A Smart Grid Planning Method with Coal-to-electricity Based on Multifactor Adaptability

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Abstract—In order to reduce coal pollution and improve air quality in winter, many cities in northern China began to promote coal-to-electricity, and a series of policy subsidies were released accordingly. With the implementation of coal-to-electricity, the characteristics of power network has been changed significantly and the traditional planning method is no longer applicable. To meet the needs of coal-to-electricity engineering, a smart grid planning method with coal-to-electricity based on multifactor adaptability is proposed in this paper. First, the coal-to-electricity load characteristics is analysed, and typical parameters is proposed based on the actual operation data, which considers the impacts of different types of equipment and breaks through the modelling difficulties of coal-to-electricity characteristics. Then, a smart grid planning method with coal-to-electricity based on multifactor adaptability is set up, which combines the influence of transmission capacity for each equipment, the investment capacity for each participant, and the social acceptance of the electricity price. Based on this model, the technical, economic, and environmental benefits of coal-to-electricity modification are coordinated. The application shows that the proposed method is concise and effective and provides useful suggestions for determining the coal-to-electricity scale, network planning and compensation policy, which supports the implementation of coal-to-electricity.

1. Introduction

With the severe challenge of serious haze weather and increasing demand of energy reform, increasing the proportion of power consumption in terminal energy has become an important strategy in China. And thus, the shift from coal heating to electric heating, which is named coal-to-electricity project develops rapidly form year of 2016[1].

The types and development potential of coal-to-electricity are analyzed in [2]-[4] and the technical characteristics like air/ground source heating pumps, phase change heat storage are introduced in [5]-[7]. The load characteristics of coal-to-electricity are obtained by statistically analyzed in [8], which shows strong negative correlation between heating loads and temperature. And the forecasting method for short-term electric heating power load is proposed in [9] and the impacts of coal-to-electricity on power grid are analyzed in [10]-[12]. Furthermore, the economic and environmental benefits, evaluation index system and engineering harmonics of coal-to-electricity are mentioned in [13]-[15]. A method for
evaluating the adjustable capacity of household heating load based on temperature forecast is presented in [16]. The planning method for enhancing the capacity of wind power consumption by coal-to-electricity equipment and the operation strategy are introduced in [17]-[18], which lays a foundation for demand side management of coal-to-electricity and is helpful for the development of the integrated energy system and enhancing of the power grid resilience.

In general, some research has been carried out in the field of coal-to-electricity. However, there is no load forecasting method of different types of coal-to-electricity for power grid planning. And most of the research focuses on the impact analysis, operation scheduling of the coal-to-electricity, and few studies are made on the power grid planning method with coal-to-electricity, aiming at promoting the implementation of coal-to-electricity and ensuring the interests of all participants like governments, enterprise, and household users. From the perspective of power balance, we have put forward a smart grid planning method with coal-to-electricity in [19], which is suitable for the regional overall scale planning but is difficult to determine the specific construction needs of substations and transformation lines. Further research is still needed today.

To scientifically plan the construction plan of power grid with coal-to-electricity, a smart grid planning method based on multifactor adaptability is proposed in this paper. Firstly, the typical parameters of different coal-to-electricity equipment for power prediction are extracted. Then, the technical constraints, economic constraints, and social constraints are considered comprehensively to maximize energy efficiency with minimum investment. Finally, taking the actual planning work of power network with coal-to-electricity in a certain region of Hebei province as an example, this paper makes an empirical analysis of the implementation scale, the construction scale of smart grid planning, investment analysis and the added electricity price of different types of coal-to-electricity.

