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# Analysis of Electric Energy Substitution Potential and Energy Structure in China under Dual Carbon Background

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**Abstract:**
The implementation of the "electricity substitution" policy will reshape the current structure of terminal energy consumption in our country, and is a crucial approach to expeditiously achieve the dual-carbon goal. This paper conducts an analysis on the structure of terminal energy consumption in China, as well as the influencing factors of electric energy alternative development. It establishes a multiple regression model for terminal energy consumption and GDP, power investment, urbanization, and carbon emissions. Finally, it carries out a quantitative analysis on the potential amount of electric energy substitution to construct a multi-objective function with maximum substitution potential and minimum construction cost under various constraint conditions. The optimization algorithm is utilized to optimize annual energy consumption in China over the next ten years and calculate the potential for electric energy replacement during that period. This study aims to provide valuable references for government departments and support power grid enterprises in scientifically implementing electric energy replacement and dual-carbon construction.

**Keywords:** terminal energy use, electric energy substitution, carbon peaks, particle swarm optimization.

## INTRODUCTION

Electricity substitution is a pivotal strategy for China to expeditiously achieve its dual carbon goals. In November 2016, the National Energy Administration jointly issued "Guiding Opinions on Promoting Electricity Substitution," which outlined comprehensive plans to advance the construction of power substitution projects during the "13th Five-Year Plan" period[1,2]. China's economy and society enter a fresh phase of advancement, the energy sector is also moving towards a high-quality development stage. The strategy of replacing electric energy should also be changed correspondingly in coordination with the national double-carbon policy, and turn to a more low-carbon, environmental-friendly and economic development direction[3], simultaneously, with the potential of electric energy substitution being continuously tapped, electric substitution will face problems such as saturation of electric energy substitution terminals and difficulty in breaking through technology. Therefore, for the purpose of help the country complete the construction of double-carbon target at an early date, it is essential to plan the evolution strategy of electric energy substitution in China in advance, and formulate a reasonable implementation plan to provide corresponding policy support for the development of electric energy substitution[4].However, the execution of projects replacing electric energy in China is in its infancy, and there are few relevant data about the quantity of electric energy replacement, so it is difficult to make accurate results by directly using modern intelligent forecasting methods such as machine learning to predict the future electric energy substitution data[5].

So, this paper uses the relevant information of the previous year to solve the electric substitution for the next year by the method of operational optimization. Firstly, it constructs an electric energy substitution potential to represent the cumulative construction amount of electric substitution projects, introduces the impaction of GDP, urbanization, double carbon targets and policy support on the implementation of electric energy substitution projects, and finally constructs different scenarios to analyze and predict the evolving trajectory of substitution potential and energy consumption structure in the future of China

## ELECTRIC ENERGY SUBSTITUTION POTENTIAL ANALYSIS MODEL CONSTRUCTION

### The Research Ideas of This Paper

Firstly, this paper studies the influence of GDP, urbanization, double-carbon target on the implementation of electricity substitution. Secondly, these influencing factors are quantified, and multiple linear regression modeling is carried out by using the annual consumption of various energy sources and their corresponding relationships are analyzed. Then, the mathematical model of electric energy substitution potential is established, and the constraints of low-carbon target, economic development and urbanization growth are introduced. On this basis, three scenarios are constructed: benchmark, high economic growth rate and policy strengthening support. Finally, in different scenarios, the substitution potential of electric energy and trend of energy consumption structure are obtained through the calculation of optimization algorithm by substituting historical data. The research flow is shown in Figure 1:

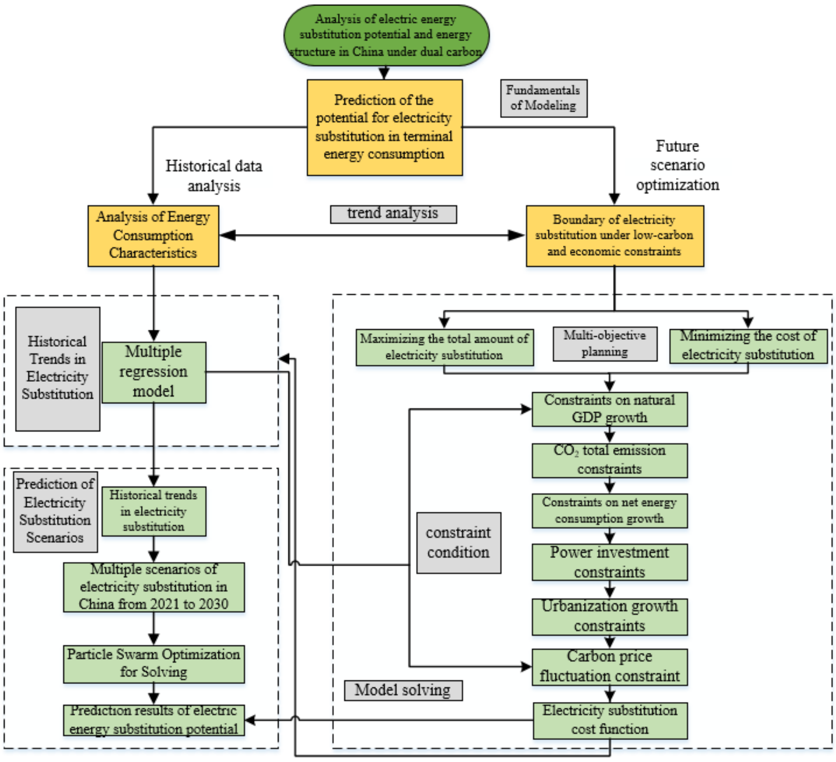


Figure 1. The flow chart of the research ideas in this paper

**Terminal Energy Consumption Matrix and Electric Energy Substitution Potential Model**

Firstly, the usage of various kinds of energy is divided, and the matrix of consumption of different kinds of energy is obtained. As shown in formula (1), $E^{(t)}$ is the end-use energy consumption matrix in the t year. According to the historical information of China, this paper divides the terminal energy consumption into 9 categories, including coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas and electricity[6].

