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Research on Energy Structure Optimization and Carbon Emission Reduction Path in Beijing under the Dual Carbon Target

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Abstract: In the context of China's dual carbon target, Beijing, as the capital of China, should play an exemplary role in carbon emission reduction. On the premise of optimizing high-emission sectors such as coal and industry, Beijing is still a certain distance from the goal of carbon neutrality. Therefore, on the basis of Beijing's energy resource endowment, considering Beijing's economic development and carbon neutrality goals and scientifically and reasonably planning Beijing's carbon emission reduction path are important tasks. We construct an energy structure optimization model to achieve the goal of carbon neutrality by 2050. The model analysis concludes that the residents and transportation sectors will account for a large proportion of Beijing's total carbon emissions in the future. To achieve the goal of carbon neutrality, the electricity substitution of fossil energy and the high proportion of external power are two necessary measures, and the optimal path of carbon emission reduction is proposed.

Keywords: dual carbon target; carbon emission reduction; path optimization; renewable energy

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1. Introduction

Achieving carbon peak and carbon neutralization is an extensive and profound economic and social systematic change, which is a major strategic decision made by China according to the internal requirements of promoting the responsibility of building a community with a shared future for humanity and realizing sustainable development. According to the gap characterizing China, the European Union, and the United States in carbon neutrality [1], China's commitment to the transition period from carbon peak to carbon neutrality is only 30 years, far shorter than developed countries. As the world's largest carbon dioxide emitter [2], China needs to make more efforts to reduce carbon dioxide and greenhouse gas emissions and transform the economy and energy system. China is a vast country with uneven resource endowments and economic development. All provinces cannot achieve carbon neutrality at the same time. All regions and provinces must formulate and implement differentiated carbon neutralization schemes according to their characteristics. As the capital of China, Beijing is ahead of other provinces in terms of economic and social development; hence, it should not lag behind other provinces in achieving the carbon neutrality goal. It is possible to achieve carbon neutrality by 2050, close to the time of many developed economies and 10 years ahead of the national goal. The low-carbon transformation of energy is significant for developing countries, which can bring them new opportunities for achieving carbon neutrality and leapfrog development [3]. To promote energy transformation, China has made many efforts in energy constitution reform [4] and technological innovation in the power and transportation sector [5], and it has achieved good carbon emission reduction results. Beijing has also implemented a series of low-carbon energy transformation measures. The first was to ease Beijing's noncapital functions [6] and eliminate inefficient, polluting industries, such as the relocation of the

Shougang group and the withdrawal of the coal power industry. The second was to formulate zero-carbon energy subsidy incentive policies [7] and vigorously develop clean energy such as solar and wind energy. The third was to promote the transformation of electric energy on the consumer side [8] and optimize the energy consumption structure, such as coal to electricity and electric vehicle promotion. On the basis of the above measures, Beijing's carbon emissions peaked in 2011, fell to 85 million tons in 2017, but then rose to 88.15 million tons in 2019 [9], due to the gradual elimination of coal in Beijing's energy consumption and the weakening of the driving force of carbon emission reduction. Beijing's energy supply is mainly external transfer. Under the circumstances of insufficient energy resources and limited external transfer of resources, considering economic development and carbon neutrality is a topic worth studying.

In summary, Beijing is facing arduous tasks under the carbon neutral goal: (1) as the capital of China, Beijing should set an example in carbon neutral action; (2) Beijing has formulated and implemented a series of measures for carbon emission reduction and achieved good emission reduction results. However, with economic development, carbon emissions have rebounded; (3) Beijing has limited energy resources, especially for clean energy. Relying on Beijing's energy resources, the emission reduction potential is limited. On the basis of the above three points, Beijing is still far from the carbon neutral target; hence, this paper chose Beijing as the analysis object. Therefore, according to this practical demand, this paper studies the path plan for Beijing to achieve carbon neutrality by 2050, analyzes the energy supply structure, energy consumption structure, and carbon emission distribution under the goal of achieving carbon neutrality, and puts forward policy recommendations for the critical influencing factors.

In the existing research, from the experience of low-carbon transformation in developed countries, the development of renewable energy and power substitution is the crucial factor in the development of urban low-carbon transformation [10,11]. As for the research on the path of carbon emission reduction in Beijing, Zhang et al. (2021) found that the primary source of carbon emission in Beijing has gradually changed from raw coal to natural gas [12], Fan et al. (2022) analyzed the consumption scenario of natural gas under the background of double carbon by building a system dynamics (SD) model, and the conclusion showed that China reached the peak of natural gas use in 2040 [13]. Huang et al. (2022) found that Beijing needs to introduce carbon capture, utilization. and storage (CCUS), carbon sinks, and other emission absorption methods to achieve carbon neutrality in 2060 [14]. Through empirical analysis of the power industry, most scholars found that upgrading the energy structure, energy efficiency [15], and the proportion of renewable energy [16–18] are the main factors in reducing carbon emissions. In addition, Cui et al. (2022) [19] and Chi et al. (2022) [20] analyzed from the perspective of regional synergy that importing green energy and developing regional power trade are also cost-effective emission reduction measures. Bian et al. (2018) analyzed China's carbon emission reduction targets from the perspective of regional differences and concluded that coordinated low-carbon development among regions could effectively promote China's regional carbon emission reduction [21]. Tan et al. (2022) showed that introducing interregional transmission lines can alleviate environmental pressure [22]. However, while vigorously developing renewable energy, it is also necessary to ensure the power grid's security. Wang et al. (2022) analyzed the power shortage in China's low-carbon transformation process through the long-range energy alternatives planning system (LEAP) model. The analysis results showed that, while vigorously developing renewable energy, a certain proportion of thermal power installed capacity and diversified energy development are required [23]. Ma and Chu (2022) concluded that ensuring sufficient reserve regulation capacity of thermal power units and increasing the proportion of renewable energy power generation are essential for the power industry to achieve emission reduction [24]. As for the research on coal power transformation, Zhang et al. (2022a) optimized China's power structure through a robust optimization model [25], and the results showed that the cost of the power structure scheme with low coal power is lower than that of the 100% clean energy supply scheme [26]. Zhang et al. (2022b) found that the transfer cost of the early coal power elimination scenario is lower than that of the typical coal power elimination scenario. Zhang et al. (2022c) showed that the new jobs in the renewable energy field can completely offset the reduction of jobs in the fossil fuel field [27]. It is not only the power generation industry that produces many carbon emissions. Chen et al. (2019) analyzed the carbon footprint of urban and rural residents. The results showed that household energy consumption accounts for 59.2% of the total urban energy consumption, and clean energy substitution in the household sector contributes to carbon emission reduction [28]; among them, clean energy heating is the best way to reduce emissions [29,30]. At the same time, the design of some mechanisms can also play a positive role in carbon emission reduction. Wang et al. (2021) predicted the peak path of CO_2 emissions in China by building a stochastic impact by regression on population affluence and technology (STIRPAT) model. The results showed that setting the CO_2 emission peak target had a significant inhibitory effect on high-carbon-emission industries and a strong promotion effect on low-carbon-emission industries [31].

