On the Development Strategy of Electric Energy Substitution

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Abstract. Energy substitution is very important for achieving environment-friendly and sustainable economic development. This paper investigates the development strategy of China’s electric power substitution thoroughly and comprehensively from a systematic perspective. A model of electric power substitution strategic planning is proposed and a multi-dimensional space is established based on more than 20 kinds of indexes that influence electric power substitution. K-means algorithm is employed to seek the local optimal solution to find an optimized model in the multi-dimensional space. With our optimized mode, the electric power substitution situation of the provinces are divided into four major zones (capturing area, breakthrough area, gradual area, and gas and electric complementary rea). The result may provide an effective support for formulating the strategic development of electric power substitute and strategy implementation in the future.

Introduction

At present, the international energy landscape is undergoing profound changes, and the path of global energy transformation is still being explored. China is also actively promoting the energy revolution to address related issues, including energy security and environmental pressure, as well as let it be an important part of the structural reform of the energy supply side.

In China’s efforts to promote the process of “re-electrification”, all sectors of society have fully realized that electric power substitution is an important strategic measure of the energy transformation and energy revolution that is happening in the world, and China has made significant progress in the replacement of electric power, which has huge potential for future development. Electricity replacement strategy is the necessary way to enhance the level of environmental quality and electrification in China. As the power substitution is continuously advanced and the related work is deepened, the influence from the lack of electric energy substitution strategy is gradually accentuated, which becomes the crux of the large-scale implementation of the electric power replacement work.

The research on electrical energy substitution in China mainly focuses on potential analysis, assessment, technical and economic analysis, while research on medium and long-term strategies is missing. According to the influence factors and basic attributes of power substitution, [1] constructs a comprehensive evaluation index system based on environmental protection, economy, policy and technology substitutability, and puts forward the evaluation method. The author uses the decoupling theory model to determine the multiple model parameters in multiple scenarios and realize the effective prediction of the replacement quantity of the terminal energy in different scenarios. A potential analysis of the power displacement potential of vector machines based on particle swarm optimization was proposed in [3]. [4] has analyzed the power and the efficiency of electric power in the harbor.

In this paper, we constructed a development strategy for electrical energy substitution, and formed a development strategy for electric power substitution, which can guide and solve the problems encountered in the process of electric power substitution development, and ensure the smooth
development of power replacement work, and provide support for government decision-making and power grid company development.

**Electrical Energy Substitution Development Strategy**

The strategic goal of rational science is the key of strategy formulation. The basis of setting the strategic goal is to build the model through a large amount of data and carry out theoretical calculation.

First, through the electrification level and energy demand forecast, the development trend of electrical energy substitution is preliminarily judged. Through the analysis, the main cause of the electric power substitution development is the natural gas competition and environmental protection constraint, and the regional clustering analysis model based on the comparative advantage of natural gas and the environmental protection constraint index is constructed to form the power substitution situation judgment of the provinces. By quantifying the environmental protection constraints, economy, energy structure and policy support of each region, the model of energy substitute prospect assessment is constructed to determine the power substitution prospect of each region. Through the above qualitative quantitative analysis, and clustering analysis, divided into electrical energy alternative partition, and determine the corresponding alternative paths, and scientific and rational strategic target, form the key strategic moves, support the implementation of strategy. The main logic ideas are as follows.

![Figure 1. The research idea of electric power substitute development strategy.](image)

**Formulation of the Strategic Goal of Electric Power Replacement**

**Prospect of Electrification Level**

As the proportion of electric power in the terminal energy will continue to rise, it will eventually become the main terminal energy consumption. According to the future development of clean energy, electricity terminal energy-using proportion continue to rise, is expected to reach 25% and 30% in
2020 and 2030 respectively in the “2°C” scenario. The proportion of 2030 is 11% higher than that of 2010. After 2030, the technology development promotes electric power substitution acceleration, so the proportion of electricity will reach 36% in 2040. By 2050, the proportion of electricity will reach 48%, China will enter the era of high electrification [5].

