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Study on Low Carbon Path in Beijing Based on LEAP Model under Dual Carbon Background

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SUMMARY: *According to Beijing's energy demand and carbon emissions data, the LEAP model is used to forecast Beijing's energy demand and carbon emissions from 2020 to 2060. Build baseline scenarios, low-carbon scenarios, and enhanced low-carbon scenarios based on the magnitude of the measures. According to the prediction results, energy flow map and carbon flow map, the results show that the energy demand is not at its peak under the baseline scenario, reaching 120.5Mt in 2060, and carbon emissions reach 221.8Mt in 2052. Under the low-carbon scenario, energy demand first increases and then stabilizes, reaching 97.1Mt in 2060 and 184.3Mt in 2038, respectively. Under the enhanced low-carbon scenario, energy demand peaked at 87.14Mt in 2057 and carbon emissions peaked at 170.3Mt in 2029. Of the three scenarios, enhanced low-carbon scenarios are most likely to achieve the "two-carbon" goal. In the enhanced low-carbon scenario, the two measures of improving the energy efficiency of the tertiary industry and industrial energy efficiency contributed the most to the energy saving, contributing 43.7% and 33.2% respectively. Using clean energy and increasing the green electricity proportion measures contributed the most to the emission reduction, the contribution rate reached 30.9% and 26.3% respectively.*

KEYWORDS: *LEAP model; Energy demand; Carbon emission; Scenario analysis; Energy flow map; Carbon flow map*

1 Introduction

In the context of global warming, controlling greenhouse gas emissions and accelerating the transformation of energy structure have become the core consensus of the international community in dealing with climate change. As the world's largest developing country and a major carbon emitter, China has taken an active part in fulfilling its international climate governance responsibilities, and has proposed a "dual carbon" strategic goal of carbon peak and carbon neutrality. Beijing, as China's political, cultural and international exchange center, its energy transformation and carbon emission control measures have an important demonstration significance for low-carbon development of the whole country and the world. Therefore, it is of certain theoretical value to systematically study the evolution trend of energy demand and carbon emissions in the future of Beijing to promote the transition of urban green and low carbon and achieve the strategic goal of "dual carbon".

The current research on carbon emissions presents multi-dimensional and interdisciplinary characteristics, which mainly focuses on the following five research directions:First, from the perspective of economics, researchers systematically analyze the quantitative relationship

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between economic growth scale, industrial restructuring and carbon emissions by constructing econometric and statistical models. Secondly, the sociological studies focus on the relationship between social behavior and carbon emissions, focusing on the impact of social and economic factors such as consumption behavior patterns, social acceptance, income distribution structure on carbon emissions[11-15], and in-depth discussion of carbon responsibility allocation mechanism[16, 17];Thirdly, the environmental and ecological studies are devoted to reveal the coercive effect of carbon emissions on ecosystems[18-23], and explore the optimization path of ecosystem carbon cycle and carbon sink capacity improvement strategy[24-26]; The fourth, the direction of policy and management research focuses on low-carbon emission reduction policy design, carbon emissions trading market mechanism and its implementation effect assessment, to provide a scientific basis for policy development[27-31]; Fifth, the research of technological innovation focuses on low-carbon technology research and development, traditional technological innovation[32, 33] and energy efficiency[34-37], to explore the technical path to achieve carbon emission control.

The above studies provide abundant theoretical support and methodological reference for carbon emissions from different disciplinary perspectives. However, most of the existing studies are characterized by single dimension and fragmentation, and lack of a systematic and comprehensive research framework for carbon emissions. In view of the complexity and multi-source of carbon emissions, it is urgent to build a research system integrating multidisciplinary theories and methods. As a comprehensive energy-environment analysis tool, LEAP model can effectively integrate the key factors of economic development, energy consumption, technological progress, etc., and dynamically simulate and forecast the evolution of energy system and carbon emission trend, which provides powerful support for making scientific and reasonable carbon emission reduction strategies. The model has been widely used in the study of carbon emissions in several provinces and cities in China, including Shanxi Province [38], Anhui Province [39], Zhejiang Province [40], Jiangsu Province [41], Shandong Province [42], Jilin Province [43], Tianjin [44] etc., but the systematic study of the whole city level in Beijing is still relatively scarce.

As the main carrier of carbon emission, the carbon emission characteristics of key areas such as energy consumption structure, transportation system, industrial production process and building energy consumption are analyzed deeply, which is an important prerequisite for making precise emission reduction strategy and promoting the urban green transformation. Based on these premises, this study took Beijing as the research object, and used LEAP model to construct baseline scenario, low-carbon scenario and intensified low-carbon scenario based on historical statistics. This paper dynamically simulates Beijing's total energy demand and carbon emission from 2020 to 2060, and explores the feasible path and policy recommendations for achieving the "dual carbon" goal by combining energy balance analysis and contribution assessment of energy conservation and emission reduction measures, so as to provide decision support for Beijing's low carbon development and provide experience reference for carbon emission control of similar cities.

2 This paper's methodology

The LEAP model, a long-term energy alternative planning system, is a bottom-up energy-environment accounting tool based on scenario analysis. It can be used to analyze energy consumption and greenhouse gas emissions under different scenarios. At the same time, it can also predict medium- and long-term energy supply, energy supply conversion, and energy end-use demand under different development conditions, and account for greenhouse gas emissions sources in the energy and non-energy sectors, including carbon emission calculations. Therefore, the LEAP model is applicable for Beijing carbon emissions accounting. The technical roadmap of Beijing LEAP model is shown in Figure 1 below:

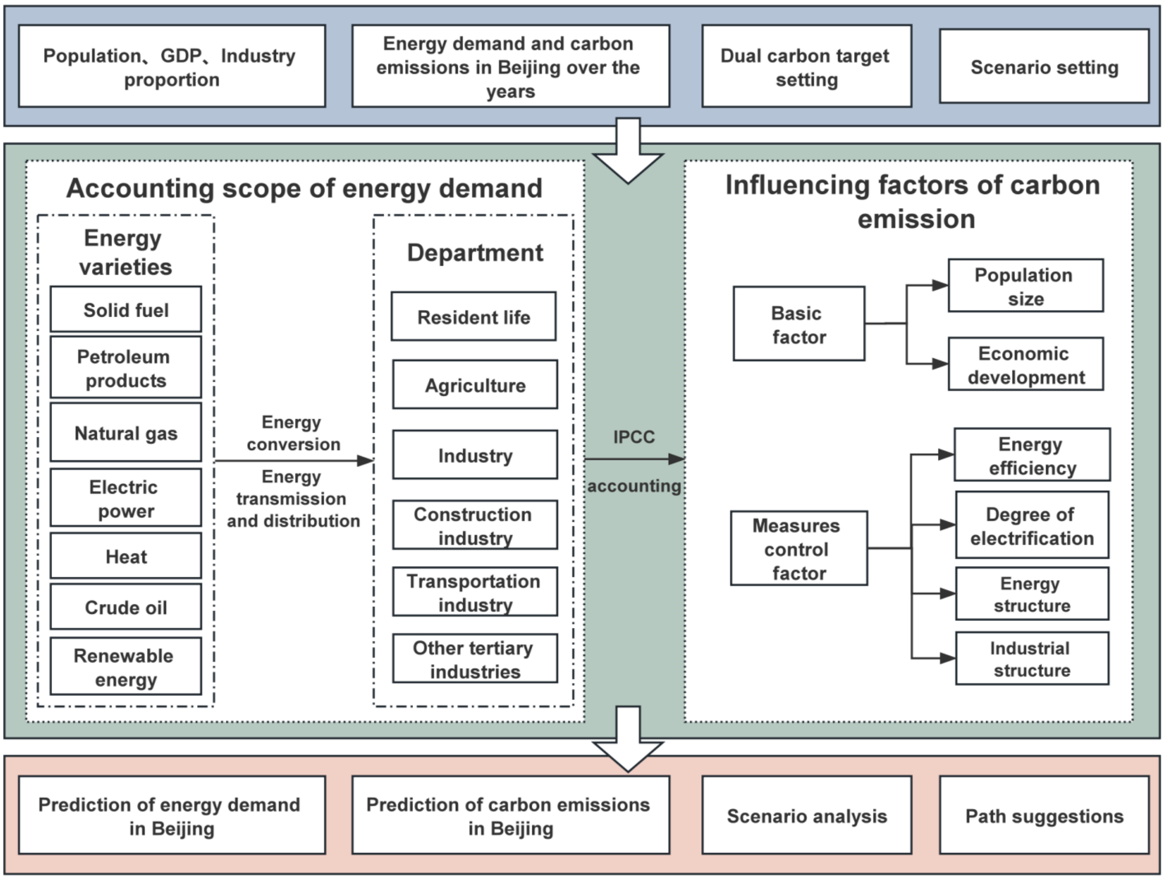


Figure 1: Beijing LEAP Model Technology Roadmap

The structure of LEAP model in Beijing is shown in Figure 2. The model mainly uses energy data (consumption of various types of energy), economic activity data (GDP, population, etc.), technical data (energy efficiency, emission factors, etc.), through different scenarios for analysis, to achieve the purpose of forecasting Beijing's energy demand and carbon emissions. According to Beijing's industrial structure, the end-use demand can be roughly divided into six sectors: agriculture, industry, construction, transportation, other tertiary industries (mainly information industries), and residential life. The difference between Beijing and other regions is that the tertiary industry accounts for 83.8% of the total. The tertiary industry is divided into two sectors, the transportation industry and other tertiary industry. The energy conversion departments are mainly divided into electric power and thermal power departments. Because the proportion of external power input of Beijing is nearly 60%, the energy conversion departments and power generation departments are discussed separately.

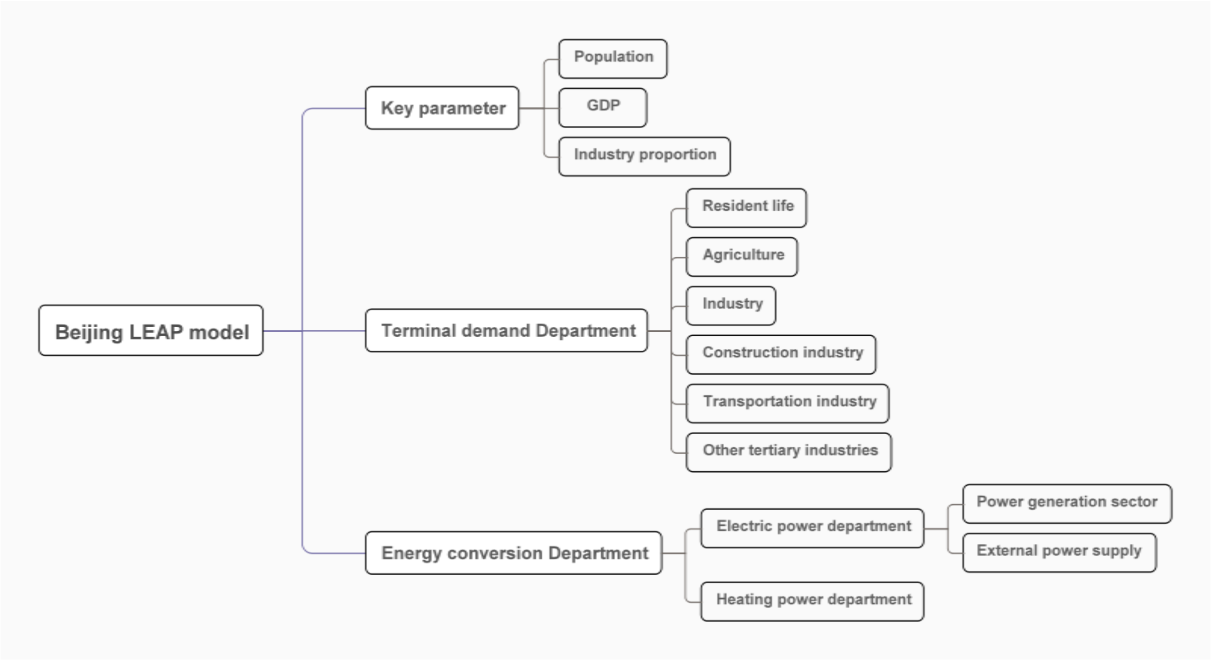


Figure 2: LEAP model structure diagram of Beijing

2.1 Major Formulas

2.1.1 End-use energy demand

Energy demand is the product of activity level and activity intensity, ECj is the end energy demand (in standard coal, the same below), ALij indicates the activity level of class j energy in the i sector, $_{EIi,}$j indicates the energy intensity of class j energy activity level in the i sector.

$$\mathrm{EC_j} = \sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{AL_{i,j}} \times \mathrm{EI_{i,j}} \tag{1}$$

2.1.2 Energy Demand in the Energy Conversion Sector

ETj represents the m-class energy input by the energy conversion department, EOk is k-class energy of local self-produced electric power and heat in Beijing, α_k is the transport loss rate of k-class energy, and $\beta_{j,k}$ is the conversion efficiency of j-class energy to k-class energy.

$$\mathrm{ET_j} = \sum_{\mathrm{k}} \mathrm{EO_k} \,/\, \left[(1 - \alpha_{\mathrm{k}}) \times \beta_{\mathrm{j,k}}\right] \tag{2}$$

2.1.3 Total energy demand

ED is the total energy demand, $\mathrm{EC_j}$ is the end energy demand, $\mathrm{ET_j}$ is the energy demand of the energy conversion department, TR is the total electric power transmitted outside Beijing.

$$\mathrm{ED} = \mathrm{EC_j} + \mathrm{ET_j} + \mathrm{TR} \tag{3}$$

2.1.4 Carbon emissions

Carbon emissions (in terms of carbon dioxide, here and below) are the product of energy requirements and emission factors. The total amount of carbon emissions can be calculated by adding the carbon emissions from different sources.

$$\mathrm{CE} = \sum_{j}\left(\mathrm{EC}_{j} + \mathrm{ET}_{j}\right) \times \mathrm{F}_{j} + \mathrm{TR} \times \mathrm{P}_{C} \tag{4}$$

CE represents the total carbon emissions, Fj represents the carbon emission coefficient of j energy, Pc is the carbon emission coefficient of external transmission electricity.

2.2 Scenario Settings

According to the different intensity of energy and emission reduction policies, Beijing LEAP model can be divided into three scenarios: baseline scenario, low-carbon scenario and intensified low-carbon scenario [45]. At the same time, according to Beijing's various energy and emission reduction policies, policy measures can be roughly divided into four categories: improve energy efficiency, promote electrification, optimize energy structure and optimize industrial structure.

Benchmark Scenario: Based on the framework of Beijing's 14th Five-Year Plan for Energy Development, the plan aims to achieve the set goals of socio-economic development while maintaining the current energy policy orientation without additional special measures. In this scenario, GDP and population are assumed to grow at a normal rate, energy and emission reduction policies are developed according to the current policy trajectory, energy conservation and emission reduction technologies are made moderate progress, and low-carbon lifestyles are gradually promoted. In this study, the baseline scenario was used as a baseline reference for assessing other policy scenarios.

Low-carbon scenario: On the basis of the baseline scenario, the GDP growth rate of the baseline scenario is maintained, and the implementation of the baseline scenario is further strengthened through four measures, namely, energy efficiency improvement, electrification promotion, energy structure optimization and industrial structure optimization.

Strengthening the low-carbon scenario: Based on the low-carbon scenario, further strengthening the implementation of measures. In this scenario, energy-efficient technologies and equipment are widely used in industry, construction, transportation and other fields to reduce energy consumption. Optimize energy use and improve energy efficiency. lower carbon emissions by strengthening electrification and reducing reliance on fossil fuels. We shall vigorously promote clean energy such as solar energy and wind energy, and increase the proportion of clean energy in the energy supply. We shall encourage the development of green and low-carbon industries, and promote the transition of traditional industries to green and low-carbon industries.