2. Load prediction integrated with coal-to-electricity

2.1. Load prediction model

The coal-to-electricity power load in each region is the summary of electric heating load of public enterprises and residents.

\[ l_c = \sum l_{cm} + \bar{L}_{user} \times N_{last,c} \times \alpha \times \beta \]  

(1)

Where, \( l_c \) represents the coal-to-electricity load integrated into point \( c \); \( \bar{L}_{user} \) represents the increased average capacity for each household; \( \alpha \) represents the load rate of electric heating equipment; \( \beta \) represents the simultaneity rate of electric heating equipment; \( N_{last,c} \) represents the implementation scale of coal-to-electricity integrated into point \( c \); and \( l_{cm}^{unit} \) represents the increased load of public enterprises, which is calculated by equipment power or heating area.

\[ l_{cm}^{unit} = \bar{L}_{unit} \times \alpha \times \beta \]  

(2)

\[ l_{cm}^{unit} = S_{unit} \times P_{unit} \]  

(3)

Where, \( \bar{L}_{unit} \) is the increased power capacity of public enterprises; \( S_{unit} \) is the electric heating area; \( P_{unit} \) is the heating load per square meter.

2.2. Typical parameters for load prediction

The main coal-to-electricity equipment includes centralized heat storage electric heaters, air source heat pumps (centralized or distributed), distributed heat storage electric heaters, distributed heat storage electric boilers. It is different in electric heating area, equipment features and power for different types of coal-to-electricity equipment, which causes the typical parameters such as load rate and simultaneity rate differently. To make the load prediction model more general and universal, the typical parameters in the model for different types of coal-to-electricity equipment are analyzed based on the historical data.
3. Proposed model formulation

3.1. Objective function

The objective function is minimizing the investment while maximizing the benefits of environmental improvement.

\[
\min \alpha_1 F_{\text{grid}}^{\text{bas}} + \alpha_2 \frac{F_{\text{coal}}}{F_{\text{coal}}} CRQ
\]

Where, \(\alpha_1\) and \(\alpha_2\) are the weight coefficients respectively; \(F_{\text{grid}}^{\text{bas}}\) is the coal-to-electricity investment of matching power projects; \(F_{\text{coal}}\) is the heating cost of burning coal before coal-to-electricity; \(CRQ\) and \(CRQ^r\) are the costs of controlling pollutants before and after the coal-to-electricity, as in

\[
CRQ = \sum (N_{\text{last}} - N_{\text{last}}) (\eta_s X_s^r + \eta_N X_N^r + \eta_D X_D^r + \eta_C X_C^r)
\]

Where \(\eta_s, \eta_N, \eta_D, \eta_C\) describe the unit controlling costs of sulfur dioxide, nitrogen oxides, soot and carbon dioxide; \(X_s, X_N, X_D, X_C\) are the average household emissions of sulfur dioxide, nitrogen oxides, soot and carbon dioxide per heating season; \(N_{\text{last}}\) represents the implementation scale of coal-to-electricity. \(N_e\) describes the number of residents in node \(c\).

3.2. Technical constraint

From the perspective of safe and stable operation of power grid, the technical constraint conditions are proposed, that is the power flow should meet the transmission capacity demands of transformers, lines, and other equipment, and operate normally in the N-1 mode.

(1) Normal operation mode
Under the normal operation mode, the power capacity needs to satisfy the power load needs of coal-to-electricity, while the output of each node and the transmission power of each operating line meet the relevant constraints.

\[
\begin{align*}
S_i^T P + G &= L_0 + L_n + L_c \\
p_{ij} - b_{ij}^{ks} (n_i^0 + n_{ij} + n_{ij}^{ks}) (\theta_i - \theta_j) &= 0 \\
p_{ij} &\leq (n_i^0 + n_{ij} + n_{ij}^{ks}) p_{ij,max} \\
g_i, i &\leq g_{i,max} \\
0 &\leq n_{ij} \leq n_{ij,max} \\
0 &\leq n_{ij}^{ks} \leq n_{ij,max} \\
i, j &\in \Omega \\
ks &\in V
\end{align*}
\]

(8)

Where \( S_i^T \) is the node line incidence matrix; \( P, G, L_0, L_n, L_c \) are the vectors for power flow of lines, power output of generators, present power loads, increased natural power load, predicted power load of coal-to-electricity; \( p_{ij} \) is the line flow between node \( i \) and node \( j \); \( b_{ij}^{ks} \) is the imaginary part of admittance matrix in DC power flow; \( n_i^0 \) is the number of existing lines between node \( i \) and node \( j \); \( n_{ij} \) is the number of original planned lines between node \( i \) and node \( j \) without considering newly constructed substations; \( n_{ij}^{ks} \) is the changes in the number of existing and original planned lines between node \( i \) and node \( j \) with newly constructed substations of mode \( ks \); \( \Omega \) is the set for power system nodes; \( V \) is the set for newly planned substations nodes.