The power of the industrial sector is increasing rapidly with the proportion of electricity in the terminal. Industrial automation and intelligent, clean power and thermal power are widely used, which will be the next key to industrial electric power. It is expected that the proportion of electricity in the industrial sector will reach 30% by 2030, 40% by 2040 and 52% by 2050.

The electric energy substitution of the transportation department will develop in jumps. Transportation electrification has become the consensus of governments and industry, and the electric vehicle industry will become the main way of "electricity generation oil" in the future. It is expected that the proportion of electric energy in the transportation sector will reach 3% by 2030, and the number of electric vehicles will increase rapidly after 2030, and the proportion of electric energy in the transportation sector will be about 18% by 2050.

Residential, commercial and other electric power substitutes will develop in a progressive and uniform manner. It is estimated that the proportion of people living, commercial and other electric energy will reach 27% and 42% in 2030 respectively, 51% and 65% in 2050 respectively.

Electric Power Demand Outlook

Electricity demand is expected to grow by 3.6% to 4.8% annually during the 13th five-year plan period, with a total of 7.1 trillion kilowatt-hours of electricity consumption. During the 13th five-year plan period, the electricity consumption of the primary industry is basic stable, the growth of electricity consumption of the secondary industry is slowing, and the electricity consumption of the tertiary industry and resident power consumption become the main factors of power growth. According to the forecast, the industrial growth will slow sharply after 2020, the output of high-power consumption products will start to decline, so the growth of power demand will fall sharply. Between 2030 and 2050, the economic structure will be further optimized, and the added value of the tertiary industry will reach a higher level, and the modern service industry will become dominant force of the tertiary industry. National electricity demand will reach saturation around 2045.

In 2030 and 2050, different technological progress and emission reduction requirements have different potential for clean replacement. Under strict emission reduction conditions, clean replacement potential has been improved by technological progress.

Energy Demand Outlook

With economic development and environmental policy strengthening, the total energy consumption will turn around in 2050. According to the trends of energy consumption departments, industrial growth is likely to fall during the 13th five-year period. Steel and cement production will enter the plateau, and industrial energy consumption will decline between 2020 and 2030. In the medium to long term, China's industrial growth will slow significantly, and transportation industry and construction industry will become the main force of energy demand growth. Construction industry and transportation industry will gradually replace secondary industry as the main driving force for terminal energy consumption. The energy consumption level of the construction industry is gradually decreasing. With the development of energy-saving technologies such as green buildings and ultra-low-energy buildings, the construction industry can reach the inflection point between 2030 and 2040. The growth of energy consumption in the transportation industry may persist for a long time.

Electrical Energy Substitution Development Trend Prediction

It is estimated that electric power replacement will increase 580 billion kilowatt-hours electric consumption annually by 2020. With a total of 1.5 trillion kilowatt-hours power replacement from 2021 to 2030, and a total of 2.1 trillion kilowatt-hours power replacement is expected to be realized in the low carbon development mode.
The Judgment on Electric Power Replacement Development Situation

Natural Gas Competition Index

The diversification use of natural gas makes it develop rapidly, and it is also taking part in the field of electric power substitution. Natural gas is mainly used in five fields, such as urban gas, power generation, industrial fuel, transportation and chemical industry, among which, urban gas, industrial fuel and transportation are the main areas of competitive relationship with electric energy replacement.

Taking into account the energy consumption inertia, energy demand potential, price competitiveness and consumption sustainability of various provinces in China, the competitiveness of natural gas in various regions is analyzed and the competitiveness index is calculated. The greater the competitiveness index is, the stronger the competitiveness of natural gas will be to electric power. The natural gas competition index of each province is shown in Figure. 2, which shows the comparison of the competition situation of natural gas with electric power in the whole country (except the five provinces of southern power grid and Tibet).

![Figure 2. The competitive situation of natural gas in China.](image)

Index of Environmental Constraints

Electric energy substitution progress is closely related to the prevention and control of environmental pollution. Heavily polluted areas are often at the forefront of electric energy substitution. The cities with a high average annual concentration of NOx are mainly concentrated in Hebei, Henan, Tianjin, Shandong, Hubei, Anhui, Beijing, Sichuan, Jiangsu and Zhejiang provinces. The cities with a high average annual concentration of SO2 is concentrated in Henan, Hebei, Tianjin, Shandong, and Beijing. In some areas, the environmental overloading rate is greater than 150%. According to the environmental data sources such as national pollution census data and environmental statistics, the constraints of environmental protection in various provinces are analyzed. According to the emission reduction rate of SO2, NOx, PM2.5 and NH3, the environmental protection index is calculated. The results show that the economically developed inland provinces have a higher environmental protection index.