The three scenarios enhance emission reduction step by step, starting from the low-carbon scenario, according to the different energy and emission reduction measures are divided into four categories. Because each type of measures corresponds to different industries and sectors, this study subdivides them into three sub-scenarios and 24 measures. The specific scenario setting and the average annual growth rate of energy intensity are set as shown in Table 1 and Table 2 below:

Table 1: Scenario setting table

scenario classification	Action Description	Action Settings
baseline scenario	The current energy and emission reduction policies of Beijing Municipality shall be continued, and no adjustment shall be made.	
low-carbon scenario (A)	Energy Efficiency Improvements (A0)	A00 Energy Efficiency Improvement for Residents
		A01 Improving Agricultural Energy Efficiency
		A02 Industrial Energy Efficiency Improvements
		A03 Energy Efficiency Improvements in Transport
		A04 Energy efficiency gains in construction
		A05 Other tertiary industries improve their energy efficiency
	Electrification Propulsion (A1)	A10 Advancing the Electrification of Residents' Living
		A11 Agricultural Electrification Promotion
		A12 Industrial Electrification
		A13 Electrification of the Transportation Industry
		A14 Construction Electrification
		A15 Promotion of Electrification of Other Tertiary Industries
	Energy Structure Optimization (A2)	A20 Clean Energy
		A21 Increased percentage of green electricity
	Industrial Structure Optimization (A3)	A30 Optimization of Industrial Structure
Enhancing Low-Carbon Scenarios (B)	Energy Efficiency Boost (B0)	Energy Efficiency Improvement of B00 Residents
		B01 Improving Agricultural Energy Efficiency
		B02 Industrial Energy Efficiency Improvements
		B03 Energy Efficiency Improvement in Transportation
		B04 Energy Efficiency Improvements in Construction
		B05 Other tertiary industries improve their energy efficiency
	Electrification Propulsion (B1)	B10 Promotion of Residents' Living Electrification
		B11 Agricultural Electrification Promotion
		B12 Industrial Electrification
		B13 Electrification of Transportation Industry
		B14 Building Industry Electrification
		B15 Promotion of Electrification of Other Tertiary Industries
	Energy Structure Optimization (B2)	B20 Clean Energy
		B21 Increased percentage of green electricity
	Industrial Structure Optimization (B3)	B30 Optimization of Industrial Structure

Table 2: Annual growth rate of energy consumption intensity setting (Unit: %)

Department	baseline scenario			low-carbon scenario			Enhancing low-carbon scenarios		
	2021 to 2035	2035 to 2045	2045 to 2060	2021 to 2035	2035 to 2045	2045 to 2060	2021 to 2035	2035 to 2045	2045 to 2060
residential life	-1.5	-1.2	-1.0	-1.6	-1.4	-1.2	-1.8	-1.6	-1.4
agriculture	-1.3	-1.1	-1.0	-1.4	-1.2	-1.1	-1.6	-1.4	-1.2
industry	-2.0	-1.5	-1.2	-2.5	-1.8	-1.4	-3.0	-2.5	-1.8
transportation industry	-2.3	-2.0	-1.5	-2.5	-2.2	-1.7	-2.8	-2.4	-1.9
construction industry	-1.6	-1.2	-1.0	-2.5	-2.0	-1.5	-3.0	-2.5	-1.8
tertiary industry	-2.5	-2.0	-1.3	-2.5	-2.8	-1.5	-3.3	-3.0	-1.8

2.3 Primary data sources

The population, GDP, and industrial structure data in 2020 and before in this study come from the Beijing Statistical Yearbook, and the carbon emissions data come from the (CEADs) China Carbon Accounting Database. The population and industrial structure data after 2020 shall be referred to the relevant official reports issued by the Beijing Municipal Bureau of Statistics. The GDP data shall be interpreted by reference to the data of the People's Government of Beijing Municipality. The specific indicator settings are as shown in Table 3 below:

Table 3: Main indicator settings

Indicator/unit	2020	setting up
population per ten thousand	2189	Natural growth rate of 0.01%
GDP growth rate/%	5.5	Every five years, GDP growth declines by 0.5%
Percentage of primary industries/%	0.3	Change by Scenario Settings
Proportion of secondary industries/%	15.9	
Tertiary sector ratio/%	83.8	

Energy intensity and energy utilization rate refer to the Energy Development Plan of Beijing during the 14th Five-Year Plan Period. Carbon emission factor data were taken from the IPCC 2006 Guidelines, and the data of Beijing Municipality in the Electricity Carbon Emission Factor 2021 were transferred into the Electricity Carbon Emission Factor, which was 0.5688 (kgCO2/kWh). All the above data are used after conversion. The parameters of scenario setting are set by referring to relevant policy documents and relevant research literature of Beijing.

3 Analysis of experimental results

3.1 Forecast and Analysis of Beijing Energy Demand

Figure 3 below shows the trend of Beijing's energy demand for three different scenarios from 2020 to 2060.

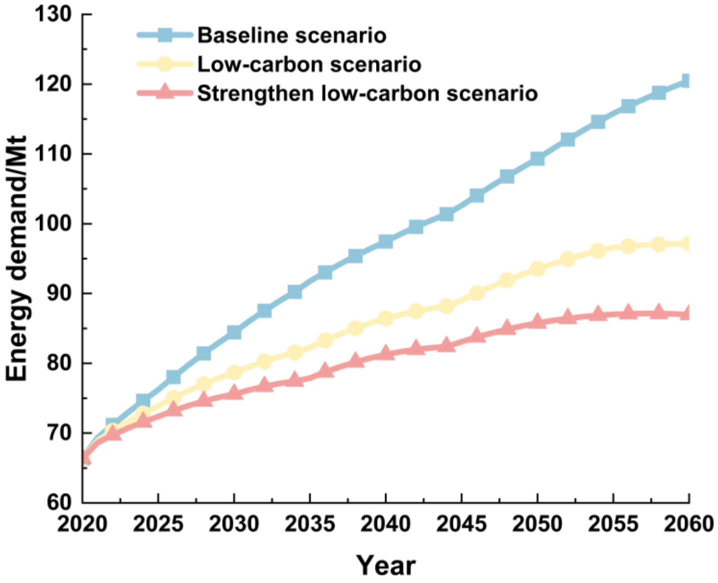


Figure 3: Energy Demand Forecast Chart of Beijing Municipality

As shown in Figure 3, Beijing's energy demand shows a remarkable characteristic of scenario divergence. Under the benchmark scenario, total energy demand shows a continuous growth trend, with the energy demand rising gradually from 66.4Mt in 2020 to 102.6Mt in 2045, and reaching 120.5Mt in 2060. In contrast to the low-carbon scenario and the intensified low-carbon scenario, the energy demand curve shows an evolutionary trend of first increasing and then stabilizing. Under the low-carbon scenario, the total energy demand in 2045 and 2060 is 89.0Mt and 97.1Mt, respectively, which is 19.4% more energy-saving than under the baseline scenario. Under the enhanced low-carbon scenario, the total energy demand in 2045 and 2060 will be 83.1Mt and 87.0Mt, with the energy saving rate rising to 27.8%. Among them, the growth rate of total energy demand will increase by stages in 2035 and 2045, which can be attributed to the significant marginal effect of energy conservation measures at the initial stage. With the time going on, energy conservation gradually touches the bottlenecks of technology and policy, leading to the decline of energy saving capacity, highlighting the need for dynamic adjustment of energy conservation strategy. From the peak characteristics, the total energy demand of Beijing will reach the peak in 2057 under the intensified low-carbon scenario only, which shows the effectiveness of the scenario in energy regulation.

3.2 Analysis of Carbon Emission Forecast in Beijing

Figure 4 below shows the trend of total emissions in Beijing for three different scenarios from 2020 to 2060.

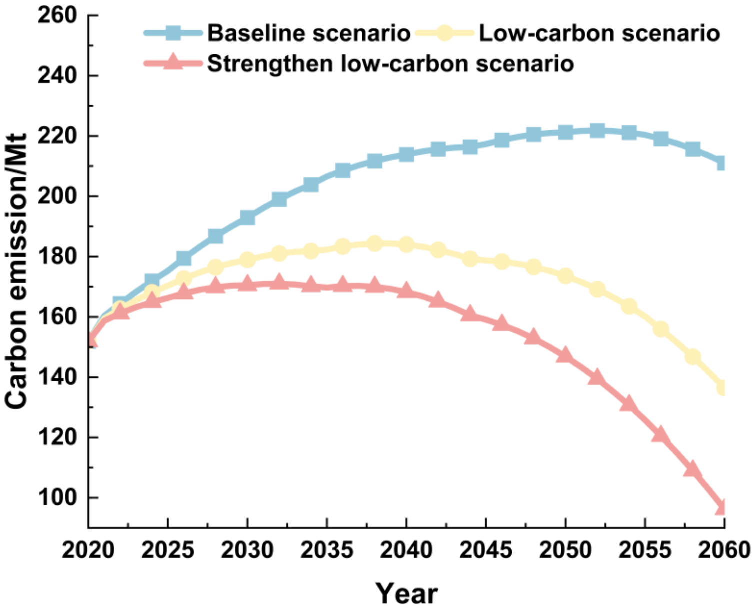


Figure 4: Energy Demand Forecast Chart of Beijing Municipality

Figure 4 shows that the total amount of carbon emissions in Beijing shows an inverted "U"-shaped evolution trajectory under different scenarios. In the baseline scenario, total emissions reach a peak of 151.9Mt in 2020, 221.8Mt in 2052, and then fall back to 211.0Mt in 2060; in the low-carbon scenario, peak emissions reach 184.3Mt in 2038 and fall further to 136.4Mt in 2060; and in the enhanced low-carbon scenario, peak emissions reach 170.3Mt in 2029 and fall significantly to 96.2Mt by 2060.

