUCF absorbed 1.115 billion tons of equivalent CO₂ in 2014. During the 6th National Forest Inventory (NFI) of China (i.e., 1999–2003), China’s forest stock was 12.4 billion cubic meters, and the value increased to 13.7, 15.1 and 17.5 billion cubic meters during the 7th, 8th, and 9th NFI (i.e., 2004–2008, 2009–2013, and 2014–2018), respectively [29] with an average growth rate of 2.7% annually. Since the contribution of LULUCF absorption rate mainly comes from the forest carbon sink, therefore, the growth rate of the carbon sink of LULUCF can be approximately regarded as the same as the growth rate of forest stock. Therefore, this paper assumes that China’s future LULUCF carbon sink absorption will increase with an average growth rate of 2.7% annually and the expression can be denoted as equation (9).

\[
M_{\text{LULUCF}}(t) = 1.115 \times \left[1 + 2.7\% \cdot (t + 2020 - 2014 + 1)\right]
\]

According to Refs. [30] and [31], China’s current CCUS annual carbon dioxide absorption is 1–10 million tons, and the world’s CCUS will reach 5.6 billion tons by 2050. In Ref. [32], the research predicted that the carbon dioxide emission captured by CCUS from China will respectively reach 0.4, 1.6, and 2.2 billion tons in 2030, 2050, and 2070. Based on these data, the carbon dioxide captured by CCUS from 2021 to 2060 in China can be approximately piecewise linear fitted as equation (10).

\[
M_{\text{CCUS}}(t) = \begin{cases} 
0.0399t + 0.001 & 0 \leq t < 10 \\
0.06(t - 10) + 0.4 & 10 \leq t < 30 \\
0.03(t - 30) + 1.6 & 30 \leq t < 50
\end{cases}
\]

Based on the above assumptions, the medium and long-term carbon sink absorption in China can be obtained as shown in Table 3. It can be found that the carbon sinks associated with LULUCF and CCUS of China are expected to reach 4.43 billion tons in total by 2060, which can support the realization of carbon neutrality.

### 2.5. Carbon sink quota and emission factor of electric power industry

It should be noted that the carbon sink absorption mentioned in section 1.4 is the total amount of the whole society. Specifically, the power industry can only get a certain quota by realizing “double carbon” goal and emission reduction transformation. As mentioned in Section 1,
the CO₂ emissions of electric power industry of China accounted for about 40.5% of total social emissions in 2020. Considering the two positive and negative factors, namely, the increase of electricity generation brought by the substitution of electric energy and the lower difficulty of unit emission reduction in the power industry compared with other industries, this study takes 40% of the total social carbon sink as the carbon sink quota of the power industry.

In addition, different types of generator units emit different amounts of carbon dioxide per unit of electricity generated. The IPCC database [33] shows the carbon dioxide emission factors for different fuels and different power generation technologies. In order to simplify the subsequent calculation, the difference between the same primary energy generation by different specific units are not distinguished in this paper. It is assumed that the carbon dioxide emission factor of coal-fired units and gas-fired units is 0.9kg/kWh and 0.4kg/kWh, respectively, and the carbon dioxide emission of nuclear power, photovoltaic, hydropower, and wind power units can be nearly ignored during operation.

2.6. Other boundary conditions

In the subsequent optimization model of emission reduction transition path, some boundary conditions including unit construction and operation cost of nuclear power, hydropower, coal-fired power and gas generation, unit cost of reserve capacity and electricity, unit cost of user demand-side response and carbon price should be given in advance, and they are shown in Table 4.

3. Optimization model of emission reduction transition path for electric power industry of China under the "double carbon" goal

According to the national plan of China, China’s current and future electric power sources are mainly composed of coal-fired power, wind power, gas-fired power, nuclear power, photovoltaic, hydropower, and biomass energy. Among them, coal and gas are the main carbon emissions sources, while the carbon emissions of wind power, photovoltaic power, nuclear power and hydropower are negligible. Biomass energy can consume a large amount of methane, so its equivalent carbon dioxide emissions in the greenhouse effect can be regarded as a negligible value.