$$E^{(t)} = [E_1^{(t)}, E_2^{(t)}, E_3^{(t)} \ldots\ldots E_i^{(t)}] \tag{1}$$

This paper describes the potential of electric substitution $E_{sub}{}^{(t)}$ to represent the increment of electric energy substitution projects built in China in that year. Assuming that the electric energy consumption in the t year is $E_k^{(t)}$ and the total energy consumption of the terminal is $\sum_{i=1}^{N} E_i^{(t)}$, and assuming that the terminal energy consumption structure remains unchanged in the t year and t-1 year, that is, the proportion of electric energy in the terminal energy consumption is equal to that in the t-1 year, the reality of electric energy in the t year is defined. As shown in Formula (2):

$$E_{sub}{}^{(t)} = E_k^{(t)} - \sum_{i=1}^{N} E_i^{(t)} \frac{E_k^{(t-1)}}{\sum_{i=1}^{N} E_i^{(t-1)}} \tag{2}$$

In the formula, $E_{sub}{}^{(t)}$ is the electrical power substitution potential in the t year, and $E_k^{(t-1)}$ is the electricity usage in the t-1 year; $\sum_{i=1}^{N} E_i^{(t-1)}$ is the total terminal energy consumption in the first year of t-1.

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**Economic Development Factors**

Energy consumption is closely related to economic development, and the regional economic situation can greatly affect the production and consumption of terminal electric energy[7]. By observing the historical data of China's GDP and social electricity consumption, we can know that the changing trend of electricity consumption and GDP is basically synchronous. At the beginning of the 20th century, China's gross domestic product (GDP) was in a high-speed rising stage, and the consumption of electric energy also showed a rapid growth trend in the same period. During the financial crisis in 2008, China's GDP growth rate dropped significantly, and the electricity consumption of end users also slowed down; After 2010, China vigorously promoted the economic transformation plan, and the economic growth rate rose steadily, followed by the accelerated growth of social electricity consumption. Therefore, it can be known that regional economic development has a positive correlation with social electricity consumption. With the acceleration of economic growth, social electricity consumption will also show a high-speed growth trend, and the demand for social electricity consumption will increase, thus promoting the process of electricity substitution.

### Influencing Factors of Urbanization

The vigorous construction of urbanization has promoted the consumption level of residents and diversified energy demand. The rapid development of urbanization has changed the energy consumption market of end residents[8]. The energy consumption of residents at the terminal is mainly concentrated in two parts: one is the direct energy consumption necessary for daily life, such as household appliances, automobiles and natural gas; The second is the energy indirectly consumed by residents in the process of daily life. From this perspective, the swift advancement of urbanization is poised to enhance the level of electrification among residents, thereby influencing both the structure of terminal energy consumption and the transition toward electric energy substitution.

### Policy Support Impact

Actively promoting the strategy of substituting electric energy not only addresses air pollution control, but also enhances the quality of people's living environment. However, in the initial stages of electric energy substitution, additional costs are often required. Without appropriate policy support and guidance, unnecessary expenses and energy waste can easily occur. Therefore, the government should develop specific implementation plans for transitioning to electric energy in accordance with China's current national conditions. This includes directing the promotion of electric energy replacement in the correct direction and tailoring policies to suit the unique conditions of different regions. Providing ample financial subsidies and support policies for the advancement of electrical power replacement will enhance the competitiveness of end-use energy market[9]. To demonstrate the influence of policies on the transition to electric energy, this article utilizes fixed asset investments in new power facilities as an indicator of the impact of policy support on the advancement of electric energy replacement.

### The Impact of The Dual Carbon Policy

Achieving the "double carbon" goal entails a challenging timeline and significant responsibilities. The consumption of electric energy is notably lower compared to other energy sources. It is an important link to gradually replace fossil energy sources in energy terminal consumption to help achieve "double carbon" at an early date[10]. On September 22nd, 2020, the double carbon target was formally put forward. Therefore, enterprises should not only consider the efficiency of electric energy substitution, but also follow the concept of low carbon and environmental protection, increase the investment in clean electric energy substitution, reduce their own carbon emissions, and strive to achieve the synergistic effect of electric energy substitution and double carbon target. Therefore, under the background of double carbon policy, China will also accelerate the process of electric energy substitution.

## RELATIONSHIP MODEL BETWEEN ENERGY CONSUMPTION AND GDP, POWER INVESTMENT, URBANIZATION AND CARBON EMISSIONS

In order to determine the constraint boundary of alternative growth of electric energy, it is necessary to scientifically analyze the main factors that affect China's GDP, electric power investment, urbanization and carbon emissions, discuss and analyze the relevant statistical data of China's energy consumption in 2005-2019, use spss software for multiple regression analysis, establish a multiple linear regression model of China's energy consumption input and related input factors, and make regression analysis on the model. Finally, the model is tested to verify its feasibility.