Through comparative analysis of different scenarios, it can be concluded that under the enhanced low-carbon scenario only, the total carbon emissions of Beijing could reach the peak value before 2030, and the emission reduction efficiency of this scenario is significantly better than that of other scenarios, thus providing a valuable path guidance for achieving the "dual-carbon" goal.

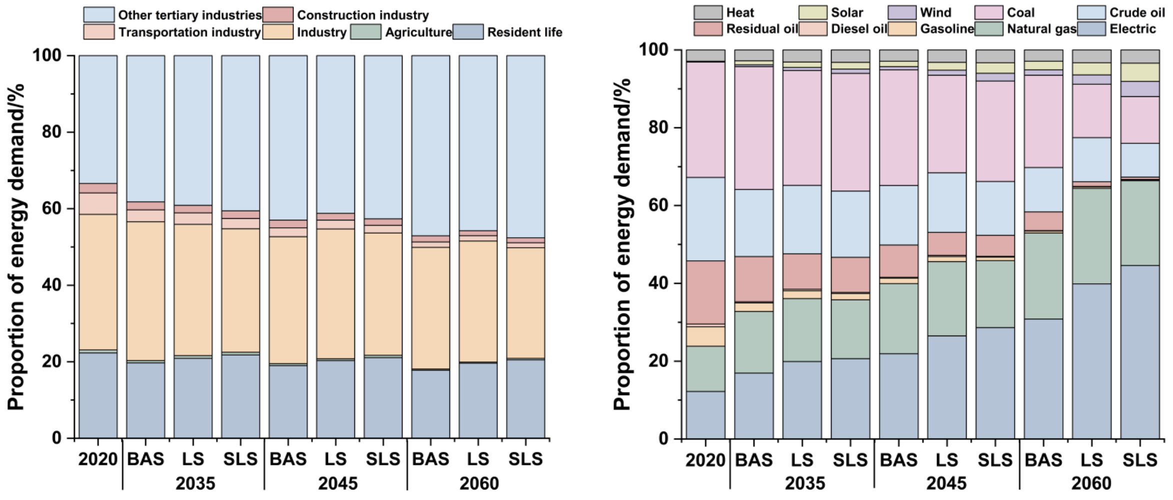
3.3 Prediction and analysis of energy demand structure under different scenarios

According to Beijing's industrial structure and energy structure, the forecast results of energy demand can be analyzed from two directions: division and variety. The industrial structure is divided into six major terminal departments according to the above-mentioned Beijing LEAP model, where the energy demand of the energy conversion department has been decomposed to the terminal department, and is not separately discussed. The energy structure is discussed according to the energy category in the document of "Beijing 14th Five-Year Plan of Energy Development". The forecast result is shown in Fig.5 below.

Figure 5 (a) presents the results of the projections of energy demand by subsector under the baseline, low-carbon and enhanced low-carbon scenarios. The data show that other tertiary industry sectors and industrial sectors account for a significant proportion of the total energy demand, constituting the main energy demand terminals in Beijing. In terms of time series, the energy demand of other tertiary industries shows a trend of continuous growth, becoming the core areas of concern for energy conservation, while the proportion of energy demand of the industrial, transportation and construction sectors decreases in varying degrees, which is in line with the development trend of Beijing Municipality to promote the optimization and upgrading of industrial structure and the transformation of traditional industrial, transportation and construction sectors into high-tech industries. In the same year, the energy demand of the industry, transportation and construction sectors under the low-carbon and intensified low-carbon scenarios was lower than the benchmark scenario, which confirmed the remarkable effects of the energy efficiency improvement measures in the above sectors.

Figure 5(b) presents the forecast results of energy demand by type under three scenarios. The analysis shows that power, coal, natural gas and crude oil play a dominant role in the energy demand structure, and their demand control becomes the key focus of energy conservation. From the time evolution, the demand for electricity and natural gas will continue to grow, while the demand for traditional energy sources, such as coal, crude oil, residual oil and gasoline, will show a downward trend. This change is closely related to the policy orientation of Beijing Municipality in vigorously promoting the process of electrification and promoting the transformation from traditional high-polluting energy sources to low-polluting energy sources, and at the same time, the promotion policy of new energy vehicles has significantly reduced the utilization rate of fuel vehicles, resulting in a decrease in the demand for gasoline and an increase in the demand for electricity. In the same year, the proportion of demand for high-polluting energy sources such as coal and crude oil under low-carbon and intensified low-carbon scenarios was significantly lower than that under the baseline scenario, while the proportion of demand for low-polluting energy sources such as electricity and natural gas was correspondingly higher, reflecting that the strategy of energy structure adjustment effectively reduced the proportion of direct use of high-polluting energy sources in the end sector.

The analysis results in Figs 5(a) and (b) show that the energy-saving transformation of the tertiary industry and industry plays a decisive role in realizing the overall energy-saving target of Beijing Municipality in the sectoral dimension, and that the promotion of the reduced use of coal and petroleum products and the improvement of the energy utilization efficiency of electric power and natural gas in the energy-saving dimension are important directions for promoting the energy-saving work of Beijing Municipality.



(a) energy demand by sector forecast (b) Variety projections of energy demand

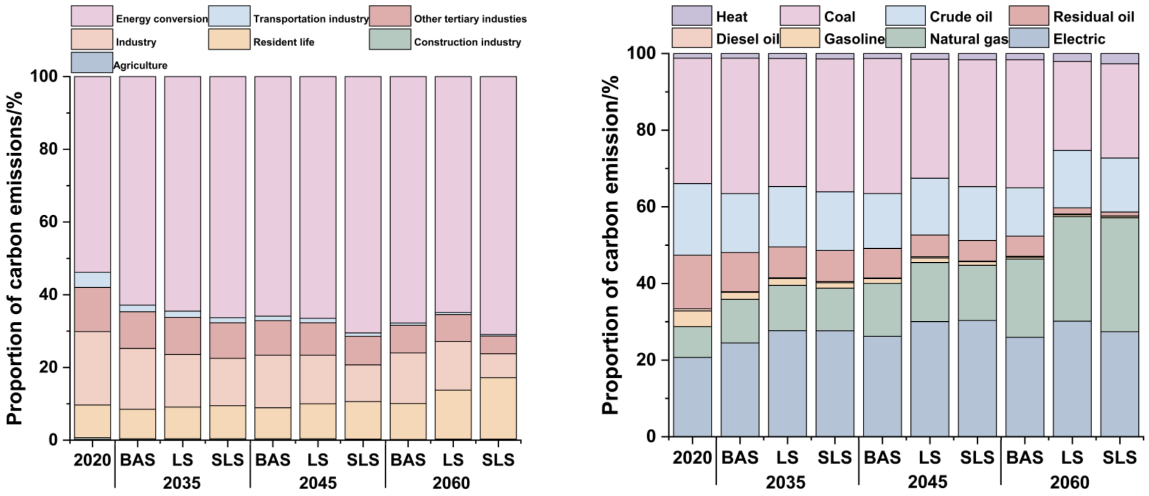
Figure 5: The results of energy demand structure prediction under different scenarios

3.4 Prediction and Analysis of Carbon Emission Structure under Different Scenarios

The carbon emission structure prediction analysis under three scenarios of baseline, low carbon and intensified low carbon is shown in Figure 6 below. Fig. 6 (a) shows the results of the projections of sub-sectoral emissions under the three scenarios. The data show that the energy conversion sector accounts for the largest share of carbon emissions, with the industrial sector and the household sector ranked second and third respectively. This is mainly attributed to the fact that more than 70% of Beijing's outward-diverting electricity comes from coal-fired provinces such as Inner Mongolia and Shanxi, which has led to a significant increase in indirect carbon emissions. From the time series change, the proportion of carbon emissions from energy conversion sector and residential sectors has a rising trend, and energy conversion sector should be the core area of concern for carbon emission control. In the same year, the carbon emission ratio of the industrial sector and the transport sector under the low-carbon and intensified low-carbon scenarios was lower than that under the baseline scenario, indicating that the emission reduction measures implemented by the above sectors have achieved significant results.