In terms of modelling methods, Fan et al. (2022) simulated China's future natural gas consumption using the system dynamics method [13]. Huang et al. (2022) and Wang et al. (2022) first predicted the carbon emission peak through STIRPAT and then used the LEAP model for scenario analysis [14,23]. Bartholdsen et al. (2019) [11], Wang et al. (2021) [15], Bian et al. (2018) [21], Ma and Chu (2022) [24], Zhang et al. (2022a) [25], Zhang et al. (2022b) [26], Zhang et al. (2022c) [27], and Wang et al. (2021) [31] built single-objective optimization or multi-objective optimization models through the selection of energy technology and cost. Given the model's limitations, the method based on SD needs to deduce the scenario from front to back according to the timeline. It cannot provide feedback on the globally optimal path. The LEAP model needs to be built from the micro level. However, Beijing's energy consumption data disclosure is limited; thus, it is not easy to build an energy supply and consumption structure model that conforms to Beijing's current situation. Therefore, this paper uses the method of optimization modeling to build a linear programming model with minimum carbon emissions as the goal.

In conclusion, the above studies mainly carried out research from two aspects: (1) combined with the existing carbon emission reduction data in China or Beijing, a model was constructed to analyze the key factors and effects of low-carbon transformation; (2) the optimization path analysis of carbon emission reduction for a high emission industry primarily focused on the power generation industry. However, the scenario under the dual carbon target needs to be simulated and predicted for the future, and the empirical method based on historical data may not be applicable. Secondly, Beijing relies heavily on external electricity. When optimizing the path of carbon emission reduction, it needs to integrate the synergy among demand-side resources, regional energy resources, and local energy resources to solve the contradiction between the lack of energy resources and energy demand under economic growth. Therefore, according to Beijing's energy resource endowment, from the perspective of industry, and considering the difference in energy use, this paper constructs an energy structure optimization model intending to meet economic development expectations and carbon neutrality, as well as designs three scenarios on the basis of Beijing's energy planning: business as usual scenario (BAU), low-carbon scenario (LC), and enhanced low-carbon scenario (ELC); it then analyzes Beijing's future energy structure under the goal of carbon neutrality carbon emissions and energy consumption by industry, and puts forward countermeasures and suggestions on the key influencing factors.

Compared with the existing research, the innovations of this paper are as follows:

(1) In terms of research methods, when building the energy structure optimization model, this paper comprehensively considers Beijing's economic development, energy supply, and energy demand, which further enriches the system analysis model under the carbon emission reduction system.
(2) In terms of application value, this paper combines Beijing's planning development and economic and energy development expectations in scenario analysis. It gives the

energy optimization results under different scenarios, providing a policy analysis tool for Beijing's low-carbon energy transformation.

2. Model

2.1. Model Framework

This paper uses the optimization modeling method to optimize Beijing's energy structure. In line with Wang et al. (2021) [15], Bian et al. (2018) [21], and Ma and Chu (2022) [24], the objective function and constraint conditions are set in the model. The framework of the model is shown in Figure 1.

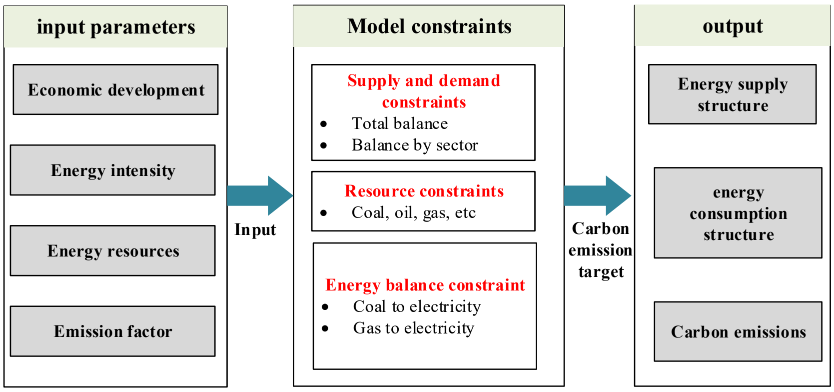

Figure 1. Model framework.

The model framework shown in Figure 1 includes model inputs, model constraints, model decision variables, and optimization objectives.

(1) The input participation of the model involves the exogenous parameters required by the model. On the basis of the development planning documents of Beijing [32,34–37], this paper sets the economic development, energy intensity, energy resources, and other parameters of Beijing from the current period to 2050 as the input parameters of the model.

(2) The constraints considered in the model mainly include three types of constraints: the balance constraint of energy consumption, i.e., the energy supply needs to be equal to the energy consumption, including the constraint of the total amount and sub-industry; resource constraints, including fuel supply and the potential of renewable energy resources; energy consumption balance constraint, which is mainly aimed at resource conversion balance in coal-fired power generation and gas-fired power generation.

(3) The decision variables in the model are the supply and consumption of various energy varieties, while the minimum carbon emission is the optimization objective. According to the optimized decision variables, the calculation results of industrial energy structure, energy consumption structure, carbon emission, and other indicators can be output.

2.2. Mathematical Description of the Model

We took Beijing 2019 as the base year, and then we set the minimum sum of total carbon emissions in 2025, 2030, 2035, 2040, 2045, and 2050 as the optimization goal. The objective function was as follows:

$$Min \sum_{i=1}^{6} \sum_{j}^{7} \sum_{k=1}^{20} Q_{i,j,k} \cdot EF_k, \tag{1}$$

where $Q_{i,j,k}$ represents the consumption of energy k in industry j in the year i, EF_k represents the carbon emission coefficient of energy k, j refers to seven sectors (agriculture (j_1), industrial sector (j_2), construction sector (j_3), transportation (j_4), residents (j_5), service sector (j_6), and others (j_7)), and k refers to 20 types of energy (coal (k_1), coal products (k_2), crude oil (k_3), gasoline (k_4), diesel (k_5), fuel oil (k_6), petroleum coke (k_7), other petroleum products (k_8), liquefied petroleum gas (k_9), natural gas (k_{10}), liquified natural gas (k_{11}), refinery gas (k_{12}), electricity from gas (k_{13}), electricity from wind (k_{14}), electricity from hydro (k_{15}), electricity from photovoltaic (k_{16}), electricity from external transfer (k_{17}), other energy sources (k_{18}), heat (k_{19}), and kerosene (k_{20})).

The optimization model includes the following constraints:

(1) Total carbon emission constraints in 2050

$$\sum_{k=1}^{20} Q_{i,j,7} \leq D_0 \ \forall i. \tag{2}$$

In Equation (2), to achieve Beijing's carbon neutrality in 2050, the emission reduction was set to be more than 95% of the base year, and D_0 represents the carbon emissions in 2050.

(2) Energy consumption constraints

$$\sum_{j}^{7} \sum_{k=1}^{20} Q_{i,j,k} = D_i \ \forall i. \tag{3}$$

$$\sum_{k=1}^{20} Q_{i,j,k} = I_{i,j} \ \forall i, j. \tag{4}$$

Equations (3) and (4) respectively represent the total energy consumption constraint and the energy consumption constraint by industry. D_i refers to the total energy consumption in year i, and $I_{i,j}$ represents the total energy consumption of sector j in year i.