When the capacity of each substation meets the load demand integrated with coal-to-electricity, there is no need to add new substations, and thus

\[
\begin{align*}
S_i^T - S_i^T \\
n_{ij}^{ks} &= 0 \\
0 &\leq l_{0,i} + l_{n,i} + l_{c,i} \leq l_{i,max}
\end{align*}
\]

(9)

Where, \( S_i^T \) is the current node line incidence matrix; \( l_{0,i}, l_{n,i} \) and \( l_{c,i} \) are the present power load, increased natural power load and predicted power load of coal-to-electricity for note \( i \); \( l_{i,max} \) is the maximum capacity that can be transformed into lower voltage for the substation at node \( i \).

(2) N-1 operation mode

It is similar in the N-1 operation mode that the power capacity needs to satisfy the power load needs of coal-to-electricity, while the output of each node and the transmission power of each operating line meet the relevant constraints.

\[
\begin{align*}
(S_m^{mn})^T P_m^{mn} + G_m^{mn} &= L_0 + L_n + L_c \\
p_{ij}^{mn} - b_{ij}^{ks} (n_i^0 + n_{ij} + n_{ij}^{ks} - 1) (\theta_i^{mn} - \theta_j^{mn}) &= 0, ij = mn \\
p_{ij}^{mn} &\leq (n_i^0 + n_{ij} + n_{ij}^{ks}) p_{ij,max,i,j} = mn \\
p_{ij}^{mn} - b_{ij}^{ks} (n_i^0 + n_{ij} + n_{ij}^{ks}) (\theta_i^{mn} - \theta_j^{mn}) &= 0, ij \neq mn \\
p_{ij}^{mn} &\leq (n_i^0 + n_{ij} + n_{ij}^{ks}) p_{ij,max,i,j} \neq mn
\end{align*}
\]

(10)

where \( mn \) represents the constraint condition in case of line breaking between node \( m \) and node \( n \).

Different from the traditional planning, this model considers the constraints of newly planned substations. The coal-to-electricity load is innovatively integrated into the mode calculated in (1).

(3) Implementation scale constraints
The regional total implementation scale of coal-to-electricity is the summary of implementation scale at each node, which is less than or equal to the number of residents in this node.

\[
N_{last} = \sum N_{last,e} \\
0 \leq N_{last,e} \leq N_e
\]  

(11)

3.3. Economic constraint

(1) Investment capacity constraint

To guarantee the implementation of coal-to-electricity, the investments of governments, enterprises and users should be within their investment capacity.

\[
0 \leq F_{bay}^{G} \leq F_{G,max} \\
0 \leq F_{bay}^{U} \leq F_{U,max} \\
0 \leq F_{bay}^{grid} \leq F_{grid,max}
\]

where \(F_{G,max}\), \(F_{U,max}\) and \(F_{grid,max}\) stand for the acceptable maximum investment for government, users and enterprises respectively; \(F_{bay}^{G}\), \(F_{bay}^{U}\) and \(F_{bay}^{grid}\) are the coal-to-electricity investments for government, users and enterprises and can be calculated as follows:

\[
F_{G} = N_{last}F_{user}^{C} + \sum w_{u}^{grid,u}F_{grid,u}^{V} + w_{grid}^{land}F_{land}^{grid} \\
F_{U} = N_{last}(F_{user}^{C} - F_{user}) \\
F_{grid}^{bay} = \sum (1 - w_{grid}^{land})F_{grid,u}^{V} + (1 - w_{grid}^{land})F_{land}^{grid}
\]

(13)

where \(F_{user}\) and \(F_{user}^{C}\) stand for the average investment for heating equipment purchase and housing insulation repairmen, and average subsidy for users per household; \(F_{u}^{grid,u}\) stands for the investment for enterprises at voltage \(u\); \(F_{grid}^{land}\) represents the investment for land acquisition and demolition; \(w_{grid}^{V}\) and \(w_{grid}^{land}\) stand for the subsidy percentage for power grid investment at each voltage level and subsidy for land acquisition and demolition.

