An electric energy substitute planning model with economic cost and environmental constraints

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Abstract. The planning of electric energy substitution is one of the important bases for the decision-making of electric energy substitution propulsion. Nevertheless, there are still some problems in the planning of electric energy substitution, since the planning relies heavily on personal experience and local calculations. In this paper, a comprehensive planning model for electric energy substitute is proposed with considering the air pollution prevention, economic cost and technical feasibility of each region. The proposed planning model could be applied to efficiently and orderly develop the electric energy substitution, and consequently help to realize the energy transformation and the establishment of a green low-carbon society.

1. Introduction
Electric energy substitution is regard as an important arrangement for the implementation of the sixth meeting of the Central Financial and Economic Group, the State Council Action Plan for Air Pollution Prevention and Control, and the National Strategic Action Plan for Energy Development [1]. The important position of electric energy substitution planning is clarified in the paper. The direction and result of electric energy substitution planning will influence the overall operation state of power grid enterprises in a long time, and then influence the business structure and operation state, and influence the efficiency effect of the whole operation. The planning of electric energy substitution is one of the important bases for the decision-making of electric energy substitution propulsion, among which the determination of the construction scale and the choice of the project determine the efficiency and effect of the electric energy substitution planning to a great extent [2].

However, there are still some problems in the planning of electric energy substitution, especially in the determination of investment scale and project planning and construction, such as the lack of mature quantitative operation means and optimization path [3]. Experience-based programmes vary from person to person, are less operational, less coherent and contrary to the concept of precise planning. The existing electric energy substitute planning of the city and above is carried out by the planner on the basis of personal experience and local computation. The lack of extensive and sufficient consideration of internal and external factors, the low importance attached to benefits, the method too dependent on personal experience management means, the lack of regulatory basis, the lack of optimization approach, resulting in extensive planning, the implementation of the direction and path of electrical energy substitution is not clear, and not well connected with the market. The specific development of electrical energy substitution in some regions is limited to the assessment or construction of specific projects, lack of overall vision, does not form a systematic strategic planning.
There are no standards and procedures for the electrical energy substitution in all parts of the country, and there is no rapid and timely formation of a benign cycle of mutual promotion and interconnection.

In the face of the emerging new problems and the increasing scale of substitution, the traditional electrical energy substitution planning methods need to be improved and adapted [4]. This paper proposes a comprehensive planning model for electric energy substitute (CPMEES) considering the air pollution prevention, economic cost and technical feasibility of each region. The planning model contributes to the efficient and orderly development of electric energy substitution, and ultimately to the realization of energy transformation and the building of a green low-carbon society.

2. Electric energy substitution planning model

The CPMEES gives the plan of dividing the technical fields and the total amount of the substitute scale suitable for the national conditions of our country and the local characteristics.

The modeling process is as follows.

\[
\begin{align*}
\min_{E_{ij}} & \sum_{i=1}^{N} \alpha_i \sum_{j=1}^{M} \beta_{ij} P_{ij} E_{ij} \\
\text{s.t.} & \sum_{i=1}^{N} \sum_{j=1}^{M} E_{ij} \geq \max \left( E^e, E' \right) \\
& L_{ij} \leq E_{ij} \leq U_{ij} \\
& \sum_{j=1}^{M} E_{ij} \geq E_i^e
\end{align*}
\]

\( N \) indicates the number of regions covered by the plan;
\( M \) indicates the number of electric energy substitution field covered by the plan;
\( P_{ij} \) indicates the unit cost driving electric energy substitution in \( j \)-th technical field of \( i \)-th region;
\( E_{ij} \) indicates the planned electric energy substitution electricity in \( j \)-th technical field of \( i \)-th region;
\( L_{ij} \) indicates the lower limit of electric energy substitution electricity in \( j \)-th technical field of \( i \)-th region;
\( U_{ij} \) indicates the upper limit of electric energy substitution electricity in \( j \)-th technical field of \( i \)-th region;
\( \alpha_i \) indicates the weight of \( i \)-th region which reflects the development situation of electric energy substitute in \( i \)-th region;
\( \beta_{ij} \) indicates the weight of \( j \)-th technical field in \( i \)-th region which reflects the national promotion of electric energy substitution key regions and key fields;
\( E^e \) indicates the electric energy substitution planning total electricity under the constraint of atmospheric environmental protection;
\( E_i^e \) indicates the electric energy substitution planning electricity under the constraint of atmospheric environmental protection in \( i \)-th region;
\( E' \) indicates the electric energy substitution total quantity estimated on the basis of electric energy substitution quantity completed last year and the rate of growth of electricity consumption in society as a whole.