(3) Energy resource constraints

$$\sum_{k=1 \& k \neq 13}^{20} Q_{i,7,k} = \alpha Q_{13} \ \forall i. \tag{5}$$

$$\sum_{j=1}^{6} Q_{i,j,13} \leq Q_{i,7,13} \ \forall i. \tag{6}$$

$$\sum_{j=1}^{6} Q_{i,j,14} \leq Q_{\mathrm{wind},i} \ \forall i. \tag{7}$$

$$\sum_{j=1}^{6} Q_{i,j,15} \leq Q_{\mathrm{hydro},i} \ \forall i. \tag{8}$$

$$\sum_{j=1}^{6} Q_{i,j,16} \leq Q_{\mathrm{solar},i} \ \forall i. \tag{9}$$

$$\sum_{j=1}^{6} Q_{i,j,17} \leq Q_{\mathrm{line},i} \ \forall i. \tag{10}$$

$$\sum_{j=1}^{7} \sum_{k=13}^{18} Q_{i,j,k} \leq Q_{\mathrm{electric},i} \ \forall i. \tag{11}$$

$$\sum_{j=1}^{7} \sum_{k=1}^{2} Q_{i,j,k} \leq Q_{coal,i} \ \forall i. \tag{12}$$

$$\sum_{j=1}^{7}\sum_{k=3}^{8} Q_{i,j,k} \leq Q_{\text{oil},i}\ \forall i. \tag{13}$$

$$\sum_{j=1}^{7}\sum_{k=9}^{12} Q_{i,j,k} \leq Q_{\text{gas},i}\ \forall i. \tag{14}$$

$$\frac{\left|Q_{i-1,j,k} - Q_{i,j,k}\right|}{Q_{i-1,j,k}} \leq \beta_{j,k}\ \forall i,j,k. \tag{15}$$

Equation (5) represents the power production balance constraints. It indicates that the electricity generated by the consumption of primary energy in the thermal power industry is equal to that consumed by all departments, and a refers to the energy conversion efficiency of electricity production. Equations (6)–(11) represent gas-fired power generation constraints, wind power constraints, hydropower constraints, photovoltaic power generation constraints, power outsourcing constraints, and the electricity summation constraints, respectively. Equations (12)–(14) represent the coal constraints, oil constraints, and gas constraints, respectively. Equation (15) represents the energy change constraints in the previous and subsequent stages. $\beta_{j,k}$ represents the change proportion of energy k in sector j.

3. Model Parameter Design

3.1. Carbon Emission Basis

The energy consumption in this paper adopted the physical energy consumption in Beijing Statistical Yearbook from 2006 to 2020 [32]. To avoid the problem of double counting, this paper considered electricity and heat to belong to clean energy, whereby they would not produce carbon emissions. However, there are carbon emissions in electricity and heat production; hence, these carbon emissions were included in Beijing's sectors used to produce electricity and heat. Therefore, the calculation equation of energy consumption was as follows:

$$I_j = C_j - M_j - O_j, \tag{16}$$

where C_j refers to the final consumption, M_j refers to the conversion of processing input, and O_j refers to the industry's energy consumption as raw materials and materials. The calculation of carbon emissions adopted the emission coefficient method [33] provided in the guidelines for preparing local greenhouse gas inventories (Trial). Carbon emissions are equal to the product of various energy consumption and corresponding emission factors.

3.2. Scenario Setting of Total Energy Consumption

According to the data of Beijing's 14th Five-Year Plan [34], taking into account the impact of inflation, the actual growth rate of Beijing's gross domestic product (GDP) is expected to be 4.5%, and the future economic growth rate of Beijing is expected to decline by 0.5% every 5 years. In the future, the specific setting of Beijing's economic growth rate is shown in Table 1.

Table 1. The setting of economic growth rate in Beijing at various stages (unit: %).

Index	2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050
Average annual growth rate	4.5	4	3.5	3	2.5	2

Combined with the binding indicators for the city's energy conservation and emission reduction and the city's energy conservation potential in "Beijing's energy conservation and consumption reduction plan and climate change response plan during the 13th Five-Year Plan Period" [35], the "13th Five-Year Plan" period of the Beijing energy development plan [36], and the "Beijing urban master plan (2016–2035)" [37], three scenarios were set, as shown in Table 2:

Table 2. The setting of Beijing's energy intensity decline (unit: %).

Scenario	2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050
BAU	16	14	12	10	8.23	8.23
LC	18	16	14	12	10	9
ELC	20	18	16	14	12	10

(1) Business as usual scenario (BAU). During 2021–2025, the downward trend of energy consumption intensity in Beijing will be slightly lower than that in the 13th Five-Year Plan. That is, the cumulative energy consumption intensity within 5 years will decrease by 16%; from 2026 to 2030, the energy consumption intensity will decrease by 14%; from 2031 to 2035, the energy consumption intensity will decrease by 12%; from 2036 to 2040, the energy consumption intensity will decrease by 10%; from 2041 to 2050, it is assumed that the downward trend of energy consumption intensity in Beijing will be the same as that in developed countries, i.e., the energy consumption intensity will decline by 1.5% annually during the forecast period.
(2) Low-carbon scenario (LC). We assume that the energy consumption intensity will decrease by 18% during 2021–2025; from 2026 to 2030, the energy consumption intensity will decrease by 16%; from 2031 to 2035, the energy consumption intensity will decrease by 14% in total; from 2036 to 2040, the energy consumption intensity will decrease by 12%; from 2041 to 2045, the energy consumption intensity will decrease by 10% in total; from 2046 to 2050, the energy consumption intensity will decrease by 9%.
(3) Enhanced low-carbon scenario (ELC). We assume that the energy consumption intensity will decrease by 20% during 2021–2025; from 2026 to 2030, the energy consumption intensity will decrease by 18%; from 2031 to 2035, the energy consumption intensity will decrease by 16%; from 2036 to 2040, the energy consumption intensity will decrease by 14%; from 2041 to 2045, the energy consumption intensity will decrease by 12%; from 2046 to 2050, the energy consumption intensity will decrease by 10%.

On the basis of the above prediction assumptions, according to the economic development trend of Beijing from 2020 to 2050, combined with the three scenarios of the changing trend of energy intensity, the prediction results of Beijing's total energy consumption were obtained, as shown in Figure 2.

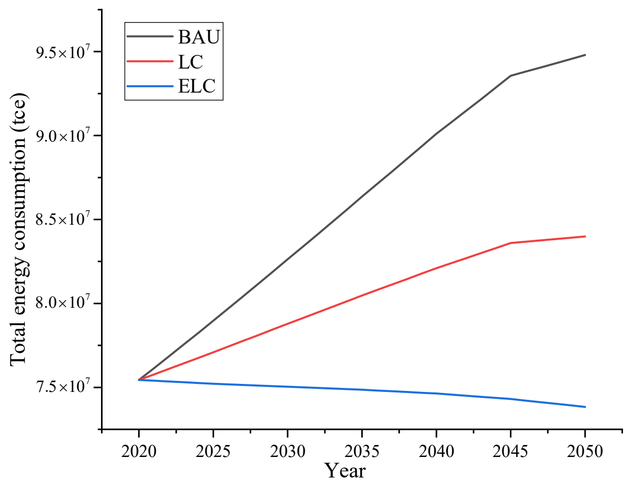

Figure 2. Prediction of total energy consumption in Beijing.

As shown in Figure 2, under the BAU and LC scenarios, although the energy consumption intensity continues to decline, driven by rapid economic development, the total energy consumption in Beijing will continue to grow in the future. However, the total energy consumption in the ELC is significantly lower than that in the other two scenarios, and the total consumption decreases yearly. Over time, the difference between the total energy consumption under the ELC and that under the other two scenarios becomes larger and larger. This shows that energy intensity and economic growth closely relate to Beijing's energy consumption growth. When the energy intensity reduction exceeds the economic growth, the smaller carbon emission base is on the energy consumption side.

