Model of Clean Energy Substitution Based on Energy Saving and Emission Reduction Targets

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Abstract. Under the situation of increasing air pollution and rapid development of clean energy, actively promoting energy substitution plays an important role in implementing energy strategy deployment and safeguarding energy security in China. This paper puts forward an energy substitution path considering the interaction between different energy sources, and establishes an energy alternative model based on energy saving and emission reduction targets. The proposed model takes the total amount of carbon emissions as the optimization target, and calculates and analyses the energy substitution path and the substitution space by considering the terminal energy consumption characteristics and the restriction of clean energy supply. Finally the paper makes instance calculations on the energy substitution space at the end of 13th five-year plan and the 14th five-year plan. The calculation result verifies the feasibility and superiority of the proposed model and solution method.

1. Introduction

China’s energy resources are characterized by abundant coal and water energy resources, relatively scarce oil and natural gas resources, and huge space for new energy development. In recent years, China’s high proportion of coal consumption has brought serious air pollution problems. Since 2006, China’s SO2, CO2 and NOx emissions have also ranked top in the world all the year round. Therefore, it is of great practical significance to optimize the structure of terminal energy consumption and reduce the emission of air pollutants to ensure China’s energy security, solve the problem of energy and environmental protection as well as improve the efficiency of energy utilization.

Energy substitution is an important means to optimize the energy structure and reduce the pressure of carbon emission. Among them, the spatial measurement of energy substitution potential, as an important basis for promoting energy substitution, has also become the focus of many scholars. On the premise of comprehensive consideration of China’s energy resources endowment, energy consumption structure characteristics and the severe environmental protection situation faced by China, this paper puts forward the energy alternative path in line with China’s actual situation and the energy alternative model based on energy saving and emission reduction goals. The energy substitution in this paper refers to the replacement of traditional fossil energy consumption such as coal and oil with clean energy consumption such as renewable energy, electricity and natural gas in the end energy consumption. The difference between the research and the traditional energy substitution space is: 1) considering China’s
energy endowment and the development trend of various energy supply and consumption; 2) taking the total annual carbon emission as the energy substitution control target; 3) calculating the energy alternative space from the perspective of the end energy consumption structure and consumption. The calculation method of the model is simpler and more practical than that of the current method.

2. Research on prediction method of terminal energy consumption

The prediction of the total consumption of terminal energy is the basis and the first premise of the research on the alternative model of clean energy. The total amount of terminal energy consumption can be seen as a comprehensive indicator, and its change can be decomposed into several main influencing factors by using appropriate algorithm. By analyzing and predicting these main influential factors, the predicted value of the total amount of terminal energy consumption can be calculated reversely.

In this paper, the terminal energy consumption is divided into two parts: the terminal energy consumption in the production field and the terminal energy consumption in the life of residents. The terminal energy consumption in the production field is predicted by the structural analysis method, which is divided into economic scale, industrial structure, energy intensity and other variables. The terminal energy consumption of residents is calculated by the strong correlation between the terminal energy consumption and the total energy consumption so as to predict the total energy consumption of the terminal.

First, set the calculation parameters:

\[ T: \text{total terminal energy consumption;} \]
\[ T^1: \text{terminal energy consumption in the field of production;} \]
\[ T^1_i, i=1,2,3: \text{total energy consumption of the first, second and third industrial terminals;} \]
\[ T^2: \text{terminal energy consumption in the life field;} \]
\[ \alpha: \text{the proportion of terminal energy consumption in the field of life in the total terminal energy consumption;} \]
\[ Y: \text{the level of economic development is reflected in gross national product;} \]
\[ I_i, i=1,2,3: \text{the proportion of added value of primary, secondary, tertiary and secondary industries in GNP;} \]
\[ C_i, i=1,2,3: \text{energy consumption intensity of primary, secondary, tertiary and secondary industries;} \]

According to the structural decomposition method, the terminal energy consumption in the production field is divided into three variables: economic development level \((Y)\), industrial structure \((I)\) change and energy intensity \((C)\). The decomposition logic is shown in formula (1).

\[
T^1 = \sum_{i=1,2,3} Y \times \frac{I_i}{Y} \times T^1_i = \sum_{i=1,2,3} Y \times I_i \times C_i
\]  \hspace{1cm} (1)

According to formula (1), after the planning that needs to be predicted is determined, the gross national product of the planning year, the proportion of the first, second and third industries in the gross national product and their respective energy consumption intensity are predicted respectively, and the terminal energy consumption in the production field of the planning year can be predicted.