Therefore, aiming at minimizing the total social cost, the objective function is constructed as equations (11)-(16).

\[
\min \left\{ \sum_{t=1}^{T} \sum_{i \in \Omega_{\text{Gen}}} C_i(t) + \sum_{j \in \Omega_{\text{DR}}} C^\text{OP}(t) + \sum_{k \in \Omega_{\text{Anc}}} C_k(t) \cdot \rho(t) \right\} \quad (11)
\]

\[
C_i(t) = C^\text{CS}(t)S^\text{CS}(t) + C^\text{DR}(t)E^\text{OP}(t) \quad i \in \Omega_{\text{Gen}} \quad (12)
\]

\[
C^\text{OP}(t) = a_iE^\text{OP}(t)p(t) \quad j \in \Omega_{\text{DR}} \quad (13)
\]

\[
C_{\text{ESS}}(t) = c_{\text{ESS}}^\Omega(t)[S^\text{ESS}(t) + C^\text{DR}(t)p^\text{DR}(t) + F^\text{ESS}(t)] \quad (14)
\]

\[
C_{\text{GS}}(t) = c_{\text{GS}}^\Omega(t)[S^\text{GS}(t) + C^\text{DR}(t)p^\text{DR}(t)] \quad (15)
\]

\[
C_{\text{Br}}(t) = c_{\text{Br}}^\Omega(t)E^\text{OP}(t) \quad (16)
\]

where \( \rho(t) = (1 + r)^{-t} \) is the conversion coefficient for costs from year \( t \) to the final year \( T \), and \( r \) is the discount rate. \( \Omega_{\text{Gen}} = \{\text{WD}, \text{PV}, \text{NU}, \text{HY}, \text{CO}, \text{GS}, \text{BE}\} \), \( \Omega_{\text{Anc}} = \{\text{ESS, RS, DR}\} \), \( \Omega_{\text{DR}} = \{\text{CO, GS, BE}\} \) are the sets of power equipment related to power generation, ancillary services and carbon emissions, respectively. \( C_i(t), S^\text{CS}(t), C^\text{DR}(t), S^\text{ESS}(t) \) and \( E^\text{OP}(t) \) respectively represent the total cost, unit installed capacity cost, unit operation price, newly installed generation capacity and electricity generation of the \( j \)th type \( (j \in \Omega_{\text{DR}}) \) of electric energy in year \( t \). \( C^\text{OP}(t), \sigma_i \) and \( E^\text{OP}(t) \) represent the carbon cost, emission factor and generation capacity of the \( j \)th type of electric energy in year \( t \), respectively. \( C_{\text{GS}}(t), C_{\text{ESS}}(t), C^\text{DR}(t), S^\text{CS}(t), S^\text{ESS}(t), E^\text{OP}(t) \) and \( F^\text{ESS}(t) \) represent the total cost of ESS, unit installed capacity cost, unit operation cost, new capacity, charge quantity and discharge quantity in year \( t \), respectively. \( C_{\text{GS}}(t), c_{\text{GS}}^\Omega(t), S_{\text{GS}}(t), c^\text{DR}(t) \) and \( E_{\text{GS}}(t) \) represent the total cost, unit capacity cost, reserve capacity, unit electricity cost and reserved electricity of reserved resources in year \( t \), respectively. \( C_{\text{Br}}(t), c_{\text{Br}}^\Omega(t) \) and \( E_{\text{Br}}(t) \) represent the total cost, unit response cost and response electricity of the demand-side response in year \( t \), respectively. Concretely, equation (12) denotes the construction and operation cost of the \( j \)th generation source \( (i \in \Omega_{\text{Gen}}) \), and it constitutes the first term of square brackets in the objective function (11). Equation (13) denotes the social cost associated with carbon dioxide emitted by the \( j \)th emission source \( (j \in \Omega_{\text{DR}}) \) for the power industry (e.g., social tax), and it constitutes the second term of square brackets in the objective function (11). Equations (14)-(16) denote the construction and/or operation costs of the \( k \)th auxiliary services \( (k \in \Omega_{\text{Anc}}) \) associated with energy storage systems, reserved resources, and demand-responses, and they constitute the third term of square brackets in the objective function (11).