3. Electric energy substitution planning example

In this example, the 26 provinces and cities (1-Beijing, 2-Tianjin, 3-Hebei, 4-Shanxi, 5-Inner Mongolia, 6-Shanxi, 7-Liaoning, 8-Jilin, 9-Heilongjiang, 10-Gansu, 11-Xinjiang, 12-Shandong, 13-Qinghai, 14-Henan, 15-Hubei, 16-Hunan, 17-Anhui, 18-Zhejiang, 19-Jibei, 20-Jiangxi, 21-Fujian, 22-Chongqing, 23-Sichuan, 24-Shanghai, 25-Ningxia, 26-Jiangsu) involved in the region of 5 technical fields (1-industry, 2-agriculture, 3-construction, 4-residential life, 5-transportation).
$P_{ij}$ is obtained by dividing the investment in $i$-th region $j$-th technical field completed last year by the scale of electrical energy substitution in $i$-th region $j$-th technical field completed last year shown in Table 1;

Table 1. Unit cost driving electric energy substitution in 5 technical field by region (yuan/kwh).

| Region          | Industry | Construction | Residential Life | Transportation | Agriculture | average cost |
|-----------------|----------|--------------|------------------|----------------|-------------|--------------|
| Beijing         | 0        | 2.881419     | 86.40852        | 11.50284       | 0           | 3.614861     |
| Tianjin         | 0.717716 | 5.438676     | 9.039732        | 1.198481       | 5.645906    | 1.351497     |
| Hebei           | 0.279828 | 2.440205     | 0               | 15.91565       | 1.090768    | 1.978301     |
| Jibei           | 0.351458 | 2.20604      | 12.41472        | 15.73354       | 0.461409    | 1.737175     |
| Shanxi          | 0.425786 | 3.25166      | 0               | 1.616471       | 0           | 0.678837     |
| Shandong        | 0.468669 | 6.22598      | 1.603204        | 9.440976       | 0.098435    | 2.056023     |
| Shanghai        | 0.103041 | 1.202685     | 2.631307        | 0.314915       | 6.168118    | 0.482203     |
| Jiangsu         | 0.609961 | 1.432702     | 1.82177         | 71.08893       | 1.246056    | 3.925734     |
| Zhejiang        | 0.29947  | 1.161392     | 3.101102        | 8.168797       | 1.585365    | 1.684306     |
| Anhui           | 0.178651 | 20.71504     | 0.52671         | 2.480017       | 6.520653    | 1.339582     |
| Fujian          | 0.168793 | 0.278485     | 0               | 2.537061       | 2.237095    | 0.318394     |
| Hubei           | 0.31031  | 7.959584     | 2.27861         | 7.195966       | 2.626436    | 3.009177     |
| Hunan           | 0.589891 | 5.121956     | 0.69301         | 4.220581       | 1.32518     |
| Henan           | 0.499927 | 0.906628     | 0.637439        | 1.312534       | 1.384747    | 0.686804     |
| Jiangxi         | 0.559057 | 1.599858     | 0.929999        | 1.24686        | 4.400188    | 0.954618     |
| Liaoning        | 0.032504 | 3.90514      | 0               | 1.846381       | 0           | 0.682034     |
| Jilin           | 0.168449 | 3.869323     | 0.83772         | 5.177299       | 0.9607      |
| Heilongjiang    | 0.427922 | 2.602967     | 0.089033        | 0.569107       | 0.415542    | 0.899871     |
| East Inner Mongolia | 0.283236 | 4.168034     | 2.495445        | 7.434587       | 1.095092    | 1.313197     |
| Shaanxi         | 0.443944 | 1.180272     | 5.06833         | 0.882674       | 2.851079    | 0.812906     |
| Gangsu          | 0.183324 | 4.303837     | 0.314994        | 1.943859       | 0.726077    | 0.746571     |
| Qinghai         | 0.505013 | 8.878621     | 0               | 0.125885       | 0           | 0.549756     |
| Ningxia         | 0.521298 | 29.26809     | 0               | 104.1575       | 13.35291    | 1.01          |
| Xinjiang        | 0.4895   | 14.018       | 725.5769        | 3.587428       | 1.503286    | 1.088144     |
| Sichuan         | 0.636449 | 7.236462     | 18.67132        | 24.01208       | 2.850273    | 3.032695     |
| Chongqing       | 0.454548 | 4.355831     | 31.29495        | 0.098348       | 51.13589    | 1.345067     |