As the proportion of China’s terminal energy consumption in the total terminal energy consumption is at a stable level all the year round, we can combine the historical data of the proportion, the situation of macroeconomic development, the characteristics of industrial structure change with the situation of residential electricity consumption to determine the proportion of terminal energy consumption in the field of life in the total terminal energy consumption \((\alpha)\) to make a prediction in the planning year, so as to calculate the total energy consumption terminal predicted value, as shown in formula (2).

\[
T = \frac{T^1}{(1-\alpha)}
\]  \hspace{1cm} (2)
3. Calculation model of energy alternative space

The energy substitution path proposed in this paper is to replace the consumption of coal and oil with the consumption of renewable energy power and natural gas in the end energy consumption, so as to achieve the total carbon emission of the end energy consumption at the target level. Therefore, there are two constraints and one controlling objective in the implementation of substitution which are the supply and consumption constraints of renewable energy power, natural gas and the total carbon emission controlling objectives.

The basic idea of the calculation of energy alternative space is to predict the consumption of all kinds of terminal energy in the planning year without the implementation of energy alternative, analyze the constraints of renewable energy power and natural gas supply, calculate the terminal energy alternative according to the carbon emission controlling objectives, and finally calculate the energy alternative space.

According to the unit carbon emission coefficient of renewable energy power, natural gas, coal and oil, in order to better achieve the carbon emission target, when implementing energy substitution, renewable energy power should take precedence over natural gas, and coal should take precedence over oil. Therefore, in the process of energy substitution calculation, within the supply capacity of renewable energy power and natural gas, it should be carried out in the order of renewable energy power replacing coal, renewable energy power replacing oil, natural gas replacing coal and natural gas replacing oil, until the carbon emissions in the total amount controlling target level or renewable energy electricity and natural gas to replace quantity respectively achieve their supply capacity limit.

3.1. Prediction of terminal energy consumption in planning year under basic level

After the calculation of the base year and the end energy consumption structure of the base year are selected, the method described in section I of this paper can be used to plan the total end energy consumption of the year for prediction, and finally calculate the end energy consumption of all kinds under the basic level of the planning year, as the consumption level of the planning year without considering energy substitution, hereinafter referred to as the basic level of the planning year.

3.2. Calculation of energy alternative space

First, set the calculation parameters:

$t_{i}, i = 1,2,3,4,5$ : It represents the consumption of renewable energy, fossil energy, natural gas, coal and oil respectively.

$A_{i}, i = 1,2,3,4,5$ : It refers to the replacement quantity of renewable energy power, fossil energy power generation, natural gas terminal, coal terminal and oil terminal respectively.

$t_{i}', i = 1,2,3,4,5$ : It respectively represents the end consumption of renewable energy power, fossil energy power, natural gas, oil and coal under the basic consumption level.

$X_{i}, i = 1,2,3,4,5$ : Carbon emission coefficients of fossil energy power, natural gas, coal and oil are respectively expressed.

$U_{i}, i = 1,2$ : Respectively represent the upper limit of renewable energy power and natural gas supply consumption.

$O$ is the carbon emission target.

$S$ is energy alternative space.

The control objective of the module is to achieve the target of total carbon emission of terminal energy in the planning year, namely:

$$\sum t_{i} \cdot X_{i} = O(i = 2,3,4,5)$$

The above variables shall meet the following relationships:

1) The final energy consumption of various types of energy in the planning year shall be the sum of the basic energy consumption of various types of final energy and the (substituted) energy consumption in the planning year.
\begin{equation}
    t_i = A_i + t_i^*, i = 1, 2, 3, 4, 5 \tag{4}
\end{equation}

2) In the planning year, the following relationships shall be met between the replacement amount of electric energy and natural gas energy, coal and oil in the end energy consumption:
\begin{equation}
    A_i + A_i^* + A_i^* + A_i^* + A_i^* = 0 \tag{5}
\end{equation}

The planned annual renewable energy consumption shall not be greater than the current year renewable energy power consumption ceiling $U_1$, that is
\begin{equation}
    t_i = A_i + t_i^* \leq U_1 \tag{6}
\end{equation}

The planned annual gas terminal consumption shall not be greater than $U_2$ of the current year's gas supply ceiling, i.e
\begin{equation}
    t_3 = A_3 + t_3^* \leq U_2 \tag{7}
\end{equation}

Take the carbon emission of the planning year as the controlling objective, that is, on the basis of meeting the above constraints, optimizing all kinds of end energy alternatives to make the total carbon emission of the end energy reach the standard, or the renewable energy power and natural gas alternatives reach the upper limit of their respective supply constraints. Under this condition, the sum of renewable energy electricity and natural gas substitution is the energy substitution space of the planning year.
\begin{equation}
    S = A_i + A_3 \tag{8}
\end{equation}

### 4. Example calculation

In this paper, 2015 is taken as the base year, 2020 and 2025 are chosen as the planning year, and the energy alternative space is calculated respectively.