In order to ensure the secure and stable society electricity consumption, the smooth transformation of emission reduction, and the “double carbon” requirements can be achieved [36, 37], the above macro requirements that need to be considered in the process of emission reduction transformation are modelled as equations (17)-(27).

\[
S^\text{CS}(t) = S^\text{CS}(t - \tau_i) + \sum_{\sigma=1}^{\tau_i} S^\text{CS}(t - \sigma) \quad i \in \Omega_{\text{Gen}} \quad (17)
\]

\[
S^\text{DR}(t) = S^\text{DR}(t - \lambda_i) \quad i \in \Omega_{\text{Gen}} \quad (18)
\]

\[
E^\text{OP}(t) = u_i(t)S^\text{OP}(t) + \rho(t) \quad i \in \Omega_{\text{Gen}} \quad (19)
\]

\[
\sum_{i \in \Omega_{\text{Gen}}} E^\text{OP}(t) \geq E_{\text{GS}}(t) + E_{\text{Br}}(t) \quad (20)
\]

\[
\left[\frac{c_{\text{GS}}^\Omega(t) + c_{\text{Br}}^\Omega(t)}{2 \cdot \eta_{\text{ESS}}} \sum_{i \in \Omega_{\text{Gen}}} E^\text{OP}(t)\right] \quad (21)
\]

Table 4. Value settings of other boundary conditions.

| Boundary Conditions | Value | Boundary Conditions | Value |
|---------------------|-------|---------------------|-------|
| \( c_{\text{GS}}^\Omega(t) \) | 10,000 | \( c_{\text{Br}}^\Omega(t) \) | 0.385 |
| \( c_{\text{GS}}^\Omega(t) \) | 2,000 | \( c_{\text{Br}}^\Omega(t) \) | 0.210 |
| \( c_{\text{GS}}^\Omega(t) \) | 3,000 | \( c_{\text{Br}}^\Omega(t) \) | 0.385 |
| \( c_{\text{GS}}^\Omega(t) \) | 2,800 | \( c_{\text{Br}}^\Omega(t) \) | 0.700 |
| \( c_{\text{Br}}^\Omega(t) \) | 10 | \( c_{\text{Br}}^\Omega(t) \) | 1,000 |
| \( c_{\text{Br}}^\Omega(t) \) | 20 | \( p(t) \) | 200 |

Note: the data is forecasted based on Refs. [34, 35] where \( c_{\text{GS}}^\Omega(t), c_{\text{Br}}^\Omega(t), c_{\text{GS}}^\Omega(t) \) and \( c_{\text{Br}}^\Omega(t) \) are the unit capacity construction costs of nuclear, hydropower, coal and gas units in year \( t \), respectively. \( c_{\text{GS}}^\Omega(t), c_{\text{Br}}^\Omega(t), c_{\text{GS}}^\Omega(t) \) and \( c_{\text{Br}}^\Omega(t) \) are the unit electricity price of nuclear power, hydropower, coal and gas units in year \( t \), respectively. \( c_{\text{GS}}^\Omega(t) \) and \( c_{\text{Br}}^\Omega(t) \) are respectively the unit capacity of reserved resources and the corresponding unit cost of electricity of reserved resources in year \( t \), and \( c_{\text{GS}}^\Omega(t) \) is the unit demand-side response electricity cost in year \( t \). It is noted that the values of \( c_{\text{GS}}^\Omega(t), c_{\text{Br}}^\Omega(t) \) and \( c_{\text{Br}}^\Omega(t) \) are determined according to the average values of the actual operation and market data in Zhejiang province and Jiujiang province of China. \( p(t) \) is the unit carbon price in year \( t \), which is a variable in this paper and will be further studied in sections 4 and 5. It should be noted that the cost unit related to capacity is CNY/kW, the unit of the cost related to electricity is CNY/kWh, and the unit related to the carbon price is CNY/ton.
Therefore, constraint (25) denotes the physical rule of net carbon dioxide emission. Constraints (26) and (27) represent the relationships between the installed generation capacity of all types of power sources in year \( t \). Constraint (26) establishes the relationship between installed generation capacity and electricity generation in year \( t \) and the decommissioning capacity and electricity generation trend, installed capacity and generation proportion, power generation trend, installed capacity and generation proportion respectively make up for 15.56%, 14.08%, 8.68%, 15.70%, 42.27%, 10.54%, 31.16%, 2.57% and 1.21% in 2030 and power generation will reach 33.57%, 28.76%, 32.00%, 47.26%, 1.64%, 7.25%, 5.02%, 5.08%, 1.74%, and the proportion of installed capacity will reach 10.42%, 2.29%. In 2060, the proportion of installed capacity will reach 33.57%, 28.76%, 32.00%, 47.26%, 1.64%, 7.25%, 5.02%, 5.08%, 1.74%, and the proportion of electricity generation will reach 33.57%, 28.76%, 5.79%, 14.56%, 9.09%, 3.78%, 4.45%, respectively. In addition, non-fossil energy is expected to account for 56.31% of the total electricity generation by 2030 and 87.13% by 2060, greatly reducing \( \text{CO}_2 \) emissions.