Fig. 6(b) presents the projections of carbon emissions by energy species under the three scenarios. The analysis shows that coal and electricity play a dominant role in carbon emission structure, and are the key objects of carbon emission control. The carbon emissions of coal, crude oil, residual oil and other energy sources have been declining over time, reflecting the positive effect of energy structure adjustment measures in reducing carbon emissions, while the carbon emissions of electricity and natural gas have been increasing, which is closely related to the policy orientation of promoting electrification process and increasing the proportion of electricity and natural gas use in Beijing. In the same year, the proportion of carbon emissions from low-carbon and intensified low-carbon scenarios for power, natural gas and other low-polluting energy sources was higher than that in the baseline scenario. However, in the intensified low-carbon scenario, the proportion of carbon emissions from coal, petroleum products and other high-polluting energy sources rebounded to some extent compared with that in the low-carbon scenario. This may be due to an aggressive strategy to boost the low-carbon scenario, which in turn leads to a higher share of carbon emissions at a time when electricity supply is still highly dependent on high-carbon energy sources.

The analysis results of Figs 6(a) and 6(b) show that the deep decarbonization between energy conversion sector and industry sector is the core focus of promoting energy conservation and emission reduction in Beijing from the sector dimension, and that reducing the use of coal and petroleum products and expanding the supply of clean energy from the energy variety dimension is of decisive significance to achieve the targets of energy conservation and emission reduction in Beijing.



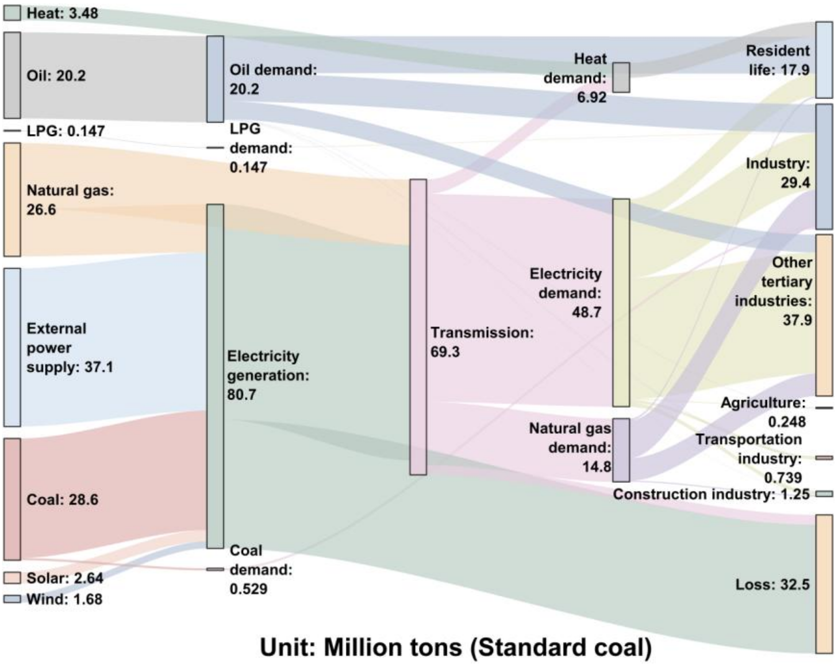
(a) Sub-sectoral projections of carbon emissions

(b) Variety projections of carbon emissions

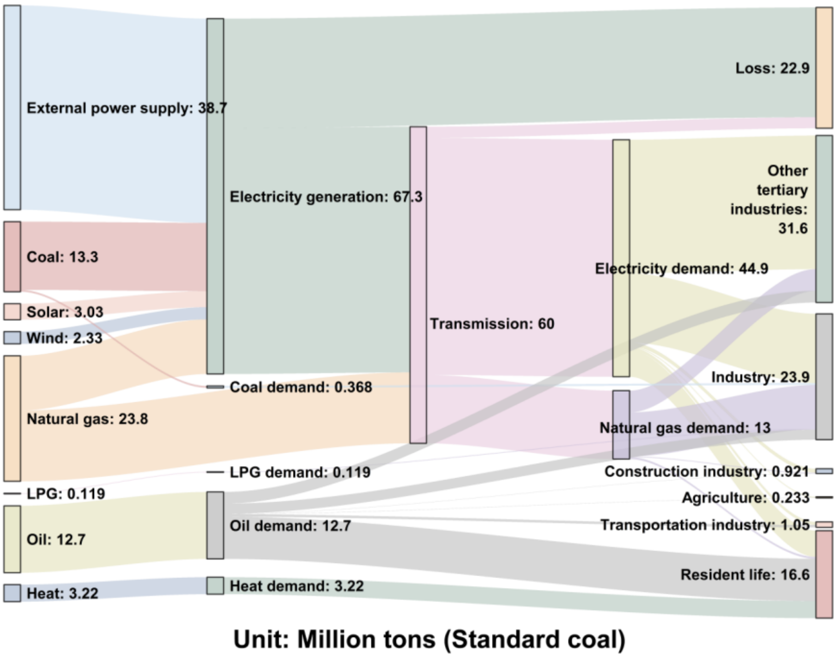
Figure 6: Predicted carbon emission structure under different scenarios

3.5 Analysis of energy flow chart in Beijing under different scenarios

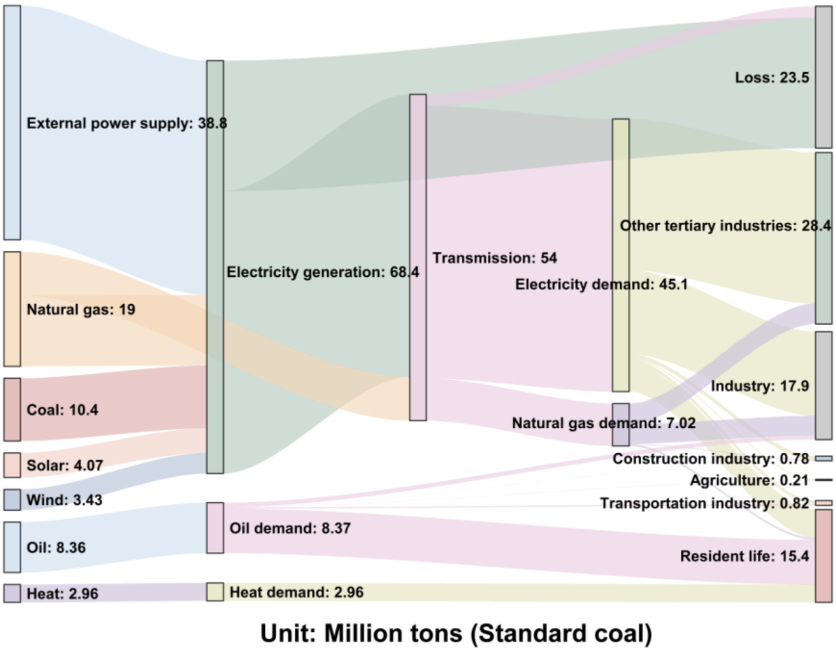
The energy flow chart directly shows the whole process of the energy from the production end to the end consumption field of industry, transportation and construction through the conversion link. By analyzing the proportion of energy flows in each link, the dominant energy types, energy conversion efficiency bottlenecks, and high energy-consuming areas of end-use consumption can be identified. The 2060 was selected as the key year for the analysis and the results are shown in Figure 7 below.



(a) baseline scenario



(b) low-carbon scenario



(c) Enhanced low-carbon scenarios

Figure 7: Energy flow maps for three scenarios, 2060

From Figure 7(a), it can be seen that in the baseline scenario, Beijing has a high share of energy from external inputs (37.1Mt, 30.8%), coal (28.6Mt, 23.7%), and natural gas (26.6Mt, 22.1%). From the perspective of energy conversion, 67% of the input energy is used for power generation, with the remaining 33% directly supplied to end-use demand. From the perspective of energy expenditure, the expenditure of power energy is mainly used in other tertiary industry and industry, and household consumption. Natural gas is mainly used in other tertiary industry and industry, while oil energy is respectively used in residential life, industry and other tertiary industry. From the energy loss point of view, 80.7Mt energy used for power generation, after energy conversion and transmission loss lost 32.5Mt of energy, the loss rate is about 40.2%.