(2) Investment of matching projects constraint

The investment for enterprises at each voltage grade is relevant to the technical constraints and is the investment summary of planned lines and substations at this voltage grade.

\[
F_{grid,u}^{V} = \sum n_{ij}L_{ij,u}^{V}C_{L} + \sum n_{ij}T_{ij,u}^{V}C_{T}
\]

(14)

Where, \(L_{ij,u}^{V}\) is the planned line length between node \(i\) and node \(j\); \(T_{ij,u}^{V}\) is the power capacity of planned substations under mode \(ks\); \(C_{L}\) is the average investment of line per kilometer; \(C_{T}\) is the average investment of substations per kVA.

3.4. Social constraint

According to the national policy in China, the investments of power enterprises will be split to the whole society via adding the sales electricity price. Therefore, the added electricity price should be within the range of social tolerance.

\[
P_{T} \leq P_{T,max}
\]

(15)

where \(P_{T,max}\) is the acceptable maximum electricity price; \(P_{NT}\) is the added electricity price (after-tax), which is a function of investment of enterprises, depreciation fee, operation and maintenance fee, loan interest and the allowable income and other factors, as detailed showed in [19].

\[
P_{T} = f(F_{grid}^{bay})
\]

(16)

4. Solving algorithm

The planning method of coal-to-electricity access distribution network based on multi factor adaptation includes current situation mapping, initialization, environmental benefit analysis, technical adaptability analysis, economic benefit analysis, evaluation, and decision-making, etc.
(1) Find out the current situation

We should collect the relevant information of users, enterprises, and governments in the coal-to-electricity area, including the user's coal-to-electricity mode, equipment power, quantity, power consumption characteristics, power supply capacity of regional power grid and relevant compensation policies of the government.

(2) Initialization

The initial transformation scale shall be set according to the implementation of coal-to-electricity conversion for all bulk coal users and central heating users in the area. Considering the need to meet the natural growth load, the projects under implementation, planned and planned are included in the project library before the implementation of coal-to-electricity. Initialization of coal-to-electricity supporting power grid transformation project is empty.

(3) Environmental benefit analysis

According to the statistical information on the average household sulfur dioxide, nitrogen oxide, smoke, and carbon dioxide emissions in the heating season, and according to the current implementation scale of coal-to-electricity conversion, the current environmental benefits of coal-to-electricity conversion are calculated and converted into pollution control costs according to the unit treatment costs.

(4) Technical adaptability analysis

Step 1: calculate the new load of replacing coal with electricity according to formula (1) and obtain the total load of each node of each system in combination with the natural growth load and the current grid load.

Step 2: consider the commissioning of coal-to-electricity supporting projects and natural growth load supporting projects and carry out power flow calculation of power grid.

Step 3: judge whether the line power flow and node load meet the constraints in combination with the line transmission capacity limit and substation capacity limit of each voltage level. If all constraints are met, skip to (5) economic benefit analysis. If the constraints are not met, plan the new project of the line or substation with this voltage level in combination with the load distribution, and perform the following steps.

Step 4: to ensure the power demand of coal-to-electricity load, judge whether the power grid construction capacity can ensure the operation of the current project. If it cannot be met, it is necessary to reduce the implementation scale of coal-to-electricity and jump to (3) environmental benefit analysis. If the demand is met, the project will be included in the construction and transformation project library of coal-to-electricity supporting power grid and skip to step 2 to recalculate the power flow.

(5) Economic benefit analysis

Step 6: calculate the total investment cost of coal-to-electricity supporting project according to the construction length, substation capacity and typical project cost.

Step 7: calculate the coal-to-electricity investment of the government and users according to the subsidy policy and the type of coal-to-electricity equipment. The diversion electricity price is calculated according to the supporting power grid investment, enterprise equipment depreciation, interest rate and other financial data.

Step 8: judge whether the investment capacity of the government, enterprises and users meets the needs of coal-to-electricity construction according to the calculated diversion electricity price and investment; Judge whether the diversion price level can be accepted by the society. If not, it is necessary to reduce the implementation scale of coal-to-electricity conversion and jump to (3) environmental benefit analysis.