3.3. Setting of Energy Consumption Structure in Various Sectors

The total energy consumption mainly includes two uses: the production power of various departments, such as fuel, electricity, and heat; the raw materials to provide intermediate factor inputs for other departments, such as lubricants and plastics. Only energy consumption as power will release carbon dioxide. Therefore, after calculating the total energy consumption, it is necessary to deduct the energy demand as raw materials. Assuming that the proportion of fossil energy as raw materials in the total energy consumption is fixed, a larger total energy consumption indicates a higher level of economic development and the more intermediate input required to produce the final economic products. We took 2019 as the reference year [32], and the ratio of total energy consumption as fuel power to total terminal energy consumption was set to 96.2%. At the same time, assuming that the proportion of energy consumption in various sectors was also fixed, on the basis of 2019, the proportion of energy consumption in agriculture was set to be about 0.82%, the proportion of the industry was about 17.02%, the proportion of the construction industry was about 1.87%, the proportion of the transportation industry was about 22.6%, the proportion of services was about 6.44%, the proportion of residents was about 24.92%, and the proportion of others was about 26.32%.

3.4. Setting of Energy Supply Constraints

Constrained by resources and carbon emissions, it was assumed that Beijing's total supply of gas-fired power generation, wind power, and hydropower will remain unchanged. Concerning the Beijing energy development plan during the 13th Five-Year Plan period [36], it was assumed that the average annual growth rate of Beijing's photoelectric supply is 6.6%, the average annual growth rate of coal supply is −15.6%, the average annual growth rate of oil energy supply is about 0.2%, and the average annual growth rate of gas energy supply is about 5.5%. The remaining energy supply is included in the external transfer of power.

3.5. Constraints on the Proportion of Changes in Energy Consumption

Because technological progress will impact the substitution and application of different energy varieties, and the substitution between different energy varieties has a development process, it necessitates the simultaneous development of technology and industry to realize the large-scale application of new technologies. Only technology and large-scale application breakthroughs can increase the proportion of specific energy consumption change sharply in a specific time cycle. Therefore, to prevent excessive changes in the years before and after a specific type of energy, the change proportion of different energy varieties in the years before and after was added to this model, and the upper limit of the annual change proportion was tentatively set at 20%.

4. Results and Discussion

Because the model is a linear programming model, the energy consumption of each industry can be obtained by solving the model using a Gurobi solver [38]. This section analyzes the energy consumption and emissions, key sectors, and net carbon emissions after considering carbon sinks.

4.1. Analysis of Total Energy Consumption and Carbon Emissions

(1) Trend analysis of total energy and carbon emissions under different scenarios

First, we analyze Beijing's total energy consumption and carbon emissions under three scenarios. As shown in Figure 3, the total energy consumption in Beijing shows an increasing trend, but its growth rate is slowing down. This trend is because Beijing's economic development cannot be separated from the support of energy. Therefore, energy input is required to maintain the stability of Beijing's economy, leading to a rise in energy demand. However, with the progress of technology, the amount of energy required per unit of GDP in Beijing is decreasing. That is, the intensity of energy consumption is decreasing, which makes the growth rate of energy consumption slow down. Secondly, Beijing's total energy consumption and carbon emissions show opposite trends. There are two reasons for this phenomenon. Firstly, the rapid development of energy conservation and emission reduction technology has reduced the amount of energy consumption per unit of GDP. A lower intensity of energy consumption results in a slower growth rate of total energy consumption and faster corresponding decline in total carbon emissions of energy consumption. Secondly, with the rapid development of electric energy substitution technology, energy consumption is becoming cleaner, and the consumption structure is increasingly approaching zero carbon, i.e., clean or zero-carbon energy is gradually being used to replace fossil energy (such as coal and natural gas) to meet the energy demand of various industries, such as new-energy vehicles in the field of transportation and "gas electricity for coal" in the field of heating. With the deepening development of various sectors, fossil energy will gradually be replaced by clean electricity or other zero-carbon energy. When the level of electricity substitution is high, the increase in total energy consumption will not cause significant pressure on the ecological environment of Beijing. Lastly, according to the established development trend of the BAU, LC, or ELC scenario, there will be 2.87 million tons, 2.49 million tons, and 1.96 million tons of carbon emissions in various scenarios by 2050. This means that the current zero-carbon technology development trend in Beijing alone may not fully meet Beijing's 2050 carbon neutrality goal. Therefore, the Beijing municipal government should adopt more diversified zero-carbon technology innovation policies, significantly reduce energy consumption intensity, and improve the level of electricity substitution.

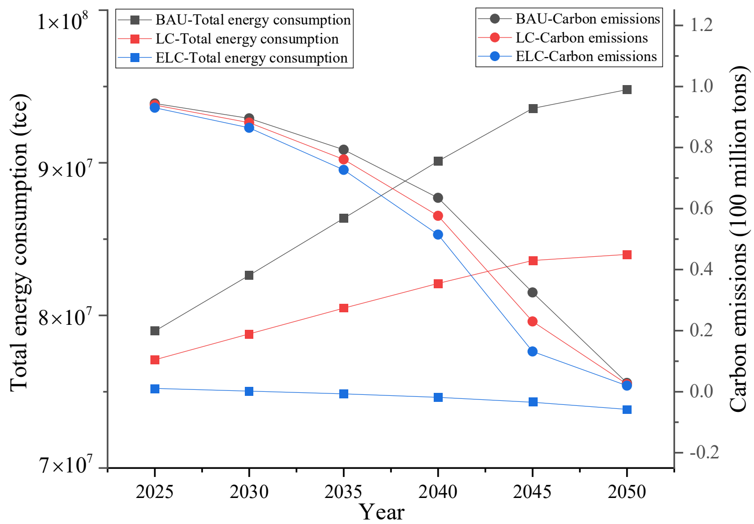

Figure 3. Change trends of total energy and carbon emissions under different scenarios.

(2) Trend analysis of the proportion of electricity consumption in total energy consumption under different scenarios

Electric energy substitution is an important measure to clean fossil energy. This section analyzes the power consumption changes in Beijing under three scenarios. Figure 4 shows the changes in the proportion of power consumption in Beijing's total energy consumption from 2025 to 2050 and the proportion of external electricity in Beijing's total power consumption under three scenarios. In terms of the proportion of electricity consumption, from 2025 to 2040, the proportion shows a slight increase and a significant fluctuation. There are two reasons for this phenomenon. Firstly, the early electric energy substitution technology is not mature enough, and the energy consumption structure of some industries is too complicated to be replaced with electricity, such as aviation kerosene consumption. Secondly, the economy of electricity substitution is poor. Compared with clean energy power generation, the cost of thermal power generation in China still has higher economic advantages. At the same time, with the increase in the electricity demand, Beijing must invest in energy storage, power grid, and other related power infrastructure to ensure the stability and security of Beijing's energy supply, significantly increasing the energy investment cost. Therefore, before 2040, Beijing's power consumption growth rate may be low. From 2040 to 2050, Beijing's power consumption proportion shows a rapid growth trend. Under the ELC scenario, Beijing's power consumption proportion is as high as 64.71% and maintains a sustained and rapid upward trend. The reason for this trend is that electric energy substitution infrastructure has gradually improved with the development of electric energy substitution technology, the reduction in power investment cost, and the continuous withdrawal of the original thermal power unit from the power market. In terms of the proportion of power outsourcing, it has increased rapidly. Under the three scenarios, the proportion of power outsourcing reached the maximum in 2040 and remained high. This phenomenon shows that Beijing's power supply highly depends on other regions. In conclusion, Beijing should pay attention to the importance of regional energy coordination for Beijing's energy supply, increase investment in the construction of external power grids, and constantly raise the ceiling of the total amount of purchasing electricity in Beijing.