$L_{ij}$ is obtained by economic potential of electric energy substitution based on energy price comparison shown in Table 2;
Table 2. Economic potential of electric energy substitution based on energy price comparison by region (10^8 kwh).

| Region         | Potential | Region         | Potential | Region         | Potential |
|----------------|-----------|----------------|-----------|----------------|-----------|
| Beijing        | 5.74      | Shandong       | 13.36     | Chongqing      | 4.19      |
| Tianjin        | 4.31      | Qinghai        | 0.96      | Sichuan        | 13.02     |
| Hebei          | 8.23      | Henan          | 10.76     | Guizhou        | 5.05      |
| Shanxi         | 4.39      | Hubei          | 11.11     | Yunnan         | 5.79      |
| Inner Mongolia | 5.27      | Hunan          | 8.39      | Tibet          | 0.0       |
| Shaanxi        | 4.62      | Guangdong      | 19.83     | Shanghai       | 8.88      |
| Liaoning       | 12.61     | Guangxi        | 5.51      | Jiangsu        | 14.22     |
| Jinlin         | 3.36      | Hainan         | 1.48      | Zhejiang       | 12.14     |
| Heilongjiang   | 5.80      | Jiangxi        | 5.29      | Anhui          | 7.46      |
| Gansu          | 3.10      | Fujian         | 6.86      | Ningxia        | 0.90      |
| Xinjiang       | 5.39      |                |           |                |           |
| Total          | 218.03    |                |           |                |           |

$U_{ij}$ is obtained by the electric energy substitution theoretical potential based on re-electrification target in $i$-th region and $j$-th field [5] shown in Table 3;

Table 3. Electrification levels and theoretical potential for electrical energy substitution in 5 technical fields.

| Technical field | Electrification level (2020) | Potential (10^8 kwh, 2020) | Electrification level (2030) | Potential (10^8 kwh, 2030) |
|----------------|------------------------------|-----------------------------|------------------------------|-----------------------------|
| 1-Industry     | 25%                          | 2608                        | 35%                          | 17281                       |
| 2-Agriculture  | 18%                          | 242                         | 25%                          | 803                         |
| 3-Construction | 2%                           | 340                         | 10%                          | 4494                        |
| 4-Residential Life | 34%                      | 605                         | 40%                          | 2794                        |
| 5-Transportation | 4%                           | 333                         | 15%                          | 4347                        |

Table 4. Potential of electric energy substitution for environmental protection by region 2017-2030 (10^8 kwh).

| Region         | Potential | Region         | Potential | Region         | Potential |
|----------------|-----------|----------------|-----------|----------------|-----------|
| Beijing        | 181.4     | Shandong       | 5035.9    | Chongqing      | 63.7      |
| Tianjin        | 242.5     | Qinghai        | 0.00      | Sichuan        | 1571.9    |
| Hebei          | 4528.7    | Henan          | 2351.3    | Guizhou        | 955.4     |
| Shanxi         | 77.2      | Hubei          | 960.2     | Yunnan         | 0.00      |
| Inner Mongolia | 0.00      | Hunan          | 1070.4    | Tibet          | 111.0     |
| Shaanxi        | 0.00      | Guangdong      | 0.00      | Shanghai       | 0.00      |
| Liaoning       | 159.5     | Guangxi        | 0.00      | Jiangsu        | 1995.3    |
| Jinlin         | 0.00      | Hainan         | 0.00      | Zhejiang       | 0.00      |
| Heilongjiang   | 0.00      | Jiangxi        | 188.4     | Anhui          | 1429.3    |
| Gansu          | 0.00      | Fujian         | 0.00      | Ningxia        | 0.00      |
| Xinjiang       | 427.7     |                |           |                |           |
| Total          | 21349.5   |                |           |                |           |