(6) Evaluation decision

Repeat the above steps until the optimal coal-to-electricity implementation scale and power grid project coordinated by environment, technology and economy are determined. Then, calculate the enterprise diversion electricity price, investment payback period and reduced pollutant emission, and evaluate the implementation benefits of coal-to-electricity from the three aspects of government, enterprises, and society as the decision-making basis for the implementation of coal-to-electricity.
5. Case study
The above model has been applied in Hebei province. The planning period is 2017~2020 and the proposed model are analyzed with different electric heating modes, shown as follows.
Case 1: Power grid without coal-to-electricity.
Case 2: Power grid with coal-to-electricity of distributed heat storage electric heaters.
Case 3: Power grid with coal-to-electricity of air source heat pumps.
Case 4: Power grid with coal-to-electricity of distributed heat storage electric boilers.

5.1. Basic information
There are 2404 public utilities and 1.9 million households with scattered coal users in the case study region. The substations of 500kV, 220kV and 110kV are 21, 177, 564; and the transformer capacity are 4.5, 6.35, 46.89 million kVA in this region. The substations of 220kV are divided into six sub-regions and the current maximum power load in the total region is 34.57 million kW in summer, and the maximum load reduces 2 million kW in winter. It is estimated that the traditional power load will increase 10 million kW during the power planning period.

In this region, the coal-to-electricity work is demanded to finish before November 15th of 2020. During this period, the original planned distribution of 500kV, 220kV and 110kV are 7, 49, 139; and the transformer capacity are 11.75, 16.38, 12.78 million kVA in this region. The planned investment of 10kV and below is 14.6 billion Yuan.

5.2. Load forecasting with coal-to-electricity
If coal-to-electricity is implemented by all residents in the region, the power load integrated with coal-to-electricity is expected to reach 48.01, 47.45 and 53.54 million kW respectively as shown in Fig.1. The newly added power load of coal-to-electricity and the maximum power load differ widely under different electric heating modes. Thereafter, the employed electric heating modes and the implemented scale of coal-to-electricity needs to be scientifically determined.

5.3. Smart grid planning with coal-to-electricity
(1) Taking environmental benefit as optimal
If \( \alpha_1 \ll \alpha_2 \), the objective function focuses on environmental benefits, and then power grid planning scheme can be obtained. In this model, coal-to-electricity is implemented by all residents of 1.9 million households. The specific construction scale is shown in Fig.2.

Only considering the environmental benefits, the number of substations needed to be built is larger than that of without coal-to-electricity in the same region. For example, there are 16, 77 and 338 substations for 500kV, 220kV and 110kV in Case 4, which are far more than 7, 49 and 139 substations of Case 1. The substations needed to be built are 2.2 times of the construction scale without coal-to-electricity and are far beyond the power grid construction capacity in a certain period. Therefore, the
implementation scale of coal-to-electricity should consider the construction capacity of enterprises while considering the environmental benefits.

Fig. 2 Construction scale of different types of coal-to-electricity

(2) Taking economic benefit as optimal

If $\alpha_1 \gg \alpha_2$, the objective function focuses on the investment cost. As the regional power load at daytime is higher than the nocturnal load, the acceptable capacity at daytime is lower than that at night. Meanwhile, the electric heating modes should also be considered. The heating equipment of distributed heat storage electric heaters and distributed heat storage electric boilers usually start operating when the power load is running low (20:00~8:00), and thus the newly added power load of coal-to-electricity is in the night. Thereafter, it is necessary to use the power supply ability at night to calculate the acceptable capacity. And the air source heat pump is the opposite. The specific construction scale is shown as follows.