From Figure 7(b), it can be seen that in the low-carbon scenario, from the perspective of energy sources, Beijing has a high share of energy input from outside (38.7Mt, 39.8%), natural gas (28.6Mt, 29.4%), and coal (13.3Mt, 13.6%). From the perspective of energy conversion, 69% of the input energy is used for power generation, with the remaining 31% directly supplied to end-use demand. From the perspective of energy expenditure, the proportion of end-demand for energy supply in each category is roughly the same as in the baseline scenario. From the energy loss point of view, 67.3Mt energy used for power generation, after energy conversion and transmission loss lost 22.9Mt of energy, the loss rate is about 34%.

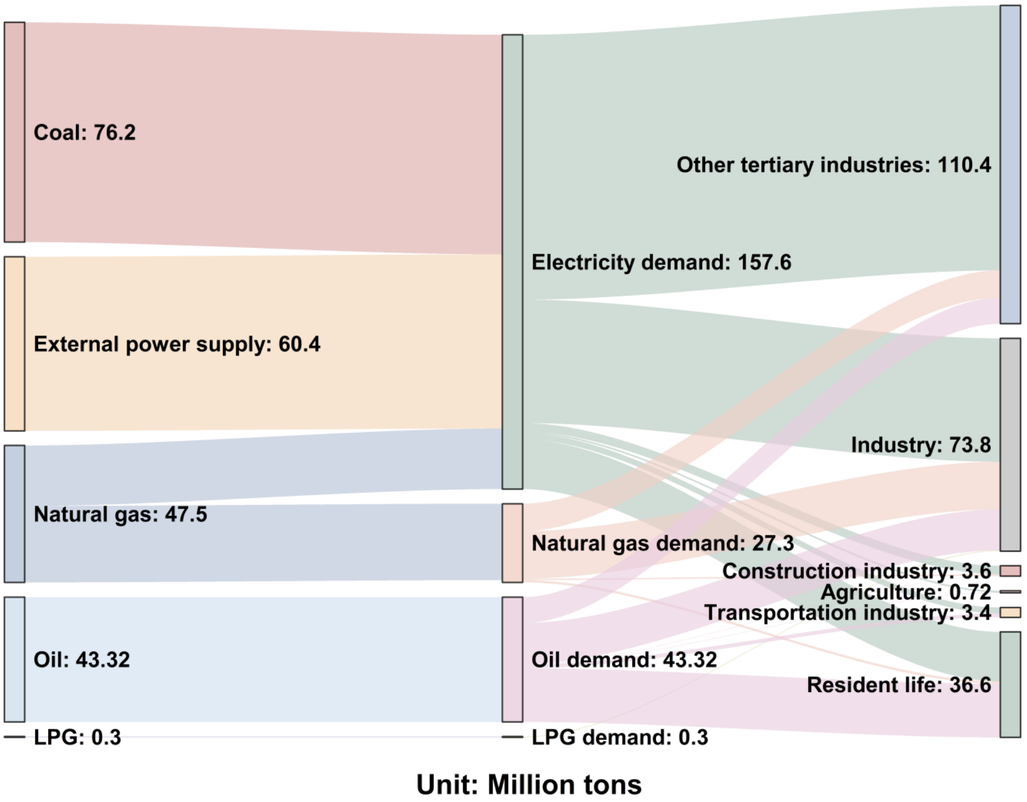
From Figure 7(c), it can be seen that under the enhanced low-carbon scenario, Beijing has a high share of energy from external inputs (38.8Mt, 44.5%), natural gas (19Mt, 21.8%), and coal (10.4Mt, 11.9%). From the perspective of energy conversion, 69% (68.4 Mt) of the input energy is used for power generation, with the remaining 31% directly supplied to end-use demand. From the perspective of energy expenditure, the proportion of end-demand for energy supply in each category is roughly the same as in the baseline scenario. From the energy loss point of view, 68.4Mt energy used for power generation, after energy conversion and transmission loss lost 23.5Mt of energy, the loss rate is about 34%.

The analysis of Beijing energy flow chart shows that the enhanced low-carbon scenario has advantages in energy structure optimization, energy efficiency improvement and carbon emission control. Compared with the benchmark scenario (power generation loss rate of 40.2%)

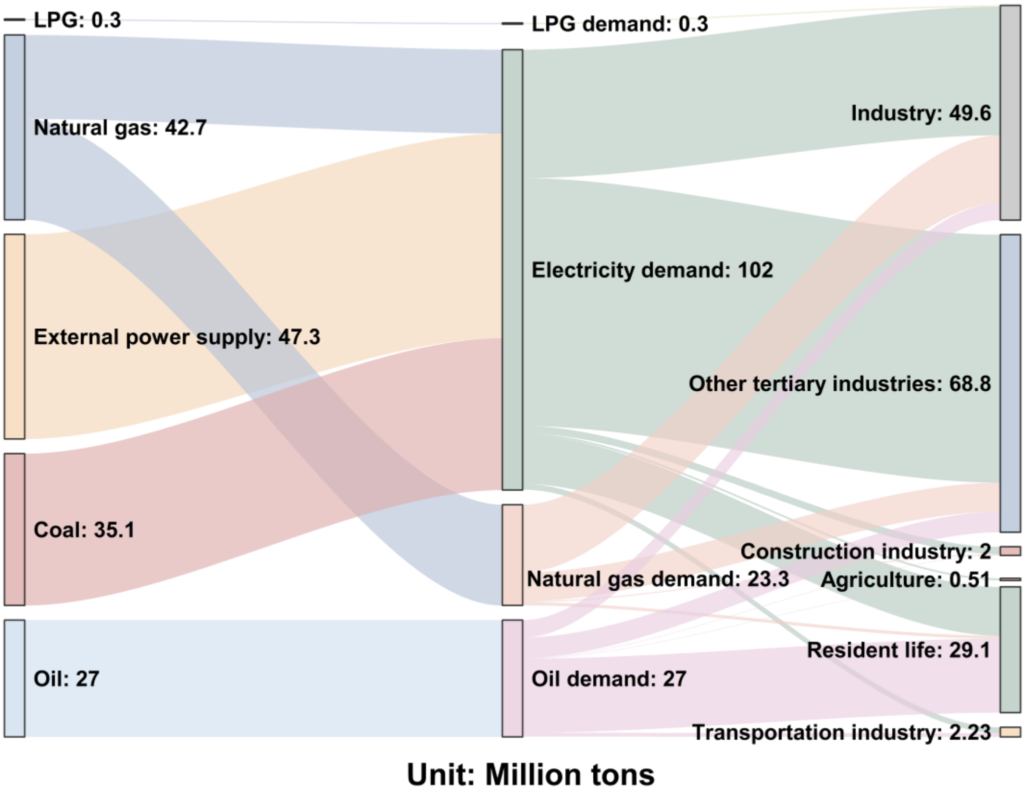
and the general low-carbon scenario (power generation loss rate of 34%), the enhanced low-carbon scenario further reduces coal dependence (11.9% vs. 23.7%) while maintaining a similar power generation scale (68.4 Mt), while increasing the proportion of outward green electricity (44.5%), resulting in a stable power generation loss rate of 34%. While the depletion rate is on a par with the typical low-carbon scenario, its greater coal substitution and renewable energy integration offer a more sustainable path to deep decarbonization in the long term.