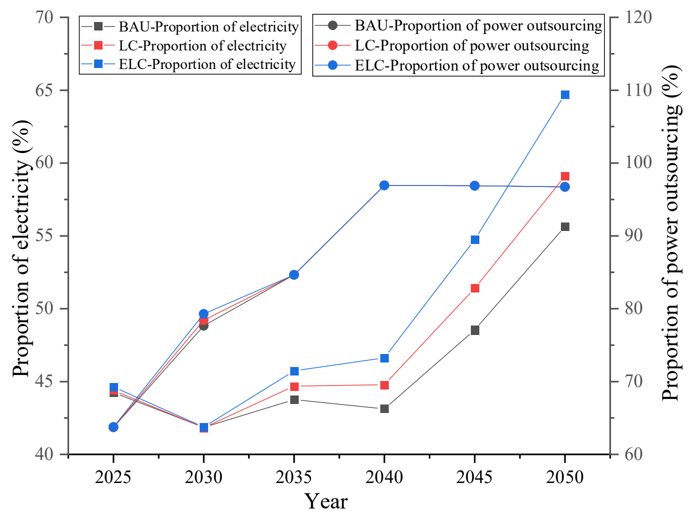

Figure 4. Analysis of the proportion of power consumption in total energy consumption and the proportion of power outsourcing.

(3) Analysis of total carbon emissions and energy consumption of various sectors under the ELC scenario

Under the ELC scenario, Beijing still has a carbon emission of 1.96 million tons. From the analysis of the carbon emission composition of the industry and the composition of energy types, it can be seen from Figure 5 that, from 2025 to 2050, the total carbon emissions of all industries show a downward trend, in which the total carbon emissions of residents and transportation account for a relatively large proportion. According to the energy consumption of different varieties in Figure 6, coal and oil products will be almost completely replaced in 2035, and natural gas will peak in 2035. By 2050, the primary energy consumption will be external electricity and other energy with low carbon emissions.

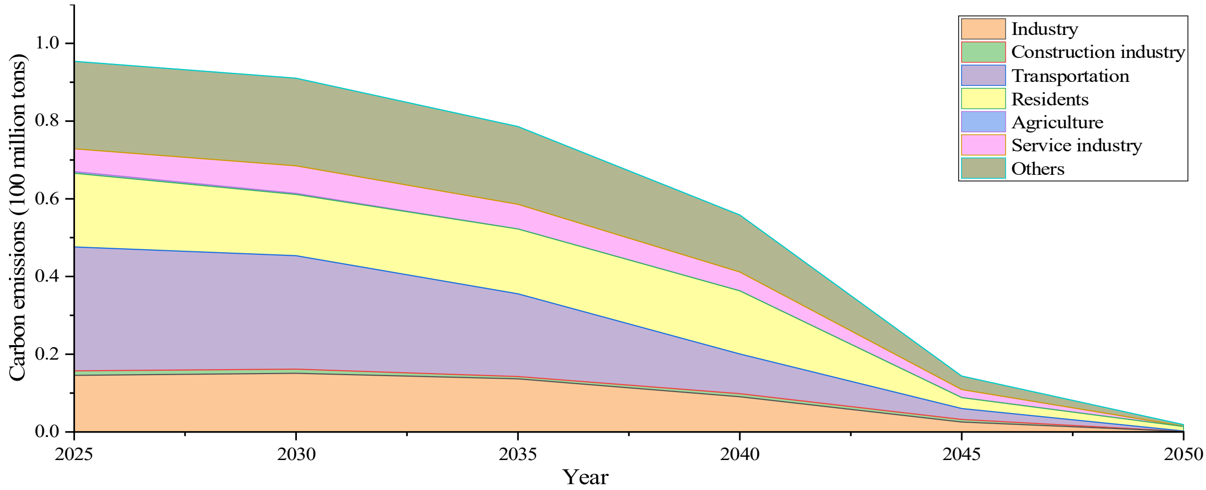

Figure 5. Summary of carbon emissions by sector under the ELC scenario.

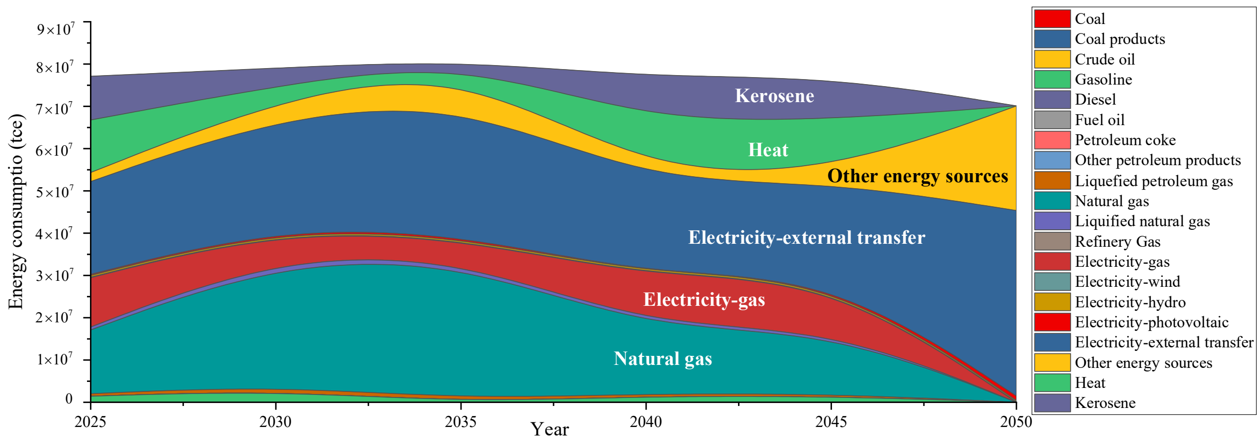

Figure 6. Summary of consumption of various energy types under the ELC scenario.

4.2. Analysis of Total Energy Consumption and Carbon Emissions

4.2.1. Industrial Sector

The industrial sector has always been a sector with substantial carbon emissions. This section analyzes the industrial sector's energy consumption and carbon emissions. Figure 7a shows the industrial sector's total energy consumption and carbon emissions. Similar to Figure 3, there is an opposite trend between total energy consumption and carbon emissions in the industrial sector. The difference is that, between 2020 and 2030, Beijing's total industrial carbon emissions may have a slow growth trend. This is because, by relieving noncapital functions, many high-energy industries will withdraw from Beijing, leaving behind relatively high-quality industries. Therefore, with the rapid economic development, compared with the early stage, the energy consumption growth rate and carbon emissions of Beijing's industries in the later stage are relatively slow. After 2030, due to the further reduction in energy consumption intensity and the improvement of power substitution level, the total carbon emissions of Beijing's industrial sector will be reduced more quickly.