Based on the emission reduction transformation model, the carbon emission reduction path of electric power industry of China under the above different scenarios can be obtained and is shown in Figure 1.

The prediction results of China's power structure transformation and generating capacity based on the model proposed in this paper under the "30·60 scenario" and corresponding prediction results of installed capacity proportion, power generation trend, installed capacity and generation capacity are shown in Figure 2, Figure 3, Table 5 and Table 6, respectively. The forecasting results under the "2·C scenario" and "1·5·C scenario" can be seen in Fig. A1-A4 and Table A1-A4 of Appendix.

In order to illustrate the effects of the carbon trading market and different carbon prices on carbon emission reduction and emission reduction transition path, this paper presents the results of the "30·60 scenario" when carbon prices are 0 CNY/t (i.e., without considering carbon market), 100 CNY/t, 200 CNY/t, 300 CNY/t, and 400 CNY/t. Among them, the \( \text{CO}_2 \) emission reduction path of electric power industry of China is shown in Figure 4, and the corresponding power generation types in 2060 are shown in Table 7.

4. Simulation results of transition path under different typical scenarios

In previous studies, "policy scenario", "enhanced policy scenario", "2·C scenario" and "1·5·C scenario" were generally used for discussion, among which "policy scenario" and "enhanced policy scenario" were both based on the NDC proposed by China in the Paris Agreement. With the announcement that China will increase its NDC and reach the carbon peak and neutrality by 2030 and 2060, the "double carbon" goal has become the new "policy scenario", while the old "policy scenario" and "enhanced policy scenario" have lost their significance for discussion. Therefore, in order to avoid confusion, the new "policy scenario" is called the "30·60 scenario", and the "2·C scenario" and "1·5·C scenario" proposed by IPCC are considered to study the typical scenario of China's energy emission reduction path. These three typical scenarios can be defined through the carbon dioxide emission requirements as:

- (1) "30·60 scenario": carbon emissions are peaked by 2030 and neutralized by 2060;
- (2) "2·C scenario": carbon emissions are peaked around 2025. In 2050, the net carbon dioxide emissions of the whole society will be about 2 billion tons, which is equivalent to about 800 million tons of net carbon dioxide emissions of the power industry.
- (3) "1·5·C scenario": carbon emissions are peaked before 2025 and basically achieve net-zero carbon dioxide emissions by 2050.

As can be seen from Figure 1, the emission reduction path of "30·60 scenario" lies between "2·C scenario" and "1·5·C scenario", and is similar to that of "2·C scenario". Therefore, "30·60 scenario" can be considered as an emission reduction path that is slightly stricter than "2·C scenario" but looser than "1·5·C scenario". In addition, the carbon emission reduction paths in the three scenarios show a trend of being slow at first, speeding up later and slowing down again. The reasons could be: (1) the "carbon lock-in" effect of coal and gas generators in the initial stage of emission reduction. (2) In the later stage of emission reduction, the growth rates of clean energy (e.g., wind power and photovoltaic) slow down due to the difficulty of secure and stable operation after large-scale penetration of intermittent energy sources.

As shown in Figure 1, the time of peaking \( \text{CO}_2 \) emission in the power industry under the three scenarios is around 2024, and the peak is about 4.236 billion tons, all of which have realized the peak requirements under their respective scenarios in advance. This is because the model proposed in this paper further considers the carbon price (200 CNY/t), and reaching the peak in advance is conducive to reducing the total social cost. In terms of the time for achieving carbon neutrality, the "30·60 scenario" will achieve net-zero emissions by 2060. The "2·C scenario" would still emit 215 million tonnes in 2060. The "1·5·C scenario" will achieve net-zero \( \text{CO}_2 \) emissions by 2050 and negative emissions of 585 million tonnes by 2060.
Figure 1. Carbon emission reduction paths of the electric power industry in China under different scenarios.

Figure 2. Prediction of power structure transformation of China under the "30⋅60 scenario".