### Data Source and Model Establishment

From 2005 to 2019, the "China Statistical Yearbook" was released from 2005 to 2019, the consumption volume of 9 types of energy such as coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity. $\boldsymbol{Y}^{(t)}$: GDP (100 million yuan), $\boldsymbol{I}^{(t)}$ : Electricity investment (100 million yuan), $\boldsymbol{O}^{(t)}$ : Urbanization, $\boldsymbol{C}^{(t)}$ : Carbon emissions (Ton), $\boldsymbol{E}_1^{(t)}, \boldsymbol{E}_2^{(t)}, \boldsymbol{E}_3^{(t)}, \boldsymbol{E}_4^{(t)}, \boldsymbol{E}_5^{(t)}, \boldsymbol{E}_6^{(t)}, \boldsymbol{E}_7^{(t)}, \boldsymbol{E}_8^{(t)}, \boldsymbol{E}_9^{(t)}$: coal (10,000 tons), coke (10,000 tons), crude oil (10,000 tons), gasoline (10,000 tons), coal oil (10,000 tons), diesel (10,000 tons), fuel oil (10,000 tons), natural gas (100 million cubic meters), and electricity

(100 kilowatt hours). $\boldsymbol{Y^{(t)}}, \boldsymbol{I^{(t)}}, \boldsymbol{O^{(t)}}, \boldsymbol{C^{(t)}}$ is the explanatory variable, $\boldsymbol{E_1^{(t)}}, \boldsymbol{E_2^{(t)}}, \boldsymbol{E_3^{(t)}}, \boldsymbol{E_4^{(t)}}, \boldsymbol{E_5^{(t)}}, \boldsymbol{E_6^{(t)}}, \boldsymbol{E_7^{(t)}}, \boldsymbol{E_8^{(t)}}, \boldsymbol{E_9^{(t)}}$ are interpreted variables, see Table 1 for data.

Table 1. Energy consumption and other data from 2005 to 2019

| Year | $E_1^{(t)}$ (10000 tons) | $E_2^{(t)}$ (10000 tons) | $E_3^{(t)}$ (10000 tons) | $E_4^{(t)}$ (10000 tons) | $E_5^{(t)}$ (10000 tons) | $E_6^{(t)}$ (10000 tons) | $E_7^{(t)}$ (10000 tons) | $E_8^{(t)}$ (Billion cubic meters) | $E_9^{(t)}$ (Billion kilowatt hours) | $Y^{(t)}$ (Hundred million yuan) | $I^{(t)}$ (Hundred million yuan) | $O^{(t)}$ | $C^{(t)}$ (ton) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 243375 | 25106 | 30088.94 | 4854 | 1076 | 10974 | 4244 | 466 | 24940 | 185998 | 6503 | 0.429 | 5407400000 |
| 2006 | 255065.4 | 27892 | 32245.2 | 5242 | 1124 | 11835 | 4368 | 561 | 28587 | 219028 | 7274 | 0.443 | 5961800000 |
| 2007 | 272745.8 | 29168 | 34031.6 | 5519 | 1243 | 12496 | 4157 | 705 | 32711. | 270704 | 7907 | 0.458 | 6473300000 |
| 2008 | 281095.9 | 29900 | 35498.24 | 6145 | 1294 | 13532 | 3237 | 812 | 34541. | 321229 | 9024 | 0.469 | 6669000000 |
| 2009 | 325003 | 36350 | 38128.59 | 6172 | 1450 | 13551 | 2828 | 895 | 37032. | 347934 | 11139 | 0.483 | 7130900000 |
| 2010 | 349008 | 38703 | 42874.55 | 6956 | 1765 | 14699 | 3758 | 1080 | 41934. | 410354 | 11915 | 0.499 | 7830600000 |
| 2011 | 388961 | 42063 | 43965.84 | 7595 | 1816 | 15635 | 3662 | 1341 | 47000 | 483392 | 11604 | 0.518 | 8569000000 |
| 2012 | 411727 | 44805 | 46678.92 | 8165 | 1956 | 16966 | 3683 | 1497 | 49762 | 537329 | 12948 | 0.531 | 8823400000 |
| 2013 | 424426 | 45852 | 48652.15 | 9366 | 2164 | 17150 | 3953 | 1705 | 54203. | 588141 | 14726 | 0.544 | 9232700000 |
| 2014 | 413633 | 46885 | 51596.95 | 9776 | 2335 | 17165 | 4355 | 1870 | 57829. | 644380 | 17433 | 0.557 | 9224100000 |
| 2015 | 399834 | 44059 | 54788 | 11368 | 2663 | 17360 | 4662 | 1931 | 58019. | 685571 | 20260 | 0.573 | 9135200000 |
| 2016 | 388820 | 45462 | 57125 | 11866 | 2970 | 16839 | 4631 | 2078 | 61205 | 742694 | 22638 | 0.588 | 9127900000 |
| 2017 | 391403 | 43743 | 59402 | 12296 | 3326 | 16916 | 4887 | 2393 | 65913 | 830945 | 22055 | 0.602 | 9334900000 |
| 2018 | 397452 | 43717 | 63004 | 13055 | 3653 | 16409 | 4536 | 2817 | 71508 | 915243 | 19342 | 0.615 | 9712800000 |
| 2019 | 401915 | 46426 | 67268 | 13628 | 3950 | 14198 | 4690 | 3060 | 74866 | 983751 | 12922 | 0.627 | 9876500000 |

**OLS Estimation Results**

The results of multiple regression model analysis are performed on energy consumption, GDP, power investment, urbanization and carbon emissions using SPSS, respectively, and the findings are depicted in Table 2-5 below:

Table 2. OLS parameter values of GDP and energy consumption

| model | | coefficient | standard deviation | Pearson correlation coefficient | |
|---|---|---|---|---|---|
| (Constant) | | 96319.272 | 73659 | | |
| Coal (10000 tons) | | -0.295 | 0.477 | 0.815 | |
| Coke (10000 tons) | | 1.691 | 4.337 | 0.849 | |
| Crude oil (10000 tons) | | 0.760 | 5.236 | 0.997 | |
| Gasoline (10000 tons) | | 7.059 | 9.696 | 0.991 | |
| Kerosene (10000 tons) | | 64.223 | 48.240 | 0.989 | |
| Diesel fuel (10000 tons) | | 7.596 | 7.119 | 0.712 | |
| Fuel oil (10000 tons) | | -10.474 | 6.210 | 0.584 | |
| Natural gas (billion cubic meters) | | 134.038 | 87.465 | 0.997 | |
| Electricity (billion kilowatt hours) | | 3.290 | 5.002 | 0.996 | |
| R-value | 0.9998 | R-squared | 0.9996 | Adjusted R-squared | 0.99 |
| Durbin-Watson | 2.843152 | Significance analysis | 0.000000056139 | | |