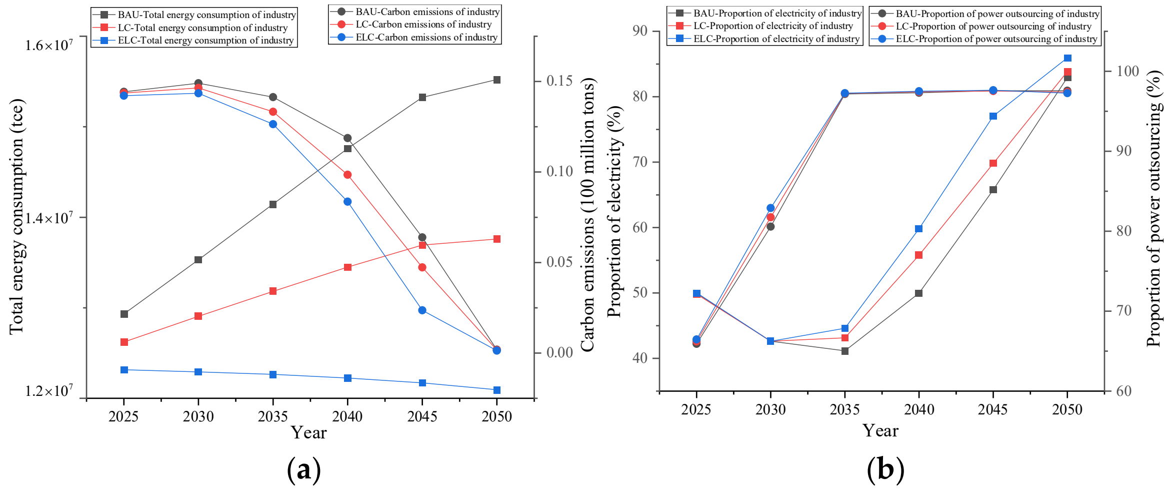

Figure 7. Analysis of the industrial sector: (**a**) total energy consumption and carbon emissions in the industrial sector; (**b**) proportion of power and external electricity in the industrial sector.

Figure 7b shows the proportion of power consumption in Beijing's industrial sector in total energy consumption and the proportion of purchasing electricity in electricity consumption. In terms of the proportion of electricity consumption in the industrial sector, first of all, before 2030, the proportion of power consumption in Beijing's industrial sector will decline. The main reason is that enterprises always take profit maximization as their business objective. When the cost of power substitution is high, enterprises in the industrial sector will give up increasing the proportion of power substitution and consume more low-cost, safer, and more reliable fossil energy. Therefore, when the demand for energy consumption increases, power consumption in the industrial sector may decline early. Secondly, after 2030, the proportion of power consumption in Beijing's industrial sector will rise rapidly, and the proportion of power consumption in Beijing's industrial sector will rise the most under the ELC scenario. This shows that stronger carbon neutralization constraints will lead to faster power substitution of Beijing's industrial sector. Regarding the proportion of purchasing power in the industrial sector, this value reaches the maximum in 2035, earlier than the peak of the purchasing power in Beijing (2040). This phenomenon shows that, with the improvement of the power substitution level in Beijing, the industrial sector may be more dependent on external power.

4.2.2. Transportation Sector

The transportation sector also has a large proportion of carbon emissions. This section analyzes the transportation sector's energy consumption and carbon emissions. Figure 8a shows Beijing's transportation industry's total energy consumption and carbon emissions trend. The figure also shows the opposite trend between total energy consumption and carbon emissions. Compared with the industrial sector, there is little difference in the carbon emission path of the transportation industry between different scenarios. This is mainly because Beijing's public transport system has achieved a high level of electrification, and the policy significantly affects the sector. Therefore, under the guidance of electric vehicle subsidies and carbon neutrality goals, the transportation industry in Beijing is undergoing rapid transformation and upgrading such that carbon emissions will decline rapidly before 2040. However, after 2040, the zero-carbonization process of the transportation industry will slow down because aviation, large transport vehicles, and other industries strongly depend on specific fossil energy.

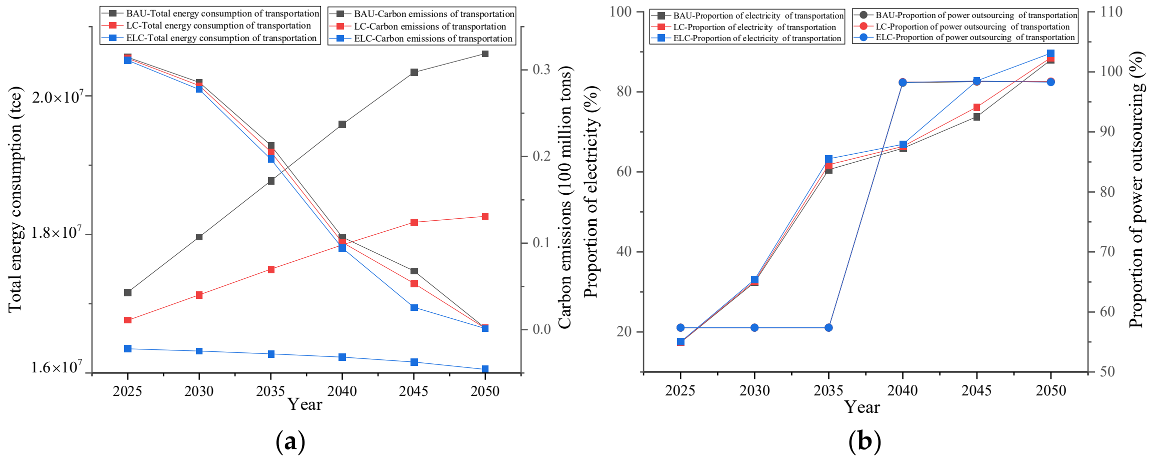

Figure 8. Analysis of the transportation sector: (**a**) total energy consumption and carbon emissions in the transportation sector; (**b**) proportion of power and external electricity in the transportation sector.

Figure 8b shows the changing trend of the proportion of power in Beijing's transportation industry and the proportion of purchasing power. In terms of the proportion of power consumption, with the rapid development of Beijing's transportation industry, the power consumption demand of this industry increases rapidly, reaching about 89% by 2050. This means that the transportation industry in Beijing still has ample space for power substitution. According to the proportion of purchasing power, before 2035, the proportion of external power consumed by Beijing's transportation industry is low, and the energy structure is relatively stable. This shows that, between 2020 and 2035, according to the existing energy development plan of Beijing, the energy demand of Beijing's transportation industry in the future can be met. However, after 2035, with the increase in power consumption in the transportation industry, Beijing must rely on external power purchases to meet the requirements of a high electrification level and a high zero-carbonization level in the transportation industry.

4.3. Analysis of Total Energy Consumption and Carbon Emissions

Referring to Xiao and Chen (2020) [39], the coefficient method was used to calculate the carbon absorption of urban green space in Beijing.

$$CA = \sum s_i \times a_i, \quad (17)$$

where CA is the total carbon absorption, s_i refers to the area of land-use types, including cultivated land, garden land, forest land, grassland, and water area, and a_i is the carbon absorption coefficient. According to the carbon absorption Equation (17), the carbon absorption of cultivated land, garden land, forest land, grassland, and water area in Beijing in 2018 was 1481.37 tons, 52,747.38 tons, 450,668.33 tons, 1728.64 tons, and 18,157.36 tons, respectively, absorbing a total of about 524,800 tons of carbon, which could reduce carbon dioxide emissions by about 1,924,300 tons. According to the Beijing urban master plan (2016–2035) [38], the predicted areas of various types of land in Beijing in the future are shown in Table 3.

Suppose that, by 2035, the green space in Beijing will reach the maximum area, i.e., the carbon sink will reach the maximum value. After 2035, the area of all kinds of land will remain unchanged. According to the prediction and enhancement scenario of green space planning, the prediction of the future carbon sink of urban green space in Beijing is shown in Table 4.

Table 3. Area, carbon absorption coefficient, and carbon absorption of land in Beijing.

Land Type	Cultivated Land	Garden Land	Forest Land	Grass Land	Water Area
Area (hm^2)	212,840.6	132,531.1	746,634.08	84,323.67	76,291.41
carbon absorption coefficient (t/hm^2)	0.00696	0.398	0.6036	0.0205	0.238
carbon sink (t)	1481.37	52,747.38	450,668.33	1728.64	18,157.36

Table 4. Prediction of carbon sink in Beijing.