Figure 3. Prediction of electricity generation of China under the "30⋅60 scenario".
It should be noted that the results predicted in this paper are based on the proposed goal of minimizing the total social cost, which may be different from the results predicted by other scholars but the general trend and order of magnitude are the same [38, 39]. It can be seen that photovoltaic and wind power generation will get leap-forward development, biomass power generation will have a large increase, nuclear power, hydropower, gas-fired power generation will have a moderate increase, and coal-fired power generation will be reduced considerably. Wind power and photovoltaic are both clean energy sources with almost no carbon dioxide emissions. Besides, their technological development capacity in China is huge and their cost is also falling rapidly [40], as a result, they are developing rapidly. Although nuclear power and hydropower are also clean energy, the cost of nuclear power is high and the construction time is long as well. The technical development capacity of hydropower in China is limited [41], and therefore its growth rate is comparably slow. Gas-fired power generation will also emit carbon dioxide, but its emissions are only half that of coal-fired electricity generation, and it will be an important peak regulation resource when more intermittent energy is penetrated to power systems in the future, thus gas-fired power generation will also have a certain proportion of growth. Bioenergy with Carbon Capture and Storage (BECCS) can achieve negative CO₂ emissions [42], but its installed capacity is limited by biomass raw materials, so the power generation growth rate is fast but the absolute value is not high.

By comparing Figure 2, Figure 3, Fig. A1, Fig. A2, Table 5, Table 6, Table A1 and Table A2, it can be found that the main difference in the forecasting results of the three scenarios lies in the change of coal-fired power. Under the “2 °C scenario”, the proportion of coal-fired power installation is 5.97%, and the proportion of electricity generation is 10.85% in 2060. In the “1.5 °C scenario”, the coal-fired power generation ratio is 2.75% and the power generation ratio is 4.68% in 2060, while the coal-fired power gap is mainly replaced by nuclear power with higher cost. Therefore, it can be speculated that the development trend of coal-fired power will play a critical role in the realization of carbon emission reduction and temperature control goals of electric power industry of China in the future. At the same time, if the 1.5 °C goal is forced to be achieved, it will cause relatively high social costs.

It can be seen from Figure 4, when the carbon price is not considered or set relatively low (e.g., 100 CNY/ton, 200 CNY/ton and 300 CNY/ton), Table 5. Prediction of installed capacity of different types of power sources in China under the “30⋅60 scenario”.

| Year | WD  | PV  | NU  | HY  | CO  | GS  | BE  |
|------|-----|-----|-----|-----|-----|-----|-----|
| 2020 | 282 | 253 | 51  | 370 | 1,245 | 100 | 23  |
| 2025 | 378 | 613 | 81  | 376 | 1,245 | 100 | 32  |
| 2030 | 778 | 1,213 | 129 | 410 | 1,212 | 100 | 47  |
| 2035 | 1,178 | 1,813 | 129 | 450 | 962  | 125 | 62  |
| 2040 | 1,578 | 2,413 | 129 | 490 | 712  | 200 | 77  |
| 2045 | 1,898 | 3,013 | 129 | 530 | 523  | 200 | 92  |
| 2050 | 1,898 | 3,482 | 129 | 570 | 491  | 265 | 107 |
| 2055 | 2,134 | 3,714 | 129 | 570 | 443  | 340 | 122 |
| 2060 | 2,515 | 3,714 | 129 | 570 | 395  | 399 | 137 |

Unit: GW.

Table 6. Electric power generation prediction of different types of power sources in China under the “30⋅60 scenario”.

| Year | WD  | PV  | NU  | HY  | CO  | GS  | BE  |
|------|-----|-----|-----|-----|-----|-----|-----|
| 2020 | 620 | 323 | 377 | 1,558 | 4,829 | 156 | 123 |
| 2025 | 831 | 782 | 599 | 1,583 | 5,249 | 156 | 171 |
| 2030 | 1,711 | 1,548 | 954 | 1,726 | 4,648 | 156 | 252 |
| 2035 | 2,591 | 2,313 | 954 | 1,894 | 4,054 | 195 | 332 |
| 2040 | 3,471 | 3,079 | 954 | 2,063 | 2,872 | 312 | 412 |
| 2045 | 4,175 | 3,845 | 954 | 2,231 | 1,983 | 312 | 493 |
| 2050 | 4,175 | 4,443 | 954 | 2,400 | 1,864 | 414 | 573 |
| 2055 | 4,694 | 4,739 | 954 | 2,400 | 1,680 | 531 | 653 |
| 2060 | 5,533 | 4,739 | 954 | 2,400 | 1,498 | 623 | 734 |

Unit: TWh.