Table 3. OLS parameter values of power investment and energy consumption

| model | | coefficient | standard deviation | Pearson correlation coefficient | |
|---|---|---|---|---|---|
| (Constant) | | 6575.171 | 6365.832 | | |
| Coal (10000 tons) | | -0.093 | 0.041 | 0.795 | |
| Coke (10000 tons) | | 0.924 | 0.375 | 0.842 | |
| Crude oil (10000 tons) | | -0.538 | 0.452 | 0.937 | |
| Gasoline (10000 tons) | | 2.538 | 0.838 | 0.953 | |
| Kerosene (10000 tons) | | 8.208 | 4.169 | 0.911 | |
| Diesel fuel (10000 tons) | | 0.840 | 0.615 | 0.795 | |
| Fuel oil (10000 tons) | | -0.222 | 0.537 | 0.608 | |
| Natural gas (billion cubic meters) | | 10.583 | 7.559 | 0.900 | |
| Electricity (billion kilowatt hours) | | 0.148 | 0.432 | 0.927 | |
| R-value | 0.99693 | R-squared | 0.99386 | Adjusted R-squared | 0.98 |
| Durbin-Watson | 2.734780 | Significance analysis | 0.000054 | | |

Table 4. OLS parameter values of urbanization and energy consumption

| model | | coefficient | standard deviation | | Pearson correlation coefficient |
|---|---|---|---|---|---|
| (Constant) | | 0.311 | 0.020860 | | |
| Coal (10000 tons) | | 0.00000003 | 0.00000013 | | 0.853 |
| Coke (10000 tons) | | 0.00000064 | 0.000001 | | 0.885 |
| Crude oil (10000 tons) | | 0.00000016 | 0.000001 | | 0.996 |
| Gasoline (10000 tons) | | 0.00000646 | 0.000003 | | 0.989 |
| Kerosene (10000 tons) | | 0.00002524 | 0.000014 | | 0.976 |
| Diesel fuel (10000 tons) | | 0.00000143 | 0.000002 | | 0.770 |
| Fuel oil (10000 tons) | | 0.00000414 | 0.000002 | | 0.564 |
| Natural gas (billion cubic meters) | | 0.00003429 | 0.000025 | | 0.986 |
| Electricity (billion kilowatt hours) | | 0.000003011 | 0.000001 | | 0.997 |
| R-value | 0.99975 | R-squared | 0.9995 | Adjusted R-squared | 0.99 |
| Durbin-Watson | 2.61558 | Significance analysis | 0.000000099623 | | |

Table 5. OLS parameter values of carbon emission and energy consumption

| model | | coefficient | standard deviation | Pearson correlation coefficient | |
|---|---|---|---|---|---|
| (Constant) | | 32370840.2 | 632800619.5 | | |
| Coal (10000 tons) | | 17519.936 | 4099.017 | 0.966 | |
| Coke (10000 tons) | | -95344.642 | 37257.973 | 0.974 | |
| Crude oil (10000 tons) | | 74522.910 | 44978.820 | 0.937 | |
| Gasoline (10000 tons) | | -39521.335 | 83297.689 | 0.909 | |
| Kerosene (10000 tons) | | -701893.045 | 414426.431 | 0.875 | |
| Diesel fuel (10000 tons) | | -81560.015 | 61159.678 | 0.884 | |
| Fuel oil (10000 tons) | | -28325.161 | 53352.234 | 0.413 | |
| Natural gas (billion cubic meters) | | 1908443.81 | 751403.664 | 0.918 | |
| Electricity (billion kilowatt hours) | | 169927.67 | 42974.914 | 0.957 | |
| R-value | 0.999568 | R-squared | 0.999136 | Adjusted R-squared | 0.99 |
| Durbin-Watson | 2.551004 | Significance analysis | 0.0000004072 | | |

Based on the above table data, the regression equation model of energy consumption with GDP, electricity investment, urbanization, and carbon emissions can be written:

1) The Relationship Model between GDP and Electricity Investment

$$\mathrm{Y}^{(\mathrm{t})} = -0.295E_1^{(t)} + 1.691E_2^{(t)} + 0.76E_3^{(t)} + 7.059E_4^{(t)} + 64.223E_5^{(t)} + 7.596E_6^{(t)} - 10.474E_7^{(t)} + 134.038E_8^{(t)} + 3.29E_9^{(t)} - 96319.272 \quad (3)$$

2) The Relationship Model between Energy Consumption and Electricity Investment

$$I^{(t)} = -0.093E_1^{(t)} + 0.924E_2^{(t)} - 0.538E_3^{(t)} + 2.538E_4^{(t)} + 8.208E_5^{(t)} + 0.84E_6^{(t)} - 0.222E_7^{(t)} + 10.583E_8^{(t)} + 0.148E_9^{(t)} + 6575.17\ldots \quad (4)$$

3) The Relationship Model between Energy Consumption and Urbanization

$$O^{(t)} = -0.00000003E_1^{(t)} + 0.00000064E_2^{(t)} - 0.00000016E_3^{(t)} + 0.00000646E_4^{(t)} + 0.00002524E_5^{(t)} + 0.00000143E_6^{(t)} - 0.00000414E_7^{(t)} - 0.00003429E_8^{(t)} + 0.00000302E_9^{(t)} + 0.311 \quad (5)$$

4) A model for the relationship between energy consumption and carbon emissions

$$C^{(t)} = 17519.93598E_1^{(t)} - 95344.6419987E_2^{(t)} + 74522.91046757E_3^{(t)} - 39521.33522323E_4^{(t)} - 701893.0446752E_5^{(t)} - 81560.01467955E_6^{(t)} - 28325.16132E_7^{(t)} - 1908443.80795583E_8^{(t)} + 169927.67688952E_9^{(t)} - 32370840.1563535 \quad (6)$$

To mitigate the impact of increasing variables on the R-squared, this article also uses the adjusted R-squared to evaluate the degree of fit. By observing that the R-squared and adjusted R-squared of the four models above are all greater than 0.9, it can be concluded that the model has a high degree of fit.