Fig. 3 Acceptable scale of different types of coal-to-electricity

The acceptable capacity of coal-to-electricity is relevant to the power load characteristics and the acceptable load difference between day and night. When the acceptable load is relatively small, the implementation scale of coal-to-electricity by Case 2 (distributed heat storage electric heaters) is relatively large, followed by Case 3 (air source heat pumps), and the number of Case 4 (thermal storage electric boilers) is minimal, as shown in Sub-region 1. However, with the increase of acceptable load and the decrease of load difference in the daytime and at night, the difference between the implementation scale of Case 2 and Case 3 is reduced, and it is even possible that the implementation scale of Case 3 is higher than that of Case 2, such as Sub-region 4. The region can accommodate 1.45, 1.17 and 0.79 million households to implement coal-to-electricity, which are all lower than the regional total number of 1.9 million households.
Table 2 The acceptable scale of different types of coal-to-electricity

| Sub-region | Daytime (thousands of kW) | Night (thousands of households) | Case 2 (thousands of households) | Case 3 (thousands of households) | Case 4 (thousands of households) |
|------------|--------------------------|--------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Sub-region 1 | 973                      | 1443.1                         | 375.8                            | 317.0                            | 205.0                            |
| Sub-region 2 | 258                      | 638.2                          | 166.2                            | 84.1                             | 90.7                             |
| Sub-region 3 | 425                      | 785.1                          | 204.5                            | 138.5                            | 111.5                            |
| Sub-region 4 | 1622                     | 1882.8                         | 490.3                            | 528.6                            | 267.4                            |
| Sub-region 5 | 128                      | 508.1                          | 132.3                            | 41.7                             | 72.2                             |
| Sub-region 6 | 184                      | 324.1                          | 84.4                             | 60.0                             | 46.0                             |
| Summary     | 3591                     | 5581.4                         | 1453.5                           | 1169.8                           | 792.8                            |

(3) Benefit analysis after coal-to-electricity

Taking multifactor adaptability as optimal, the optimal implementation scale of coal-to-electricity is usually the largest acceptable capacity of coal-to-electricity. Under this implementation scale, the investment cost is minimal and within their investment capacity and construction capacity. The investment cost of all participants after coal-to-electricity is analyzed by taking the least amount of implementation scale of 0.79 million households in the region as an example. As shown in Fig.4, the increased investment cost of Case 3 is least reaching 36.2 billion Yuan for power grid companies, followed by Case 2 reaching 37.1 billion Yuan, and Case 4 is most reaching 40.9 billion Yuan. For users, the adoption of air source heat pumps (Case 3) will greatly increase the heating cost reaching about 17 billion Yuan, which is 8.3 times that of the distributed heat storage electric heaters (Case 2). For governments, under the current subsidy policy (7400 Yuan/household), different types of heating modes are subsidized by 5.8 billion Yuan. However, it is necessary to increase the sales electricity price to dredge the power grid investment cost, which is about 3.21–4.04 cents/kWh, which increases the social cost. Therefore, it is recommended that the heating mode of distributed heat storage electric heaters is preferred to be adopted to balance the investment cost of users, enterprises, government and social cost.

Fig.4 Investment of different types of coal-to-electricity

Fig.5 Added sales electricity price of different types of coal-to-electricity
From the perspective of environmental protection, the reduction amount of burning coal is 1.99 million tons in every heating season. As the emission reductions for each ton of coal are 2.493 tons of carbon dioxide, 0.68 tons of dust, 0.075 tons of sulfur dioxide and 0.0375 tons of nitrogen oxides, the pollutant emissions are reduced that of 4.95 million tons of carbon dioxide, 1.35 million tons of dust, 150,000 tons of sulfur dioxide and 70,000 tons of nitrogen oxides, which bring obviously environmental benefits.

6. Conclusions
In this paper, a smart grid planning method with coal-to-electricity based on multifactor adaptability is proposed to consider the influence of coal-to-electricity. A power prediction method with coal-to-electricity is proposed and typical parameters for different types of heating modes are extracted based on historical operational data, which lays a foundation for the study on coal-to-electricity integrated power grid. Furthermore, a smart grid planning method with coal-to-electricity is introduced, considering the investment cost of each participant, the construction capacity of power grid, and the social acceptance degree of electricity pricing comprehensively. The proposed model is universal and practical and meets the needs of smart grid planning and engineering practice under the new situation in China, which provides references for the subsidy policy formulation and is conducive for government to implement coal-to-electricity.