Table 7. Prediction of installed capacity of different types of power sources in China in 2060 with different carbon prices considered under the “30⋅60 scenario”.

| Type | Carbon Price (CNY/ton) |
|------|------------------------|
| WD   | 32.66% 34.02% 32.00% 30.26% 39.61% |
| PV   | 46.04% 45.19% 47.26% 48.41% 38.30% |
| NU   | 1.16% 1.16% 1.64% 2.20% 2.54% |
| HY   | 8.31% 7.80% 7.25% 7.32% 7.89% |
| CO   | 5.06% 5.05% 5.02% 5.01% 3.86% |
| GS   | 5.02% 5.04% 5.08% 5.04% 5.96% |
| BE   | 1.75% 1.75% 1.74% 1.76% 1.84% |

Figure 4. Carbon emission reduction paths of the electric power industry in China under the “30⋅60 scenario” with different carbon prices considered.
the optimized paths based on the proposed model will reach carbon neutrality in 2060. When the carbon price is set high (e.g., 400 CNY/ton), China's power industry will be neutralized in advance in 2057. It can also be seen from Figure 4 that when the carbon price is not taken into account, the emission reduction path after the peak will have a quite long plateau period, and will not significantly decline until 2036. When the carbon price is increased, the plateau period after the peak will gradually shorten, which shows that reasonable carbon price contributes to guiding the rapid emission reduction of carbon dioxide.

It can be seen from Table 7 that the proportion of clean energy will be greatly increased with the increase of carbon price, while the proportion of gas-fired power generation and biomass power generation has been generally stable and slightly increased with the increase of carbon price. The main reason is although biomass energy is negative emission energy, the available amount is limited, and gas-fired power generation, as an important peak regulation resource, also needs to maintain a certain proportion.

From the perspective of carbon price change, the results show that the proportion of all kinds of power supply is roughly stable if the carbon price is 0–200 CNY/ton. The proportion of nuclear power will increase greatly when the carbon price is low if the carbon price is 300 or 400 CNY/ton. The proportion of coal-fired power generation will decline rapidly if the carbon price is 400 CNY/ton. This is because the use of coal will greatly increase the total cost of the whole society with the rise of carbon prices. In the case of large-scale penetration of intermittent energy (e.g., wind power and photovoltaic), the share of coal-fired power will be replaced by nuclear power. This result is also consistent with the analysis aforementioned.

6. Conclusions

In this paper, the optimization model of emission reduction transformation path is proposed to minimize the total transformation cost of electric power industry under the ‘double carbon’ background. The corresponding boundary conditions are given based on the existing statistical data and reasonable assumptions, so as to predict the future power supply structure in China. The optimization results show that ‘30-60 scenario’ is a scenario between ‘2 C scenario’ and ‘1.5 C scenario’. Under the three scenarios, wind power and photovoltaic power will develop rapidly, and non-fossil energy will generate nearly 90% electricity in 2060. At the same time, the setting of carbon prices will directly affect the process of emission reduction. When the carbon price is not set or relatively low, there will be an obvious carbon emission platform period; when the carbon price is high, carbon emissions will decline rapidly under the guidance of economic factors.

The work in this paper is an attempt to model the emission reduction transformation of the power industry in China. Although there are many predictions about the future power structure in China in the previous studies, there are few specific mathematical models and detailed boundary conditions given. At the same time, it should be pointed out that the proposed model only considers the most important macro constraints, and the specific values of related boundary conditions are reasonably extrapolated through statistical data. Therefore, the optimization results can reflect the overall trend of future development, but there may be some bias with the actual situation of future development. In view of this, the impact of information, physics and society on the electric power industry should be considered as much as possible, and the analysis framework of Cyber-Physical-Social-System in Energy (CPSSE) should be further constructed. Therefore, a more accurate prediction of emission reduction path of China under the ‘double carbon’ background is an important research paradigm and research direction in the future.

Declarations

Author contribution statement

Shengyuan Liu: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Zhenzhi Lin, Li Yang, Feng Lu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.
Yicheng Jiang: Conceived and designed the experiments; Analyzed and interpreted the data; wrote the paper.
Tianhan Zhang, Weitao Tan: Analyzed and interpreted the data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.
Appendix A

Fig. A1. Prediction of China's power structure transformation under the "2 °C scenario".