Based on the Pearson correlation coefficient, it is evident that there is a robust positive correlation between the consumption of crude oil, gasoline, kerosene, natural gas, and electricity and GDP growth. Furthermore, a strong positive correlation exists between gasoline, kerosene, natural gas, and electricity consumption and investment in electricity. Moreover, the consumption of crude oil, gasoline, kerosene, natural gas, and electricity shows a noteworthy correlation with increased levels of urbanization. Additionally, there is a significant positive correlation between coal consumption, crude oil consumption, electricity consumption, and carbon emissions, all of which are supported by significant statistical tests.

**A PREDICTION MODEL FOR ELECTRICITY SUBSTITUTION POTENTIAL BASED ON GA OPTIMIZATION**

**Optimization Model for Electricity Substitution Potential**

This article takes the annual consumption of various types of energy in China as a decision variable and establishes a multi-objective programming model for the potential of electricity substitution. The objective functions are to maximize the potential for electricity substitution and minimize the total cost of electricity substitution. Set multiple constraints on GDP, urbanization, and policy oriented electricity investment, as well as annual carbon emission limits, and use electricity substitution related data from year t-1 to solve the electricity substitution potential related data from year t. Therefore, the following multi-objective constraint model is constructed.

***Objective function***

1) The objective function 1 is to maximize the cumulative annual increment of electricity substitution potential, as shown in equation (7):

$$\max \Delta E_{sub}{}^{(t)} \tag{7}$$

Because the construction process of electricity substitution is constantly accumulating, the current construction of electricity substitution projects will have an impact on the promotion of future electricity substitution strategies. Therefore, it is necessary to accumulate and add up the potential of electricity substitution each year from the benchmark year to represent the development trend of electricity substitution projects starting from the benchmark year[11].demonstrating that the construction of electricity substitution projects is a trend of continuous development and accumulation. Formula (8):

$$\Delta E_{sub}{}^{(t)} = \sum_{t=1}^{M} E_{sub}{}^{(t)} \tag{8}$$

2) Objective function 2 considers two factors: construction cost and maintenance cost of electricity substitution, and constructs the objective function with the minimum annual total cost as the objective, as shown in equation (9):

$$\min Q_1 + Q_2 \tag{9}$$

Q1 represents the construction cost of electricity substitution in the current year, and Q2 represents the annual maintenance cost of electricity substitution. The specific expression is as follows:

$$Q_1 = E_{sub}{}^{(t)} S_1{}^{(t_0)} (1 - r^{(t)})^{\log_2 \frac{\Delta E_{sub}{}^{(t)}}{\Delta E_{sub}{}^{(t_0)}}} \tag{10}$$

$$Q_2 = S_2^{(t_0)} (F/P, i, n) \Delta E_{sub}{}^{(t-1)} \tag{11}$$

In equation (10), $E_{sub}{}^{(t)}$ represents the newly added electricity substitution construction in year t, $S_1^{(t_0)}$ is the unit construction cost of electricity substitution in the base year, and $r^{(t)}$ is the proportion of electricity consumption in terminal energy. Because in the process of electricity substitution development, due to the increase in market development and development difficulty, the unit construction investment cost will decrease with the increase in the scale of electricity substitution construction. This trend is often determined by the growth rate of electricity substitution project development and the proportion of electricity consumption in terminal energy. Therefore, the s ^ ((t) in equation (10) is obtained $s^{(t)} = s^{(t_0)} (1 - r^{(t)})^{\log_2 \frac{\Delta E_{sub}{}^{(t)}}{\Delta E_{sub}{}^{(t_0)}}}$. In equation (11), $\Delta E_{sub}{}^{(t-1)}$ represents the cumulative completed electricity substitution construction before year t, and $S_2^{(t_0)}$ represents the unit cost of maintaining the electricity substitution project in year t 0. Considering the time value of currency, $(F/P, i, n)$ is introduced to represent the annual unit maintenance cost using future values.

1) Carbon dioxide emission restrictions

$$C_{min}{}^{(t)} \leq C^{(t)} \leq C^{(t)}{}_{max} \tag{12}$$

In the formula, $C^{(t)}$ is the multiple regression equation between carbon dioxide emissions and energy consumption calculated based on 3.2, where $C_{min}{}^{(t)}$ and $C^{(t)}{}_{max}$ are the maximum and minimum emission limits for the t-th year.

2) GDP growth constraints

$$Y^{(t)}{}_{min} \leq Y^{(t)} \leq Y^{(t)}{}_{max} \tag{13}$$

In the formula, $Y^{(t)}$ is the multiple regression equation between GDP and energy consumption calculated based on 3.2. $Y^{(t)}{}_{min}$, $Y^{(t)}{}_{max}$ are the maximum and minimum limits on the total GDP at year t.

3) Urbanization growth constraints

$$O^{(t)}{}_{min} \leq O^{(t)} \leq O^{(t)}{}_{max} \tag{14}$$

In the formula, $Y^{(t)}$ is the multiple regression equation between urbanization and energy consumption calculated according to 3.2, where $O^{(t)}{}_{max}$ and $O^{(t)}{}_{min}$ are the maximum and minimum constraints on urbanization in the t-th year.

4) Power investment constraints

$$I^{(t)}{}_{min} \leq I^{(t)} \leq I^{(t)}{}_{max} \tag{15}$$

In the formula, $I^{(t)}$ is the multiple regression equation between the electricity investment amount and energy consumption calculated according to 3.2. $I^{(t)}{}_{min}$, $I^{(t)}{}_{max}$ is the maximum and minimum limit of the electricity investment amount in the t-th year.