#### 4.1. Prediction of main variables

Based on the analysis of the historical data of the proportion of terminal energy consumption in the total energy consumption in the life field and the comprehensive consideration of China’s macro-economic development situation, the trend of industrial structure change, the level of residential electricity consumption and other factors, it is predicted that the proportion of residential terminal energy consumption in the total energy consumption in 2020 and 2025 will be 12.6% and 12.7% respectively.

| Forecasting the year | Proportion of secondary industry/% | Proportion of tertiary industry/% | Economic growth/% | Energy intensity of ten thousand tons of standard coal/ten thousand yuan |
|----------------------|-----------------------------------|---------------------------------|-------------------|------------------------------------------------------------------------|
|                      |                                   |                                 |                   | Primary industry | Secondary industry | Tertiary industry |
| 2020                 | 41.5                              | 55.1                            | 6.8               | 0.11                 | 0.75                | 0.19               |
| 2025                 | 39.9                              | 55.7                            | 6.3               | 0.08                 | 0.69                | 0.17               |

By using the method described in section I of this chapter, the total energy consumption of terminals in 2020 and 2025 and the energy consumption of each terminal can be predicted, and the results are shown in Table 2.

### Table 2. Terminal energy consumption of 2020 and 2025

| Year | Total | Renewable power | Traditional electric power | Natural gas | Coal | Petroleum | Other |
|------|-------|-----------------|----------------------------|-------------|------|-----------|-------|
| 2020 | 364587| 18014           | 56879                      | 22734       | 155568| 88375     | 23017 |
| 2025 | 397082| 19619           | 59848                      | 24760       | 169434| 96252     | 25069 |
4.2. Constraints and controlling objectives

1) Constraints on power supply and consumption of renewable energy

According to “the Thirteenth Five-Year Plan of Energy Development”, “the Thirteenth Five-Year Plan for Hydropower Development”, “the Thirteenth Five-Year Plan for Wind Power Development”, “the Thirteenth Five-Year Plan for Solar Energy Development” and “the Thirteenth Five-Year Plan for Nuclear Industry Development” issued by the national energy administration, combined with China’s renewable energy development situation and relevant policies, the annual installed capacity of hydro power, photo voltaic, wind power, nuclear power and average utilization hours of equipment during the 13th five year plan and 14th five year plan are predicted, and the upper limit of renewable energy consumption in 2020 and 2025 is predicted by taking into account the factors such as plant power consumption and line loss. The results are shown in Table 3.

| renewable energy                   | annual consumption ceiling/(100 million kWh⁻¹) | standard coal/(10,000 t·a⁻¹) | annual consumption ceiling/(100 million kWh⁻¹) | standard coal/(10,000 t·a⁻¹) |
|-----------------------------------|-----------------------------------------------|------------------------------|-----------------------------------------------|------------------------------|
| hydroelectric combined to the grid | 12748                                         | 15668                        | 14278                                         | 17548                        |
| photovoltaic power generation     | 3473                                          | 4268                         | 4466                                          | 5487                         |
| total                             | 17468                                         | 21469                        | 22551                                         | 27714                        |

2) Natural gas supply and constraints

According to “China Natural Gas Development Report (2016)”, China’s natural gas supply in the future will constitute a resource guarantee system with multiple main bodies and equal emphasis on domestic and foreign resources. It is estimated that by 2020, China’s natural gas supply capacity will reach more than 360 billion m³, with an average annual growth rate of 5.15%. It is estimated that by 2020, the total mileage of China’s long-distance natural gas pipeline will reach 100000-120000 km, and the primary pipeline capacity will reach 370-400 billion m³/a.

In 2020 and 2025, China’s end energy and natural gas consumption should not exceed the natural gas supply capacity and primary pipeline transportation capacity of that year. Therefore, it is estimated that the upper limit of China’s end energy and natural gas consumption in 2020 and 2025 will be 360 billion m³ and 465 billion m³ respectively, equivalent to 478.8 million tons standard coal and 618.45 million tons standard coal.