Fig. A2. Prediction of electricity generation of China under the "2 °C scenario".

### Table A1. Prediction of installed capacity of different types of power sources in China under the "2 °C scenario".

| Year | WD  | PV  | NU  | HY  | CO  | GS  | BE  |
|------|-----|-----|-----|-----|-----|-----|-----|
| 2020 | 282 | 253 | 51  | 370 | 1245| 100 | 23  |
| 2025 | 378 | 613 | 81  | 376 | 1245| 100 | 32  |
| 2030 | 778 | 1213| 131 | 410 | 1099| 100 | 47  |
| 2035 | 1178| 1813| 131 | 450 | 958 | 125 | 62  |
| 2040 | 1578| 2413| 131 | 490 | 708 | 200 | 77  |
| 2045 | 1903| 3013| 131 | 530 | 509 | 215 | 92  |
| 2050 | 1913| 3479| 131 | 570 | 469 | 290 | 107 |
| 2055 | 1981| 3911| 131 | 570 | 469 | 322 | 122 |
| 2060 | 2315| 3911| 131 | 570 | 469 | 325 | 137 |

Unit: GW.
Table A2. Electric power generation prediction of different types of power sources in China under the "2 °C scenario".

| Year | WD  | PV  | NU  | HY  | CO  | GS  | BE |
|------|-----|-----|-----|-----|-----|-----|----|
| 2020 | 620 | 323 | 377 | 1558| 4829| 156 | 123|
| 2025 | 831 | 782 | 599 | 1583| 5249| 156 | 171|
| 2030 | 1711| 1548| 969 | 1726| 4632| 156 | 252|
| 2035 | 2591| 2313| 969 | 1894| 4039| 195 | 332|
| 2040 | 3471| 3079| 969 | 2063| 2857| 312 | 412|
| 2045 | 4188| 3845| 969 | 2231| 1931| 335 | 493|
| 2050 | 4209| 4440| 969 | 2400| 1779| 452 | 573|
| 2055 | 4357| 4990| 969 | 2400| 1779| 502 | 653|
| 2060 | 5092| 4990| 969 | 2400| 1789| 506 | 734|

Unit: TWh.

Table A3. Prediction of installed capacity of different types of power sources in China under the "1.5 °C scenario".

| Year | WD  | PV  | NU  | HY  | CO  | GS  | BE |
|------|-----|-----|-----|-----|-----|-----|----|
| 2020 | 282 | 253 | 51  | 370 | 1245| 100 | 23 |
| 2025 | 389 | 613 | 81  | 376 | 1245| 100 | 28 |
| 2030 | 789 | 1213| 131 | 410 | 1195| 100 | 35 |
| 2035 | 1189| 1813| 131 | 450 | 977 | 125 | 43 |
| 2040 | 1589| 2413| 131 | 490 | 727 | 200 | 50 |
| 2045 | 1964| 3013| 131 | 530 | 529 | 200 | 58 |
| 2050 | 1964| 3517| 131 | 570 | 492 | 275 | 65 |
| 2055 | 2205| 3765| 131 | 570 | 446 | 350 | 73 |
| 2060 | 2605| 3774| 131 | 570 | 390 | 421 | 80 |

Unit: GW.

Fig. A3. Prediction of China's power structure transformation under the "1.5 °C scenario".
Table A4. Electric power generation prediction of different types of power sources in China under the “1.5 °C scenario”

| Year | WD | PV | NU | HY | CO | GS | BE |
|------|----|----|----|----|----|----|----|
| 2020 | 620 | 322 | 377 | 1558 | 4829 | 156 | 122 |
| 2025 | 912 | 782 | 599 | 1583 | 5168 | 156 | 171 |
| 2030 | 1792 | 1548 | 969 | 1726 | 4434 | 273 | 252 |
| 2035 | 2672 | 2313 | 1339 | 1894 | 3390 | 393 | 332 |
| 2040 | 3552 | 3039 | 1487 | 2063 | 2103 | 507 | 412 |
| 2045 | 4432 | 3158 | 1803 | 2231 | 1251 | 624 | 493 |
| 2050 | 5028 | 3039 | 2160 | 2400 | 762 | 791 | 573 |
| 2055 | 5177 | 3708 | 2160 | 2400 | 762 | 791 | 573 |
| 2060 | 5912 | 3708 | 2160 | 2400 | 772 | 795 | 734 |

Unit: TWh.
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