Year	2025	2030	2035	2040	2045	2050
Carbon sink (t)	551,761.65	555,794.46	559,843.23	559,843.23	559,843.23	559,843.23
Absorbed CO_2 emissions (10 kt)	202.31	203.79	205.28	205.28	205.28	205.28
Net CO_2 emissions (10 kt) [1]	9101.17	8440.24	7060.31	4942.44	1113.54	−9.14

[1] The net CO_2 emission under the ELC scenario is the CO_2 emission minus the absorbed CO_2.

As shown in Table 4, in 2050, about 2 million tons of CO_2 can be absorbed through the carbon sink, achieving the goal of net zero-carbon emission of energy under the ELC scenario, whereas it is challenging to achieve carbon neutrality in the BAU and LC scenarios.

5. Conclusions and Policy Implications

According to the actual needs of China's dual carbon goals and considering Beijing's economic development needs and energy resource endowment, this paper constructed an energy structure optimization model to achieve the goal of carbon neutrality by 2050. The model analysis concluded that a large proportion of Beijing's total carbon emissions in the future will come from residents and the transportation industry. The power substitution of fossil energy and a high proportion of access to external electricity are also necessary to achieve the goal of carbon neutrality. Therefore, combined with the analysis results, we put forward the following suggestions for the realization path of Beijing's carbon neutrality goal:

(1) Government departments should prioritize reducing energy intensity and improving energy efficiency when formulating energy policies. On the basis of the analysis of the three scenarios in this paper, under the assumption of constant economic growth, only the total energy consumption under the ELC scenario shows a decreasing trend, and the emission reduction effect caused by the reduction in energy intensity is particularly significant. At this time, the average annual energy intensity reduction needs to reach 20%, which puts tremendous pressure on emission reduction in Beijing. Therefore, Beijing should focus its energy policy on energy conservation and efficiency improvement, strengthen the energy control measures of the government, enterprises, institutions, and other entities, and enhance the residents' awareness of energy conservation.

(2) The power channels with surrounding provinces should be increased, and the guarantee mechanism for the consumption of clean energy power should be strengthened. Presently, the power industry in Beijing is dominated by gas-fired power generation, with limited hydropower, photovoltaic, and wind power generation. The development of local power resources in Beijing is limited. According to the analysis results of this paper, by 2050, to achieve Beijing's carbon neutral goal, Beijing's electricity will account for more than 65% of energy consumption, of which outsourcing electricity will account for more than 90% of electricity consumption. Therefore, Beijing needs to connect the power resources of surrounding provinces, especially to ensure that the power comes from clean power, while guiding the demand-side behavior to absorb clean power in a high proportion.

(3) Traffic electrification should be promoted, and green travel should be encouraged. As shown in Figure 5, Beijing's transportation sector has the most significant energy consumption. However, with the increase in power consumption in the transporta-

tion sector, its carbon emissions are not the largest. It can be seen that clean energy alternative technologies such as electricity instead of oil will have significant emission reduction effects on the transportation sector. Therefore, it is necessary to vigorously promote transportation electrification, cultivate electric vehicles and hydrogen fuel trolleys, and replace oil with electricity or hydrogen, thus gradually building a decarbonized transportation energy system.

(4) Technology substitution in the industrial sector should be promoted, and enterprises in the industrial sector should be appropriately subsidized. According to the analysis results in Figure 7, the carbon emission rate of the industrial sector will decrease slowly. This is because changing the industrial sector's production and energy consumption mode requires more costs for enterprises. Therefore, under the goal of carbon neutrality, the government department can appropriately subsidize the equipment transformation of enterprises in the industrial sector to promote their transformation to low-emission production technology.

(5) The substitution of electric energy for residents' life should be promoted, and the service level of the distribution network should be improved. As shown in Figure 5, the carbon emissions caused by residents' living have always accounted for a large proportion. Therefore, to achieve Beijing's carbon neutral goal, it is necessary to increase the proportion of low- and zero-emission energy consumption. Changing residents' energy consumption habits and realizing energy electrification through electric energy substitution technology are the keys to residents' living energy consumption. Heating, refrigeration, lighting, cooking, household appliances, etc. can be electrified, and industrial waste heat can also be used. Implementing ultralow-energy-consumption buildings, introducing digital and intelligent applications, and popularizing smart homes and smart household appliances will accelerate the decarbonization of residents' living.

(6) Carbon sink technology should be encouraged, and the carbon trading market should be promoted. The development of clean energy is limited. Under the constraints of ensuring economic development and carbon emission reduction, there is a certain distance between the BAU and the carbon neutralization target. As shown in Table 4, to achieve the carbon neutralization target, it is also necessary to neutralize this proportion of carbon emissions through carbon sinks. Beijing has limited carbon sink capacity; therefore, it can use the carbon trading market and other policy tools to guide carbon emission reduction, such as carbon trading, climate investment and financing, energy transformation funds, and carbon neutralization promotion laws.