5) Power capacity constraints

$$E_k^{(t-1)} \leq E_k^{(t)} \leq \sum_{l=1}^{k} \mu_l P_l{}^t \tag{16}$$

$E_k^{(t)}$ is the electricity consumption in year t, $E_k^{(t-1)}$ is the electricity consumption in year t-1, and $P_l{}^t$ is the installed capacity of various types of electricity in China in year t, $\mu_l$ is the average available hours of the power supply.

6) Clean energy utilization efficiency

$$\partial_1{}^t E_k^{(t)} + \partial_2{}^t E_k^{(t)} + \partial_3{}^t E_k^{(t)} + \partial_4{}^t E_k^{(t)} \geq E_{ce}^{(t)} \tag{17}$$

The development trend of future electricity substitution will move towards cleaner and more efficient electricity substitution. Therefore, it is necessary to make certain plans for the consumption of non fossil electricity energy in the future. In equation (17), $\partial_1{}^t, \partial_2{}^t, \partial_3{}^t, \partial_4{}^t$ are the proportion coefficients of water power, nuclear power, wind power, and solar power to the total installed capacity in year t, respectively. $E_{ce}^{(t)}$ is the target value set for non fossil energy consumption in year t.

7) Limitations on energy supply capacity

$$E_{imin}^{(t)} \leq E_i^{(t)} \leq E_{imax}^{(t)} \tag{18}$$

$$E_i^{(t)} \geq 0 \tag{19}$$

Equation (18) represents the relationship between annual consumption of various types of energy and energy supply and production.

**Particle Swarm Optimization Algorithm**

Traditional single objective solving methods are difficult to solve multi-objective problems. Currently, solving multi-objective problems is a hot topic, and scholars such as Goldberg have proposed a more comprehensive multi-objective solving method combining Pareto theory and evolutionary algorithms, which has been widely cited. This article combines particle swarm optimization algorithm with Pareto theory to solve the potential prediction model for electricity substitution. The particle swarm optimization system has fewer parameter settings, a simple structure, and is easy to implement in engineering optimization. When in a local non inferior optimal domain, it has the characteristic of flying over and can cross the local optimal domain to solve the global optimal solution.

The principle of PSO algorithm is as follows: assuming the total number of particles is m, the position of the i-th particle in n-dimensional space is represented as $x_i = (x_{i_1}, x_{i_2}, x_{i_3} \dots \dots, x_{i_m})$, and the flight speed is represented as $v_i = (v_{i_1}, v_{i_2}, v_{i_3} \dots \dots, v_{i_m})$. According to the different objective functions, each particle will set a corresponding fitness value, and the size of the fitness value will continuously change according to the changes in its current position $x_i$, until the best position is found in the entire population to make its fitness in the optimal state. The position of the PSO algorithm's population particles is updated and iterated using the following formula:

$$v_{id}^{(k+1)} = w * v_{id}^{(k)} + c_1 * r_1 * \left(p_{id} - x_{id}^{(k)}\right) + c_2 * r_2 * \left(p_{gd} - x_{id}^{(k)}\right) \tag{20}$$

$$x_{id}^{(k+1)} = x_{id}^{(k)} + v_{id}^{(k+1)} \tag{21}$$

In equation (20), $v_{id}^{(k)}$ is the flight speed of the i-th particle in the d-space dimension during the k-th iteration; $x_{id}^{(k)}$ is the position component of the i-th particle in the d-space dimension during the k-th iteration; $p_{gd}$ is the best position of group g in d-dimensional space; $p_{id}$ is the best position of particle i in the d-dimensional spatial component; $r_1$ and $r_2$ are random numbers within 0-1; $c_1$ and $c_2$ are weight factors[12].

The optimization algorithm process of multi-objective particle swarm optimization is shown in Figure 2. Compared with the PSO, multi-objective programming introduces the Pareto optimal solution set after particle optimization update. The most valuable particles obtained from each particle update are placed in the Pareto solution set. After the algorithm iteration is completed, the Pareto optimal front is found in the surface formed by the target vector in the target space corresponding to the Pareto optimal solution[13], which is the optimal solution set of the multi-objective function.

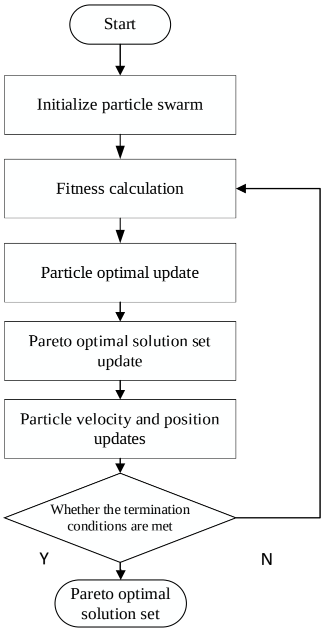


Figure 2. PSO Algorithm Process

## ANALYSIS OF POTENTIAL EXAMPLES OF ELECTRICITY SUBSTITUTION IN MULTIPLE SCENARIOS

### Scenario Construction

This article constructs three different scenarios of electricity substitution development by setting GDP, urbanization rate, carbon emissions, and annual growth rate of electricity investment. Scenario 1 is set as the baseline scenario under the current natural development of electricity substitution in China, without introducing the impact of strengthening the economic side and government measurement on the process of electricity substitution; Scenario 2 introduces the impact of government policies that strongly support electricity substitution and strengthen low-carbon emission reduction on the process of electricity substitution; Scenario 3: Construct the impact of China's sustained high-speed economic development and accelerated urbanization rate on the process of electricity substitution. The concrete scenario is depicted in Table 6.