$\alpha_i$ is obtained by the development strategy of electric energy substitution in different regions [6], 26 regions were divided into four levels according to the cluster analysis of regional electric energy substitution situation. $\alpha_i=1$ in the areas with the best electric energy substitution situation (Beijing, Hebei, Tianjin, Shandong and so on), $\alpha_i=1.25$ in the areas with good electric energy substitute situation (Shanxi, Anhui, Hubei and so on), $\alpha_i=1.5$ in the areas with difficult electric energy substitution popularization (Hainan, Fujian, Heilongjiang and so on), $\alpha_i=2$ in the most difficult areas to promote electric energy substitution (Xinjiang, Shanxi, Sichuan);
\( \beta_{ij} \) is valued based on the annual priorities of the national government and the state grid corporation. For example, promoting clean heating in the north and electric power construction of ports along the Yangtze river basin are the key work of the state grid in 2018. Therefore, Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai and other 14 provinces (autonomous regions and municipalities) as well as parts of Henan Province as designated by the Northern Region Clean Heating Plan (2017-2021) are key work regions for substituting electricity for coal \( \beta_{3} = 1 \), while the rest \( \beta_{3} = 1.5 \). Similarly, 8 provinces (Hubei, Hunan, Anhui, Jiangxi, Chongqing, Sichuan, Shanghai, Jiangsu) in the Yangtze river basin are key work regions for substituting electricity for diesel oil \( \beta_{5} = 1 \), while the rest \( \beta_{5} = 1.5 \).

\( E_{e} \) and \( E_{e}^r \) are obtained by the potential model of electric energy substitution for environmental protection based on emission reduction targets [7] shown in Table 4: \( E_{e} = 1236.25 \times 10^{8} \text{kwh} \). State Grid Corporation achieves 115 billion kilowatt-hours of electricity substitution in 2017, with full-year sales up 7.5 per cent.

In this example, according to CPMEES, the planned electric energy substitution electricity in \( j \)-th technical field of \( i \)-th region \( E_{ij} \) are shown in Table 5.