The proposed model and calculation method mainly aims for residents and public enterprises. But the above model does not consider industrial electrical boilers, electrical kilns, and other types of coal-to-electricity. The key point for further research is how to comprehensively study the power load characteristics and influences of industrial type coal-to-electricity.

References
[1] Liu ZY (2015) Global energy internet., China Electric Power Press, Beijing China.
[2] Tong ZQ (2016) Related issues of electric energy replacement implementation in Hebei Southern Power Grid, North China Electric Power University, Jul. 2016.
[3] Liang XL, Lu WB, Zhou HM (2015) Alternative energy in the energy network. Smart Grid, 2015, 3(12): 1192-1196.
[4] Yuan XR, Wu L, Zhang J, et al (2015) Situation of energy substitution and economic analysis of electric heating in Tianjin. Power demand side management, 2015, 2(5):24-29.
[5] Craciun VS, Trifa V, Bojesen C, et al (2012) Air source heat pump a key role in the development of smart buildings in future energy systems: Low cost and flexible experimental setup for air source heat pumps. In: Proceedings of the 2012 International Conference and Exposition on Electrical and Power Engineering, Iasi, Romania, 25-27 Oct. 2012, 984-989.
[6] Lin KP, Zhang YP, Di HF, et al (2004) Thermal performance of underfloor electric heating system with shape-stabilized PCM plates. Journal of Tsinghua University(Science and Technology), 2004, 44(12):1618-1621.
[7] Han JL, Ma GZ, Hu SY, et al (2018) Analysis of electric heating load characteristics in south hebei power grid. In: Proceedings of the 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 22-23 Oct. 2018, 1094-1098.
[8] Chen H, Zhu J, Zhang B, et al (2017) A Novel combined forecasting method for short-term distributed electric heating power load. In: Proceedings of the 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 26-28 Nov. 2017, doi: 10.1109/EI2.2017.8245378.
[9] Ma LF, Long GB, Li XL, et al (2017) Research on influence of large-scale air-source heat pump start-up characteristics to power grid. In: Proceedings of the 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 26-28 Nov. 2017, doi: 10.1109/EI2.2017.8245377.
[11] Liu YR, Yang WH, Wang J, et al (2017) Load characteristic analysis of rural network before and after the coal-to-electricity project. Electrical Engineering, 2017, 18(4): 110-115.

[12] Shao H, ZHOU LM, Yuan JP, et al (2018) Analysis on impacts of domestic air source heat pumps to distribution networks in coal-to-electricity projects. In: Proceedings of the 6th Annual International Conference on Material Science and Engineering (IOP Conference Series: Materials Science and Engineering 397 (2018) 012001), 2018, 563-568.

[13] Weu JX, Ma ZB, Huang GS, et al (2016) Economic and environmental benefit from "electric power replacement" project in kiln production. North China Electric Power, 2016(3):66-70.

[14] Hou B, Zhang HY, Yu XJ, et al (2018) Research on comprehensive benefits evaluation of “Coal-to-Electricity” project based on combination weighting TOPSIS method. In: Proceedings of the 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 22-23 Oct. 2018, 1870-1875.

[15] Li ZW, Zhu WL, Sun PF, et al (2018) Study on power quality impacts of rural distribution network with large-scale heat pumps. In: Proceedings of the 2018 2nd International Conference on Power and Energy Engineering (ICPPEE 2018), Xiamen, China, 3-5 Sept, 2018, 1-7.

[16] Huang YF, Zhu YJ, Mu G, et al (2018) Assessment of adjustable capacity of household heating load based on temperature forecast. doi: 10.13335/j.1000-3673.pst.2018.0547.

[17] Zhang N, Lu X, Mcelroy MB, et al (2016) Reducing curtailment of wind electricity in China by employing electric boilers for heat and pumped hydro for energy storage. Applied Energy, 2016, 184:987-994.

[18] Zhao J (2016) Study on the capacity of central heating and electric heating based on thermal scheduling to consume wind power. North China Electric Power University, 2016

[19] An JK, Sun PF, Han JI, et al (2018) A power network planning method with coal-to-electricity considering technical and economical adaptability. In: Proceedings of the 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 22-23 Oct. 2018, 1110-1115.