3.6 Carbon Flow Map Analysis in Beijing under Different Scenarios

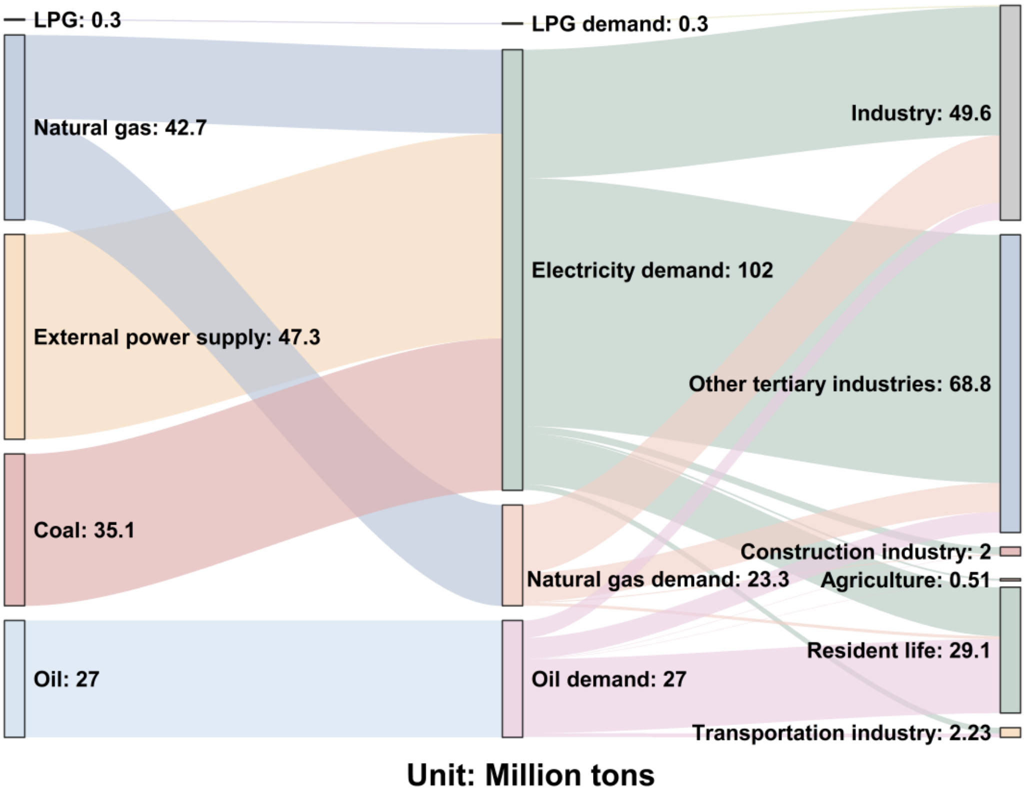
Carbon emission flow graph system shows the whole process of carbon release from the source, and ultimately produces emissions in the end-use areas of industry, transportation, construction, and so on. By quantifying carbon emissions and contribution in each link, the main sources of carbon emissions can be accurately located, and the key nodes of high-carbon industry can be identified, which provides data support and decision-making reference for the establishment of emission reduction path, optimization of industrial structure, and promotion of low-carbon technology application. The results are presented in Fig. 8 below, with an analysis of 2060 as a key year.



(a) baseline scenario



(b) low-carbon scenario



(c) Enhancing low-carbon scenarios

Figure 8: carbon flow diagram under three scenarios in 2060

Under the baseline scenario, coal (76.2Mt, 33.4%), electricity from external transfers (60.4Mt, 26.5%) and natural gas (47.5Mt, 20.8%) account for a high proportion of carbon emissions from sources of emissions. From the demand classification analysis, carbon emissions are mainly generated by the demand for electricity supply (157.6Mt, 69.2%), oil products (43.3Mt, 19%) and natural gas (27.3Mt, 11.9%). At the end level, the three sectors with higher carbon emissions are the other tertiary sector (110.4Mt, 48.4%), industry (73.8Mt, 32.4%) and residential life (36.6Mt, 16.1%).

In the low-carbon scenario, the carbon emissions from power (47.3Mt, 31.0%), natural gas (42.7Mt, 28.0%) and coal (35.1Mt, 23.0%) are higher than those from other sources. In terms of demand classification, carbon emissions are mainly generated by the demand for electricity supply (102Mt, 66.9%), oil products (27Mt, 17.7%) and natural gas (23.3Mt, 15.2%). At the end-level, the three sectors with higher carbon emissions are the other tertiary sector (68.4Mt, 44.8%), industry (49.6Mt, 32.5%) and residential life (29.1Mt, 19.0%).

Under the enhanced low-carbon scenario, the carbon emissions from natural gas (34.2Mt, 30.6%), external power input (31.6Mt, 28.3%) and coal (28.2Mt, 25.2%) account for a high proportion from the perspective of emission sources. In terms of demand classification, carbon emissions are mainly generated by the demand for electricity supply (81.7Mt, 73.1%), oil products (17.7Mt, 15.8%) and natural gas (12.6Mt, 15.8%). At the end level, the three sectors with higher carbon emissions are the other tertiary sector (50.8Mt, 45.5%), industry (32.8Mt, 29.4%) and residential life (24.8Mt, 22.2%).

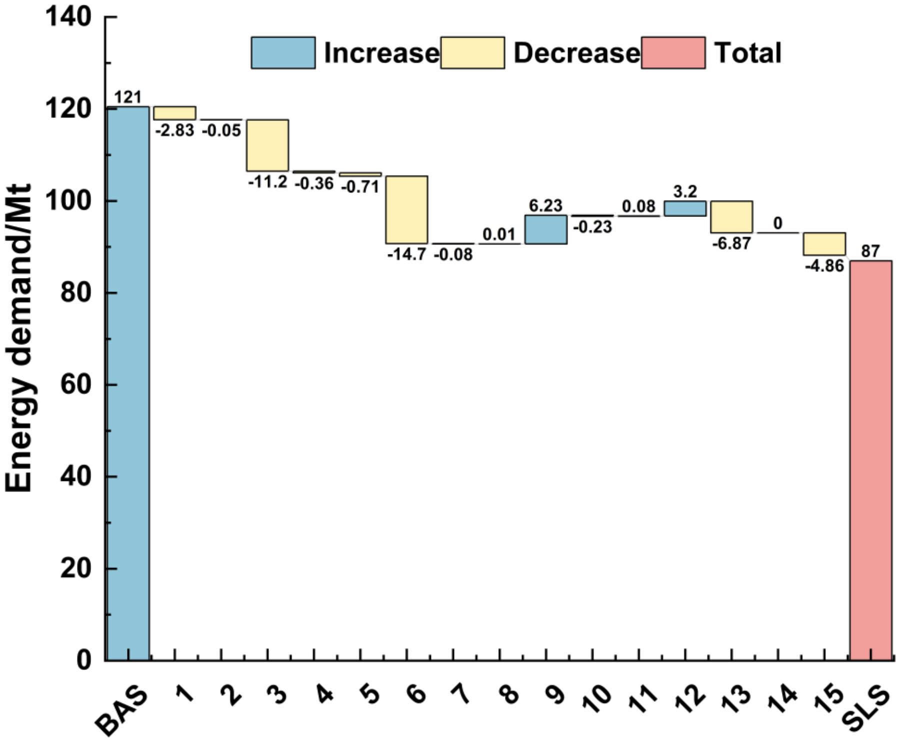
Based on the above analysis, the enhanced low-carbon scenario shows significant advantages in carbon emission control. Compared with the baseline scenario (total emissions 228.1Mt) and the low-carbon scenario (152.6Mt), the enhanced low-carbon scenario further reduced total emissions to 111.6Mt, with a reduction of 51.1% and 26.9% respectively. The scenario not only significantly reduced coal-related emissions (to 25.2%), but also increased carbon emissions from power supply to 73.1% by enhancing the low-carbon substitution role of clean electricity (28.3%) and natural gas (30.6%), highlighting the potential for emission reduction in the context of energy structure optimization. At the same time, emissions from the tertiary industry, industry and residential life in the end sector have all been systematically reduced, especially the industrial sector, which has a significantly reduced share (29.4% vs. 32.4%), indicating that the enhanced low-carbon scenario can more effectively coordinate economic growth with deep decarbonization. Therefore, the scenario should be regarded as the core path to achieve carbon neutrality, which takes into account the characteristics of emission control and energy security and provides a scientific basis for policy development.

3.7 Analysis of Energy Saving and Emission Reduction Measures in Beijing under Different Scenarios

Based on the above analysis, only the enhanced low-carbon scenario is closer to achieving the dual-carbon goal. Therefore, this section will focus on strengthening energy conservation and emission reduction measures under the low-carbon scenario, in-depth excavation in the contribution rate of each measure, to provide path recommendations for the realization of carbon neutrality goal.

3.7.1 Contribution Analysis of Energy Saving Measures

Choose 2060 as the key year for contribution analysis, and compare the baseline scenario with the enhanced low-carbon scenario, the specific energy conservation measures contribution analysis results are shown in Figure 9 below.