### Table 5. Unit cost driving electric energy substitution in 5 technical field by region (10^4kwh).

| Region          | Industry | Construction | Residential Life | Transportation | Agriculture | Total        |
|-----------------|----------|--------------|------------------|----------------|-------------|--------------|
| Beijing         | 2648.094 | 170749.2     | 416.626          | 13561.87       | 1843.115    | 189218.902  |
| Tianjin         | 220142.8 | 30154.4      | 1991.209         | 43388.26       | 1771.195    | 297447.864  |
| Hebei           | 450276.8 | 91795.56     | 2805.856         | 54914.5        | 42172.14    | 641964.856  |
| Jilin           | 409721.6 | 38077.28     | 2899.787         | 38262.22       | 13003.65    | 501964.53   |
| Shanxi          | 540177.4 | 24602.82     | 9689.478         | 97743.76       | 17201.3     | 689414.758  |
| Shandong        | 810807   | 173466.7     | 47405.06         | 116937.1       | 142225.8    | 1290841.58  |
| Shanghai        | 155278.5 | 96450.88     | 759.559          | 95263.7        | 648.496     | 348401.175  |
| Jiangsu         | 59201.6  | 145180.2     | 3293.5           | 34885.88       | 6420.256    | 779981.436  |
| Zhejiang        | 360636.8 | 58828.38     | 5159.456         | 80550.42       | 5046.156    | 508221.212  |
| Anhui           | 425410.6 | 20757.86     | 15188.62         | 50806.1        | 8894.814    | 521057.99   |
| Fujian          | 568926.6 | 78117.16     | 25288.18         | 40204          | 3576.066    | 709812.006  |
| Hubei           | 244916.4 | 8441.76      | 3510.912         | 55586.7        | 5330.418    | 396876.19   |
| Hunan           | 379731.4 | 80438.02     | 558.6872         | 92350.76       | 11372.84    | 564451.7092 |
| Henan           | 736106.8 | 156624.3     | 15687.78         | 82283.56       | 75103.96    | 1065806.422 |
| Jiangxi         | 125210.9 | 31252.78     | 8602.16          | 36892.68       | 5454.312    | 207412.872  |
| Liaoning        | 430720   | 47629.54     | 5303.342         | 115902.4       | 7453.026    | 607008.288  |
| Jilin           | 189968.1 | 48070.42     | 165.9476         | 31036.64       | 3476.716    | 272717.8636 |
| Heilongjiang    | 98148.82 | 52248.06     | 22463.56         | 31628.48       | 28877.98    | 233366.9    |
| East Inner Mongolia | 92092.06 | 5758.11     | 641.682          | 12105.58       | 14610.64    | 130978.076  |
| Shaanxi         | 171192.7 | 50835.74     | 4340.68          | 106494.6       | 9119.354    | 341983.074  |
| Gansu           | 229102.4 | 9294.032     | 19047.96         | 87454.9        | 24790.76    | 369690.05   |
| Qinghai         | 221776.7 | 2252.602     | 1438.938         | 15887.54       | 2388.624    | 243744.306  |
| Ningxia         | 176482.6 | 2255.016     | 185.4109         | 7680674        | 1198.241    | 180198.0742 |
| Xinjiang        | 273748.8 | 6991.012     | 66.15426         | 6690.03        | 21286.7     | 308782.696  |
| Sichuan         | 559353.8 | 27083.06     | 3749.066         | 55721.96       | 6315.184    | 652225.07   |
| Chongqing       | 131999.1 | 23876.04     | 1917.242         | 40671.92       | 7822294     | 199246.5716 |
| Total           | 859477.8 | 1551933      | 208346.8         | 1437302        | 460364      | 12252724.47 |
4. Summary
Based on the goal of minimizing the total economic cost of electrical energy substitution, this paper constructs a planning model of electrical energy substitution based on the constraints of completing national environmental protection requirements and policy requirements and meeting the actual development of electric energy substitution in various regions. First, according to the investment cost and substitute electricity quantity in the development of electric energy substitution in China, the unit economic cost of electric energy substitution in each region is calculated. Second, according to the environmental capacity of various regions in China and the emission of major pollutants in the exhaust gases calculate substitute electricity quantity in various regions under the constraints of environmental protection. Third, determine the upper and lower limits of substitute electricity quantity in each region according to economic potential of electric energy substitution based on energy price comparison and electric energy substitution theoretical potential based on re-electrification target. Fourth, estimate the electric energy substitution total quantity according to electric energy substitution quantity completed last year and the rate of growth of electricity consumption in society as a whole. Through the above steps, the programming model is established, and the optimal solution method can be used to solve the programming model.

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References
[1] Guiding Opinions on Promoting Electric Energy Substitution 2016.5.16
[2] Implementing Electric Energy Substitute and Promoting Energy Consumption Revolution 2016 China Economic and Trade Guide
[3] Wei Tang 2017 Scientific Implementation of Electric Power Substitute Planning China Electric Power Enterprise Management
[4] Yi Sun, Peng Xu, Baoguo Shan, Bing Qi 2016 Roadmap for “internet plus” energy substitution in electricity retail market reform in China Power System Technology 2016 40(12)
[5] Yu Zhang, Fen Lin, Fengkui Luan and Ke Xiong 2018 Analysis of Electric Energy Substitution Potential Based on Re-electrification Target 2018 International Conference on Electrical, Control and Mechanical Engineering (ECME2018)
[6] Wei Tang, Yu Zhang, Baoguo Shan, Peng Wu, Fen Lin, Ke Xiong 2018 On the Development Strategy of Electric Energy Substitution 2018 International Conference on Energy, Environment and Power Engineering (EEPE2018)
[7] Yu Zhang, Fen Lin, Ke Xiong 2018 A potential model of electric energy substitution for environmental protection based on emission reduction targets 2018 International Conference on Energy, Environment and Power Engineering (EEPE2018)