Calculation of Electric Energy Substitution Development Prospect

For comprehensive evaluation the factors affecting the development of electric energy substitution, we build estimate model to prospect electrical energy substitution development scale by 4 first-level indicators including 15 second-level indicators. First, we need to construct of indicators system, and then further quantitate the indicators, in a way that is numerical evaluation of development potential of electric energy substitution under multiple factors constraints. The development potential of electric energy substitution is valuable as decision-making reference.
Construction of Indicators in the Model

Because electric energy substitution is a relatively new thing, there needs to be the driving force of industrial development (national energy consumption structure adjustment and environmental constraints), economic cost advantages (mainly compared to natural gas), and appropriate supporting capacity in the region (policy support, the surplus electricity). Therefore, the provincial prospect estimation model is divided into 4 first-level indicators including energy consumption structure, environmental constraints, economical comparison, and the coordinative supports, while each first-level indicator is subdivided into multiple second-level indicators. For each second-level indicator, the quantifiable factors are chosen to be quantified.

The first-level indicator of energy consumption structure is divided into three second-level indicators, namely coal consumption, natural gas consumption and electricity consumption. The main potential of electric energy substitution is to replace coal. Natural gas that also belong to clean energy, is electric energy competitor. Therefore, the greater the coal consumption and power consumption of a region are, the greater the potential of electric energy substitution is in the region. The greater the consumption of natural gas is, the greater the resistance to electricity is in the region.

The first-level indicator of environmental restriction is divided into three second-level indicators, namely civil scattered coal quantity (including rural life, hotel catering, urban life, agricultural production), average annual air PM2.5 concentration, number of motor vehicle. It is the key and difficult point to control the air pollution and to control the scattered coal burning. Compared with the centralized coal burning, the scattered coal burning is often lack of desulfurization and dust removal and difficult to supervise. The low-quality coal with high ash content and high sulfur content is often used for scattered coal burning. The unit emission intensity of scattered coal burning is much higher than that of concentrated coal burning, and the emission intensity of scattered coal burning is about 8 times that of electricity. As a result, the distribution of coal in the area is the driving factor of environmental protection. The more serious the situation of environmental protection in a region is, the greater the development opportunity of electric energy substitution is. Therefore, the average concentration of PM2.5 in the region is selected as the calculating factor to represent the environmental protection requirement. Without considering energy consumption in the whole life cycle, just from the point of view of the vehicle, the electric vehicle has a certain effect of energy saving. The more traditional fuel vehicle, the greater the demand for gasoline, diesel oil and other energy consumption, and the greater the demand for electric vehicle. Therefore, the number of carbon fuel vehicle in the region is selected as the calculating factor to represent the environmental protection requirement.

Since national strategies encourage electricity and natural gas to replace fossil fuels, the economic comparison is mainly between electricity and natural gas. The first-level indicator of the economic comparison is divided into five second-level indicators, including industrial gas price, residential gas price, residential electricity price, large industrial electricity price and general industrial and commercial electricity price. Resident’s gas price and electricity price are mainly for distributed electric heating, heat pump and electric cooker. Industrial gas prices, large industrial electricity price and electricity price of general industry and commerce are mainly for electric heating boiler, furnace and intermediate frequency furnace building materials. The general idea is that the lower the price of electricity in a region, the greater the potential of electric energy substitution. The lower the price of natural gas, the greater the competition resistance in the region.

The development of electric energy substitution is inseparable from supporting policies. Therefore, the first-level indicator of support is divided into four second-level indicators, namely environmental policy, tariff subsidies policy, planning policies and the regional electric energy surplus. Stricter environmental policies can promote the development of electric energy substitution. Electricity price subsidies for electric energy substitution enhance cost advantage for the user. Planning policy (electric vehicle, distribution network construction, etc.) can promote the development of related industries to electric energy substitution. The degree of regional electric energy surplus determines
the local drive to develop electric energy substitution. Each model index and their relationship are shown in Figure 3.