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References

1. Zhao, X.; Ma, X.; Chen, B.; Shang, Y.; Song, M. Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resour. Conserv. Recycl.* **2022**, *176*, 105959. [CrossRef]
2. Jiankun, H.; Zheng, L.; Xiliang, Z.; Hailin, W.; Wenjuan, D.; Ershun, D.; Shiyan, C.; Xunmin, O.; Siyue, G.; Zhiyu, T.; et al. Towards carbon neutrality: A study on China's long-term low-carbon transition pathways and strategies. *Environ. Sci. Ecotech.* **2022**, *9*, 105959. [CrossRef]
3. De la Pena, L.; Guo, R.; Cao, X.; Ni, X.; Zhang, W. Accelerating the energy transition to achieve carbon neutrality. *Resour. Conserv. Recy.* **2022**, *177*, 105957. [CrossRef]
4. Liu, P.; Peng, H. What drives the green and low-carbon energy transition in China?: An empirical analysis based on a novel framework. *Energy* **2022**, *239*, 122450. [CrossRef]
5. Heggelund, G.M. China's climate and energy policy: At a turning point? *Int. Environ. Agreem. Politics Law Econ.* **2021**, *21*, 9–23. [CrossRef]
6. Central Finance and Economics Committee (CFEC). Outline of Coordinated Development of the Beijing-Tianjin-Hebei Region. 2015. Available online: https://wenku.baidu.com/view/d152ed72383567ec102de2bd960590c69ec3d817.html (accessed on 25 July 2022).
7. Beijing Economic-Technological Development Area. Measures of Beijing Economic and Technological Development Zone on Implementing the New Development Concept and Accelerating the High-Quality Development of Yizhuang New Town (Version 4.0). 2022. Available online: http://www.beijing.gov.cn/zhengce/zhengcefagui/202205/t20220519_2716298.html (accessed on 25 July 2022).
8. National Development and Reform Commission, National Energy Administration et al. Guidance on Promoting Electric Energy Substitution. 2016. Available online: http://www.nea.gov.cn/2016-05/25/c_135387453.htm (accessed on 25 July 2022).
9. China Emission Accounts & Datasets. Emission Inventories for 30 Provinces in 2019. 2021. Available online: https://www.ceads.net/user/index.php?id=1137&lang=en (accessed on 25 July 2022).
10. Zhang, X.; Lu, Z.; He, M.; Wang, J. What can Beijing learn from the world megacities on energy and environmental issues? *Energy Rep.* **2022**, *8*, 414–424. [CrossRef]
11. Bartholdsen, H.-K.; Eidens, A.; Loffler, K.; Seehaus, F.; Wejda, F.; Burandt, T.; Oei, P.-Y.; Kemfert, C.; von Hirschhausen, C. Pathways for Germany's Low-Carbon Energy Transformation Towards 2050. *Energies* **2019**, *12*, 2988. [CrossRef]
12. Zhang, H.; Chen, B.; Deng, H.; Du, H.; Yang, R.; Ju, L.; Liu, S. Analysis on the evolution law and influencing factors of Beijing's power generation carbon emissions. *Energy Rep.* **2022**, *8*, 1689–1697. [CrossRef]
13. Fan, J.; Wang, J.; Liu, M.; Sun, W.; Lan, Z. Scenario simulations of China's natural gas consumption under the dual-carbon target. *Energy* **2022**, *252*, 124106. [CrossRef]
14. Huang, R.; Zhang, S.; Wang, P. Key areas and pathways for carbon emissions reduction in Beijing for the "Dual Carbon" targets. *Energy Policy* **2022**, *164*, 112873. [CrossRef]
15. Wang, S.; LÜ, L.; Zhang, B.; Wang, S.; Wu, J.; Fu, J.; Luo, H. Multi Objective Programming Model of Low-Cost Path for China's Peaking Carbon Dioxide Emissions and Carbon Neutrality. *Res. Environ. Sci.* **2021**, *34*, 2044–2055. (In Chinese) [CrossRef]
16. Hao, J.; Gao, F.; Fang, X.; Nong, X.; Zhang, Y.; Hong, F. Multi-factor decomposition and multi-scenario prediction decoupling analysis of China's carbon emission under dual carbon goal. *Sci. Total Environ.* **2022**, *841*, 156788. [CrossRef] [PubMed]
17. Li, Z.; Cai, Y.; Lin, G. Pathways for sustainable municipal energy systems transition: A case study of Tangshan, a resource-based city in China. *J. Clean. Prod.* **2022**, *330*, 129835. [CrossRef]
18. Wu, G.; Niu, D. A study of carbon peaking and carbon neutral pathways in China's power sector under a 1.5 degrees C temperature control target. *Environ. Sci. Pollut. Res.* **2022**. [CrossRef] [PubMed]
19. Cui, G.; Yu, Y.; Zhou, L.; Zhang, H. Driving forces for carbon emissions changes in Beijing and the role of green power. *Sci. Total Environ.* **2020**, *728*, 138688. [CrossRef]
20. Chi, Y.; Zhou, W.; Tang, S.; Hu, Y. Driving Factors of CO_2 Emissions in China's Power Industry: Relative Importance Analysis Based on Spatial Durbin Model. *Energies* **2022**, *15*, 2631. [CrossRef]
21. Bian, Y.; Yu, Z.; Zeng, X.; Feng, J.; He, C. Achieving China's Long-Term Carbon Emission Abatement Targets: A Perspective from Regional Disparity. *Sustainability* **2018**, *10*, 4244. [CrossRef]
22. Tan, X.; Lin, S.; Liu, Y.-L.; Xie, B.-C. Has the inter-regional transmission expansion promoted the low-carbon transition of China's power sector? *Comput. Ind. Eng.* **2022**, *168*, 108059. [CrossRef]
23. Wang, B.; Wang, L.; Zhong, S.; Xiang, N.; Qu, Q. Low-Carbon Transformation of Electric System against Power Shortage in China: Policy Optimization. *Energies* **2022**, *15*, 1574. [CrossRef]
24. Ma, Y.; Chu, X.D. Optimizing Low-Carbon Pathway of China's Power Supply Structure Using Model Predictive Control. *Energies* **2022**, *15*, 4450. [CrossRef]
25. Zhang, Y.; Zhang, X.; Lan, L. Robust optimization-based dynamic power generation mix evolution under the carbon-neutral target. *Resour. Conserv. Recy.* **2022**, *178*, 106103. [CrossRef]
26. Zhang, W.; Meng, Z.; Yang, J.; Song, Y.; Zhou, Y.; Zhao, C.; Yuan, J. Managing the phaseout of coal power: A comparison of power decarbonization pathways in Jilin Province. *Resour. Conserv. Recy.* **2022**, *180*, 106216. [CrossRef]
27. Zhang, X.; Cui, X.; Li, B.; Hidalgo-Gonzalez, P.; MKammen, D.; Zou, J.; Wang, K. Immediate actions on coal phaseout enable a just low-carbon transition in China's power sector. *Appl Energ.* **2022**, *308*, 118401. [CrossRef]

28. Chen, C.; Liu, G.; Meng, F.; Hao, Y.; Zhang, Y.; Casazza, M. Energy consumption and carbon footprint accounting of urban and rural residents in Beijing through Consumer Lifestyle Approach. *Ecol. Indic.* **2019**, *98*, 575–586. [CrossRef]
29. Zhang, Y.; Zheng, W.; Fang, H.; Xia, J. Clean heating in Northern China: Regional investigations and roadmap studies for urban area towards 2050. *J. Clean. Prod.* **2022**, *334*, 130233. [CrossRef]
30. Yuan, X.; Su, C.-W.; Umar, M.; Shao, X.; Lobont, O.-R. The race to zero emissions: Can renewable energy be the path to carbon neutrality? *J. Environ. Manag.* **2022**, *308*, 114648. [CrossRef]
31. Wang, F.; Gao, C.; Zhang, W.; Huang, D. Industrial Structure Optimization and Low-Carbon Transformation of Chinese Industry Based on the Forcing Mechanism of CO_2 Emission Peak Target. *Sustainability* **2021**, *13*, 4417. [CrossRef]
32. Beijing Municipal Bureau of Statistics. *Beijing Statistical Yearbook 2006–2020*; China Statistics Press: Beijing, China, 2021.
33. National Development and Reform Commission. Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (Trial). 2011. Available online: http://www.ncsc.org.cn/SY/tjkhybg/202003/t20200319_769763.shtml (accessed on 25 July 2022).
34. National Development and Reform Commission. The 14th Five Year Plan of Beijing for National Economic and Social Development and the Outline of Long-Term Goals for 2035. 2021. Available online: https://www.ndrc.gov.cn/fggz/fzzlgh/dffzgh/202103/t20210331_1271321_ext.html (accessed on 25 July 2022).
35. The People's Government of Beijing Municipality. Beijing's Energy Conservation and Consumption Reduction Plan and Climate Change Response Plan during the 13th Five Year Plan Period. 2016. Available online: http://fgw.beijing.gov.cn/fzggzl/sswgh2016/ghwb/201912/P020191227581293473571.pdf (accessed on 25 July 2022).
36. The People's Government of Beijing Municipality. Beijing's Energy Development Plan during the 13th Five Year Plan Period. 2017. Available online: http://www.beijing.gov.cn/zhengce/gfxwj/201905/t20190522_60416.html (accessed on 25 July 2022).
37. The People's Government of Beijing Municipality. Beijing Urban Master Plan (2016–2035). 2017. Available online: http://www.gov.cn/xinwen/2017-09/30/content_5228705.htm (accessed on 25 July 2022).
38. Gurobi Optimization, L.L.C. Gurobi Optimizer Reference Manual. 2022. Available online: https://www.gurobi.com (accessed on 25 July 2022).
39. Xiao, W.; Chen, J. Research on the calculation of Beijing Tianjin Hebei ecological compensation from the perspective of carbon footprint. *Rural. Econ. Sci. Technol.* **2020**, *31*, 48–50. (In Chinese)