3) Carbon emission control objectives

According to “the BP World Energy Statistical Yearbook”, the data of China’s total carbon emissions from 2005 to 2015 are sorted out, and the emission trend is shown in Figure 1.

![Diagram of energy national total carbon emissions trend from 2005 to 2015](image_url)
According to “the Thirteenth Five-Year Plan of Energy Development” published by the national development and reform commission and China’s environmental protection trend, China’s carbon emission target for 2020 is 9.927 billion tons. If calculated based on the 18% reduction of CO2 emission per unit of GDP in 2025 compared with that in 2020, China’s carbon emission target in 2025 can be calculated as 10.437 billion tons.

4) Calculation of energy alternative space

After using the calculation method described in this section, we can get the energy consumption and energy substitution space of each terminal when the energy substitution is implemented in 2020 and 2025 to reach the carbon emission target, and the results are shown in Table 4 and Table 5.

**Table 4. Measurement results of energy substitution space of 2020**

| Terminal Energy Consumption/10,000 t Standard Coal | Substitution Quantity/10,000 t Standard Coal | Energy Substitution Space | Carbon Emissions/100 Million Tons |
|--------------------------------------------------|---------------------------------------------|---------------------------|----------------------------------|
| Electricity consumption of renewable energy      | 27392                                       | 9379                      |                                  |
| Traditional electricity consumption               | 56879                                       | 10740                     | 104.22                           |
| Natural gas consumption                            | 24095                                       | 1362                      |                                  |
| Coal consumption                                  | 144828                                      | -10740                    |                                  |
| Oil consumption                                   | 88375                                       |                           |                                  |

Note: the value in the table is positive to represent the substitution, and negative to represent the substitution

**Table 5. Measurement results of energy substitution space of 2025**

| Terminal Energy Consumption/10,000 t Standard Coal | Substitution Quantity/10,000 t Standard Coal | Energy Substitution Space | Carbon Emissions/100 Million Tons |
|--------------------------------------------------|---------------------------------------------|---------------------------|----------------------------------|
| Electricity consumption of renewable energy      | 39074                                       | 19454                     |                                  |
| Traditional electricity consumption               | 58998                                       | /                         | 44703                            | 109.58                           |
| Natural gas consumption                            | 61948                                       | 25248                     |                                  |
| Coal consumption                                  | 140989                                      | -28446                    |                                  |
| Oil consumption                                   | 79994                                       | -16257                    |                                  |

Note: the value in the table is positive to represent the substitution, and negative to represent the substitution

In 2020, the national energy alternative space will be 107.40 million tons of standard coal, which can control the carbon emission at the target level of 10.422 billion tons of total carbon emission in 2020. In 2025, the national energy alternative space will be 447.03 million tons of standard coal, which can
control the carbon emission at the target level of 10.958 billion tons of total carbon emission in 2025.

Thus, it can be analyzed that China's energy alternative path in the period of "13th five-year plan" and "14th five-year plan" is to replace the end consumption of traditional fossil energy such as coal and oil with the end consumption of clean energy such as renewable energy, electricity and natural gas. By 2020, renewable energy power of 93.79 million tons of standard coal and natural gas of 13.62 million tons of standard coal will replace coal terminal energy consumption, and total carbon emissions will be controlled at the target level. In 2025, the use of renewable energy power of 194.54 million tons of standard coal and natural gas of 252.48 million tons of standard coal will replace the coal terminal energy consumption, and the total carbon emissions will be controlled at the target level.

5. Conclusion
In this paper, an energy alternative model considering the energy conservation and emission reduction objectives and energy supply constraints is established, which improves the objectivity, accuracy and ease of operation of energy alternative, and has a strong reference role in promoting energy conservation and emission reduction and energy alternative work, as follows:

1) Based on the total amount and structure of the terminal energy consumption, the calculation method avoids the shortcomings of the current energy substitution potential calculation method which mainly relies on the caliber for statistics and large workload;
2) Taking the total amount of carbon emission as the goal of energy consumption control, the end energy consumption structure and energy alternative path that meet the requirements of energy conservation and emission reduction can be effectively calculated;
3) Considering the constraints of renewable power and natural gas supply and consumption, the calculation results provide important reference and theoretical support for renewable power generation and natural gas development and relevant supportive policies.

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