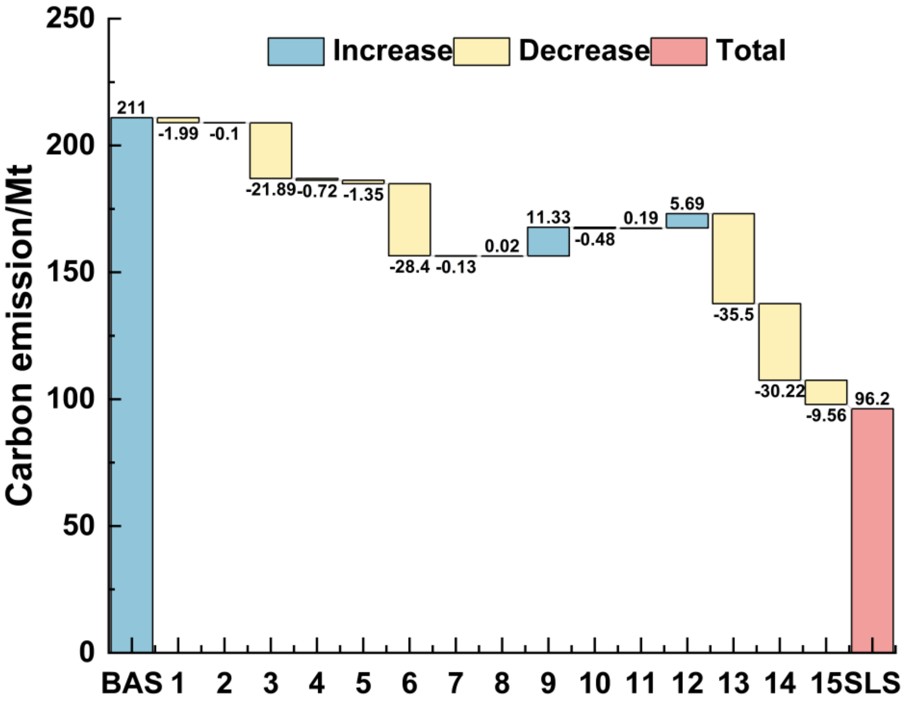
Note: BAS: Benchmark Scenario 1: Energy Efficiency Improvement in Household Living 2: Energy Efficiency Improvement in Household Living 3: Energy Efficiency Improvement in Industry 4: Energy Efficiency Improvement in Transportation 5: Energy efficiency of construction industry 6: Energy efficiency of tertiary industry 7: Household electrification 8: Agricultural electrification 9: Industrial electrification 10: Transport electrification 11: Construction industry electrification 12: Tertiary industry electrification 13: Clean energy 14: Green electricity proportion increase 15: Industrial structure optimization SLS: Strengthening low-carbon scenario

Figure 9: Contribution Chart of Energy Saving Measures in 2060

Figure 9 shows that the energy efficiency improvement strategy of the tertiary industry plays a leading role in energy conservation and consumption reduction, and cumulatively achieves the energy demand reduction of 14.67Mt, contributing 43.7% to the total energy conservation; the energy efficiency optimization measures of the industrial sector take second place, and the energy demand reduction is 11.15Mt, contributing 33.2%. However, the measures taken to promote the electrification of the industrial and tertiary industries have the incremental effect of energy demand, which is closely related to the energy conversion characteristics and the energy efficiency loss of the system. The process of electrification realizes the end-use energy cleanliness through the direct combustion of electricity instead of coal, natural gas and other primary fossil energy. However, as a secondary energy, the whole life cycle of electricity covers power generation, transmission, distribution and end-use, and there are irreversible energy conversion loss in each link. Under the background of high proportion of high-carbon energy in the power production structure and no significant improvement of grid transmission and distribution efficiency, the electrification transformation can easily lead to the increase of the overall energy consumption of the system, which presents the contradictory characteristics of "clean transformation and energy consumption growth coexistence".

3.7.2 Analysis of contribution of emission reduction measures

Choose 2060 as the key year for contribution analysis, and compare the baseline scenario with the enhanced low-carbon scenario, the specific contribution analysis results of emission reduction measures are shown in Figure 10 below.



Note: BAS: Benchmark Scenario 1: Energy Efficiency Improvement in Household Living 2: Energy Efficiency Improvement in Household Living 3: Energy Efficiency Improvement in Industry 4: Energy Efficiency Improvement in Transportation 5: Energy efficiency of construction industry 6: Energy efficiency of tertiary industry 7: Household electrification 8: Agricultural electrification 9: Industrial electrification 10: Transport electrification 11: Construction industry electrification 12: Tertiary industry electrification 13: Clean energy 14: Green electricity proportion increase 15: Industrial structure optimization SLS: Strengthening low-carbon scenario

Figure 10: Contribution chart of emission reduction measures by 2060

Figure 10 shows that the clean energy alternative strategy plays a central role in carbon emission reduction, and the cumulative carbon emission reduction achieved 35.5Mt, contributing 30.9% to the total emission reduction. The second is green electricity proportion improvement measures, achieving 30.22Mt carbon emissions reduction, contributing 26.3%. By contrast, the effectiveness of the measures to promote electrification is limited, and the process of industrial and tertiary industry electrification even shows the growth trend of energy demand. This phenomenon is closely related to the dynamic imbalance between power supply and demand and the structural characteristics of energy: the transformation of electrification has significantly increased the demand for end-use power, and when the power supply system is unable to respond to incremental demand in a timely manner, the share of high-carbon power, such as coal-fired power, in the energy mix has been passively increased to meet the power gap. Because the carbon intensity of coal-fired power generation is significantly higher than that of clean energy, the reverse adjustment of energy structure leads to the increase of the overall carbon emissions, which forms the contradictory feature of "the co-existence of electrification process and carbon emission growth".

4 Conclusion

Based on the system model prediction and structure analysis, the following conclusions can be drawn:

1. The evolution characteristics of energy demand: under the benchmark scenario, Beijing's energy demand continued to grow, reaching 120.5Mt by 2060, failing to reach the peak demand; under the low-carbon scenario, although the growth trend was gradual, the energy demand was 97.1Mt in 2060, saving 19.4% of energy compared with the benchmark scenario, but still not reaching the peak; under the intensified low-carbon scenario, the energy demand peaked in 2057, fell to 87.0Mt in 2060, saving 27.8%, showing remarkable effects of demand control.

2. Dynamic trends in carbon emissions: Under all three scenarios, carbon emissions show an inverted "U"-shaped curve, with peaks in 2052 (baseline scenario), 2038 (low-carbon scenario) and 2029 (enhanced low-carbon scenario). Although emissions under the enhanced low-carbon scenario fell to 96.2Mt by 2060, the closest "carbon neutral" scenario to the target, none of the three scenarios fully met the "carbon neutral" requirement.

3. From the sectoral perspective, energy efficiency improvement in the tertiary industry and the industrial sector is the core focus of energy conservation, while the deep decarbonization of the energy conversion sector and the industrial sector constitutes the dominant driving force for emission reduction. At the energy variety level, significant synergistic effect of emission reduction can be achieved by reducing the consumption of high-carbon energy such as coal and oil, improving the utilization efficiency of electric power and natural gas, and expanding the proportion of clean energy.

4. Energy saving and emission reduction optimal scenario: energy flow map and carbon flow map analysis shows that the enhanced low-carbon scenario shows the optimal performance in energy efficiency improvement and carbon emission control. The scenario not only significantly reduces the energy consumption rate of power generation (34% vs. 40.2% in the baseline scenario), but also achieves the most significant carbon reduction effect by optimizing the energy structure (the share of coal reduced to 11.9%, and the share of green electricity increased to 44.5% in the external deployment scenario) (total emission 111.6Mt, 51.1% lower than the baseline scenario). Strengthening low-carbon scenarios can achieve effective energy conservation and emission reduction through systematic energy structure adjustment and energy efficiency improvement, and should be the preferred implementation path of regional carbon neutrality strategy.

5. Emission reduction measures effectiveness evaluation: Energy efficiency improvement has significant effect on reducing energy demand, and the synergistic promotion of energy structure optimization and energy efficiency improvement can effectively reduce carbon emissions. It should be noted that the short-term electrification process may lead to an increase in carbon emissions due to the high carbon energy share in the power supply structure, but from a long-term perspective, electrification will be an important path to carbon emission reduction with the decarbonization of the grid and the increase in the share of clean energy.

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