![Figure 3. The model index of electricity substitution.](image)

**Evaluation Method of Indicators in the Model**

After the model is determined, the weight of each indicator and the evaluation value of each region are calculated by the entropy weight method. Entropy weight method is an analysis of the amount of information provided by the indicator. For an indicator, the larger the difference of the indicator value, the greater the role of the indicator in the comprehensive evaluation. If the value of the indicator is all equal, the indicator will not work in the comprehensive evaluation. By using the entropy weight method, the weights of each indicator can be calculated to provide the basis for comprehensive evaluation of multiple indicators.

As shown in Table 1, the weight of indicators to value the potential of electric energy substitution in 2020 are shown in the table. The three indicators with the largest weight are the supporting policies, the electricity price for great industry and the coal consumption. Table 1 shows the quantity of electric energy substitution by regions in 2020 (I3, terawatthours TWh). The three provinces with maximum amount of electric energy substitution are Shandong, Hebei and Shanxi respectively, while the smallest one is Tibet. Table shows the influence weight of indicators to value the potential of electric energy substitution in 2030. As can be seen from the figure, the most weighted indicator becomes coal consumption. I4 (TWh) in Table is the quantity of electric energy substitution by regions in 2030, and Henan replaces Shanxi as the third major electric energy substitution province.

<table>
<thead>
<tr>
<th>Influence index weight</th>
<th>2020</th>
<th>2030</th>
<th>Influence index weight</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supporting policies</td>
<td>0.117</td>
<td>-</td>
<td>Residential electricity price</td>
<td>0.056</td>
<td>-</td>
</tr>
<tr>
<td>Scattered coal</td>
<td>0.111</td>
<td>0.160</td>
<td>Industrial power price</td>
<td>0.052</td>
<td>-</td>
</tr>
<tr>
<td>Air quality</td>
<td>0.044</td>
<td>0.160</td>
<td>Commercial electricity price</td>
<td>0.117</td>
<td>-</td>
</tr>
<tr>
<td>Vehicle ownership</td>
<td>0.074</td>
<td>0.132</td>
<td>Coal consumption</td>
<td>0.098</td>
<td>0.197</td>
</tr>
<tr>
<td>Industrial gas price</td>
<td>0.037</td>
<td>-</td>
<td>Natural gas consumption</td>
<td>0.038</td>
<td>0.087</td>
</tr>
<tr>
<td>Resident gas price</td>
<td>0.043</td>
<td>-</td>
<td>Power consumption</td>
<td>0.137</td>
<td>0.132</td>
</tr>
<tr>
<td>Power balance</td>
<td>0.076</td>
<td>0.132</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the calculation model to prospect the development of electric energy substitution, the calculation procedure of entropy weight method is as follows:

1) Data normalization
Standardize the data of each indicator. Suppose there are k indicators $X_1, X_2... X_k$, where $X_i=\{x_{i1}, x_{i2}... x_{in}\}$. In this calculation, $k=15$, $i=1,2,...,k$ stands for one of the 15 secondary indicators, $n=26$, $j=1,2,...,n$ stands for 26 provinces or cities. Suppose that the normalized value of each index data is $Y_1, Y_2,... Y_k$, $Y_i=\{y_{i1},y_{i2}...,y_{ijn}\}$.

\[ Y_i = \frac{x_i - \min(X_i)}{\max(X_i) - \min(X_i)} \]  

(1)

2) Find the information entropy of each indicator.

According to the definition of information entropy in information theory, information entropy of a set of data is:

\[ E_i = -\ln(n)^{-1} \sum_{j=1}^{n} p_{ij} \ln(p_{ij}) \]

\[ p_{ij} = \frac{Y_{ij}}{\sum_{j=1}^{n} Y_{ij}} \]

If $p_{ij}=0$, lim $p_{ij} \ln(p_{ij})=0$ is defined.

3) Determine the weight of each indicator.