Table 6. Scenario assumptions

| Scenario setting | Specific situation |
|---|---|
| Scenario 1 | Maintain the current energy substitution process; |
| Scenario 2 | The introduction of the government's strong support for electricity substitution policies and low-carbon policies; |
| Scenario 3 | The scenario of China's sustained rapid economic development and accelerated urbanization rate; |

### Parameter Settings

#### *GDP*

The changes in regional economy will have a certain degree of impact on terminal energy consumption. Here, the WEM model is used as the benchmark model for predicting the growth of China's GDP economy. It is estimated that China's GDP growth rate from 2020 to 2030 will be 5.2%. Therefore, under the benchmark scenario, the range of China's GDP benchmark growth rate from 2020 to 2030 is 0-5.2%.

***Urbanization***

In 2019, "Urban Blue Book: China Urban Development Report No.12" highlighted China's urbanization rate, which stood at 59.58% in 2018. Projections suggest that by 2030, China's urbanization rate will likely reach approximately 70%[14]. With China currently in the middle and later stages of urbanization, there remains substantial development potential before 2030. Hence, under the benchmark scenario, the projected range for China's average annual urbanization growth rate from 2020 to 2030 is set conservatively at 0-1%.

***Electricity investment amount***

In 2021, Southern Power Grid issued the "14th Five Year Plan" for the development of the power grid, proposing that Southern Power Grid Company will vigorously promote the speed of modern power construction and increase investment in power construction during the "14th Five Year Plan" period. Compared with the planned power investment amount during the "13th Five Year Plan" period, it has increased by 33%. This article sets a benchmark growth rate based on this goal and sets an annual average growth rate range of 0-6.6% for power investment amount between 2020 and 2030.

***Carbon emissions***

Based on the expected GDP growth rate under China's benchmark scenario, the total GDP of China by 2030 can be calculated to determine China's carbon emissions by that year. It is projected that China's total carbon emissions will reach 11.61 billion tons by 2030, marking an 18.2% increase compared to 2019, with an average annual growth rate of 1.6%. Consequently, the benchmark annual growth rate range for carbon emissions from 2020 to 2030 is established at 1-1.6%.

Based on this, three scenarios are set up in this article to analyze the potential for future electricity substitution in China, as illustrated in Table 7.

Table 7. Basic parameter settings for scenario analysis

| | Annual GDP growth rate | Annual growth rate of urbanization | Annual growth rate of electricity investment | Annual growth rate of carbon emissions |
|---|---|---|---|---|
| Scenario 1 | 0%-5.2% | 0%-1% | 0%-6.6% | 1%-1.6% |
| Scenario 2 | 0%-5.2% | 0%-1% | 6.6%-10% | 0%-1% |
| Scenario 3 | 5.2%-8% | 1%-1.5% | 0%-6.6% | 1%-1.6% |

**Experimental Results and Analysis**

Based on the above three scenarios, use the model and method constructed in Section 4 to predict and analyze the electricity substitution and energy consumption from 2020 to 2030. The potential for terminal energy substitution will show varying degrees of growth trends in different scenarios between 2020 and 2030. As shown in Figure 3, the growth trend of electricity substitution potential in Scenario 1 is much smaller than that in Scenarios 2 and 3, and the growth rate will slow down after 2025. This is because Scenario 1 does not introduce relevant factors such as policy support and economic growth to promote the development process of electricity substitution in natural development. With the saturation of the terminal market, the development process of electricity substitution will inevitably be in a slowing state. In Scenario 3, with the acceleration of economic development and urbanization, the demand for electrified products among residents will increase, leading to a concentration of electricity substitution in the residential electrification substitution field in the early stage of Scenario 3, which will indirectly accelerate the process of electricity substitution. However, between 2025 and 2030, the growth rate of electricity substitution in Scenario 3 will gradually slow down. This is because under the natural development of high-speed economy and urbanization, the electricity substitution infrastructure field for residents is approaching saturation. Without policy guidance, the terminal market for electricity substitution is saturated and the development potential of projects is insufficient, and the development process of electricity substitution will gradually slow down.

Compared with Scenario 1, the development process of electricity substitution in Scenario 2 and Scenario 3 shows that the growth of its electricity substitution potential is significantly greater. Moreover, the introduction of policy support and dual carbon policies in Scenario 2 has a more significant effect on the promotion of electricity substitution work, far exceeding the increment of electricity substitution potential under the background of rapid GDP and urbanization growth in Scenario 3. It can be concluded that under the current global low-carbon policy goals, strong support for electricity substitution construction will be more effective in accelerating the development of the electricity substitution process. The introduction of the dual carbon policy and the introduction of policies supporting electricity substitution first clarify the development goals of China's future electricity substitution, guiding enterprises to innovate cleaner development paths for electricity substitution and reduce emissions of pollutants such as carbon dioxide. Secondly, it is possible to expand research in the relevant fields of electricity substitution, increase policy support and investment in electricity substitution projects to improve technological level, break through development bottlenecks, and accelerate the enhancement of the potential for electricity substitution.

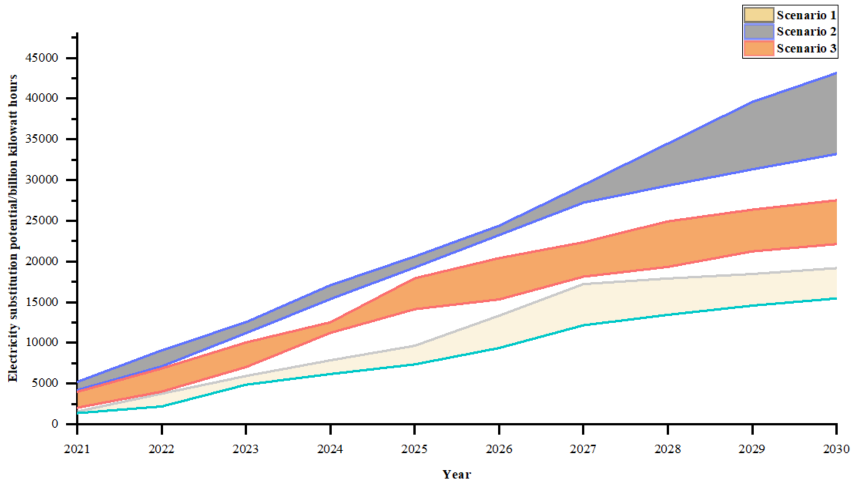


Figure 3. Prediction results of electricity substitution potential under multiple scenarios from 2020 to 2030