According to the calculation formula of information entropy, the information entropy of each indicator is calculated as $E_1$, $E_2$, and... $E_k$. Calculate the weight of each indicator through information entropy:

\[ W_i = (1-E_i) / (k - \sum_{i=1}^{k} E_i), i=1,2,...,k. \]  

(3)

4) Final score

According to the calculated indicator weight, and the scores of 15 indicators in each province. Let $Z$ be the final score of the $j$ th province:

\[ Z_j = \sum_{i=1}^{k} W_i x_{ij} \]  

(4)

5) Calculate the electric energy substitution development situation. Set $S_j$ as the electric energy substitution development situation of the $j$ th province:

\[ S_j = AZ_j / \sum_{j=1}^{n} Z_j \]  

(5)

Where $A$ is the overall electric energy substitution planning target for all regions.

In practical application, according to the influence to the electric energy substitution, there are more than 10 kinds of indicators to establish multidimensional space. The multi-dimensional space is constructed according to the multiple indicators in the regional electric energy substitution situation evaluation indicator system. In this paper, we adopt popular heuristic partition clustering algorithm (K-MEANS algorithm) to cluster in multi-dimensional space for local optimal solution. To choose a number of areas of K, which is the primary center of the cluster, it’s based on the k-means algorithm by the numerical value of the electric energy substitution situation in the area.

Basic steps of K-MEANS algorithm:

1) Choose K objects from N data objects as the initial cluster center.

2) Based on the average value of each cluster object (central object), the distance between each object and these central objects is calculated. The corresponding objects are divided according to the minimum distance.

3) Recompute the central object of each cluster.

4) Calculate standard measure function. If function converges, the algorithm terminates. If function does not converges, back to the step2.
According to the optimal solution of clustering, the energy substitution situation of the provinces is divided into four major zones (occupying area, breakthrough area, gradual area, and gas-electric complementary area), and providing support for the development of electric energy substitution strategy and strategy implementation in the future. For the sake of demonstration, comprehensive natural gas comparative advantage, environmental protection constraints and other factors, the electric energy substitution of the provinces is presented in the 2-D coordinate system, and the electric energy substitution situation of the province is shown in Figure 4.

Figure 4. Provincial electricity substitution situation cluster diagram.

The provinces represented by Beijing are in the occupying area, and there are strong environmental protection constraints and relatively weak natural gas competitiveness in the capturing area. Therefore, it is the window period for electric energy substitution. The provinces represented by Shanxi and Anhui province are in the breakthrough area, and there are medium stringent environmental constraints and natural gas competitiveness. It is possible to take certain advantage of electric energy substitution as a breakthrough point to develop electric energy substitution according to local conditions. The provinces represented by Hainan and Fujian province are in the gradual area, and there are less environmental constraints and low natural gas competitiveness. It is shortage of driving force for development of electric energy substitution. Therefore, we plan to roll electric energy substitution out in the area over time. The provinces represented by Xinjiang province are in
the gas-electric complementary area, and there are little environmental constraints and high natural
gas competitiveness. It is shortage of driving force for development of electric energy substitution.
Therefore, we plan to roll electric energy substitution out in the area if natural gas pipeline doesn't
have coverage in the area.

Measures of Electric Energy Substitution

We have combed out the main measures in the electric energy substitution. The first is special
engineering including clean heating, intelligent manufacturing, agricultural electrification, electric
vehicles, port electrification and domestic electrification, etc. The second is comprehensive
application including urban comprehensive energy use, area comprehensive energy use and area
renewable energy use. The classification of strategic measures is shown in the figure 5.

Summary

Natural gas comparative advantage and environmental protection constraint are the two main factors
that influence the electric energy substitution in each region. According to the data of
multi-dimensional indicators including environmental protection and natural gas competitiveness, the
provinces and cities in China can be divided into four categories, namely, occupying area,
breakthrough area, gradual area, and gas-electric complementary area. We should grab the
opportunity to seize the market in the occupying area, find the breakthrough point in the breakthrough
area, roll electric energy substitution out in the gradual area over time, and develop electric energy
substitution to complement natural gas in the gas-electric complementary area.

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