At the same time, the annual consumption of various types of energy corresponding to the above three scenarios is shown in Figure 4. From Figure 4, it can be seen that under the baseline scenario, the annual consumption of coal, coke, gasoline, combustion oil, and natural gas will show a downward trend over time, while the annual consumption of crude oil, kerosene, diesel, and electricity will show an upward trend. In scenarios 2 and 3, the annual consumption of coal, crude oil, kerosene, diesel, combustion oil, and natural gas is lower than the baseline scenario, while the annual consumption of electricity is much higher than the baseline scenario. The proportion of electricity in terminal energy consumption increases, indicating that both scenarios have played a promoting role in the current development of electricity substitution. Compared with natural gas, the annual consumption of coal in Scenario 3 is far less than that in Scenario 2. This is because natural gas and coal currently account for a large proportion in the lives of Chinese residents, which also shows that under the condition of rapid economic and urbanization development, the demand for coal and gas electrification in households will increase accordingly, leading to the acceleration of the development process of electric energy substitution. Next are crude oil and electricity. Under the conditions of Scenario 2, the annual consumption of crude oil is much lower than Scenario 1 and Scenario 3, while the annual consumption of electricity is much higher than Scenario 1 and Scenario 3. This indicates that under the support of policies related to electricity substitution and the introduction of dual carbon policies, electricity substitution work mainly focuses on the field of electricity replacing oil. "Electricity replacing oil" mainly occurs in agriculture, transportation and other fields. At the same time, electricity replacing oil technology (such as electric vehicles and other power replacement products) also conforms to the development of dual carbon policies, which can effectively reduce carbon dioxide emissions and reflect the mutual synergy between dual carbon and electricity substitution support policies.

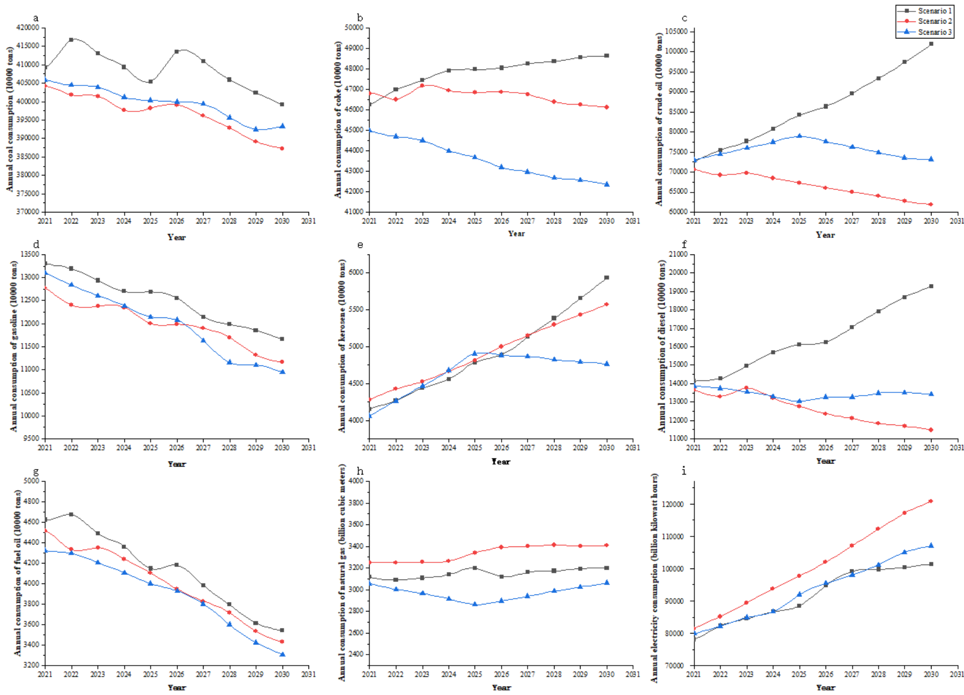


Figure 4. Results of energy consumption in China under multiple scenarios from 2020 to 2030

## CONCLUSION AND OUTLOOK

By comparing and analyzing the evolution of electricity substitution under the three different scenarios mentioned above, it can be concluded that the development process of electricity substitution is influenced by economic growth, urbanization rate, government policy support, and the degree of implementation of the dual carbon policy. Among them, the government's support for electricity substitution policy and the promotion of the dual carbon goal together are the most helpful for the progress of electricity substitution projects. Therefore, the following suggestions are proposed for the development of future electricity substitution projects in China:

(1) For regions with high urbanization rates in China, the implementation of household electrification substitution projects is of utmost importance. Relevant policy guidance should be introduced based on the local implementation of electricity substitution to prevent the slowdown of substitution process caused by the saturation of market demand for end residents.

(2) The technological research and development of electric energy substitution related projects should increase investment to improve the benefits that unit electric energy substitution projects can bring and break through the development barriers of electric energy substitution.

(3) Introduce relevant support policies for electric energy substitution, such as the implementation of electric vehicle project construction. The government needs to increase the popularization of electric vehicles and subsidy policies to coordinate the market demand of enterprises and residents to increase the market share of electric vehicles in the automotive market.

(4) The introduction of the dual carbon target furthermore enhances the importance of the electricity substitution strategy and provides a clear clean and green development policy for China's future electricity substitution. In the future process of electricity substitution, it is necessary to promote the use of green electricity to replace primary energy sources such as coal, oil, and gas, making energy consumption more green and environmentally friendly, and helping China achieve its dual carbon goals as soon as possible.

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