Study on Planning Method of Distributed Electric Heating System at Rural Areas in Northern China Considering Demand-side Response and Heating Load Characteristics

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Abstract. Frequently, severe air pollution in Northern China was largely induced by coal-based energy consumption, especially bulk coal usage. The adoption of the distributed electric heating (DEH) system at rural areas in Northern China could dramatically reduce the total amount of coal consumption for heating purposes, which contributed to a reduction in air pollution and promoted structural adjustment and the technological advance of heat supply. Existing research primarily focused on lower the operation cost of DEH system under certain scenarios, lacking a systematic approach to total cost-benefit analysis. This paper discussed how to achieve minimum total heat supply system cost based on optimized planning method of DEH system considering demand-side response and heating load characteristics. We predicted the total scales of DEH system in Beijing-Tianjin-Hebei (BTH) region according to implementing plan of BTH’s clean heating with a comprehensive cost-benefit analysis. Taken heating load characteristics and demand-side response into consideration, we found that our proposed planning method of DEH system effectively reduced the construction cost of heat supply system with a small amount of heating demand loss. The future scale of DEH system application would be huge in BTH region and a case study in the appointed region confirmed the rationality of our proposed planning method.

Introduction

China’s coal-based energy consumption and relative high proportion of bulk coal usage caused frequent and severe air pollution. Bulk coal consumption, together with automobile emissions and adverse weather conditions shrouded Northern China in thick fog and haze during winter season. Limited heating budget, low heating demand density, poor building energy efficiency, and insufficient infrastructure coverage made inexpensive bulk coal powered heating system an unconscious selection for residents living in rural areas of Beijing-Tianjin-Hebei (BTH) region. In recent years, Beijing had introduced multiple policies promoting clean heating system adoption and energy consumption reformation, among which decentralized electric heating (DEH) system stood out due to its high practicality.

A deterministic optimal operation model, maximum comfort, operation strategy and robust optimization model of the minimum operating cost of the intelligent electric Heating network was proposed in [1]. In [2], a model for rural electrification in developing countries was constructed. An analysis method of electric energy substitution benefit was proposed in [3]. [4] presented the equivalent thermal parameters (ETP) model of electric heating equipment and the process of centralized load direct control and the algorithm to provide continuous load adjusting standby by using thermal energy storage load were presented in [5]. The power curve shaping of the thermal energy storage load was realized by load dispatch in [6]. In [7], a load dispatch model based on the
operating cost was constructed by using the thermal energy storage to respond to real-time pricing. In [8], a two-stage stochastic mixed integer linear programming model was utilized to determine the optimal scheduling of combined heat and power with electric and thermal storage systems considering industrial customers inter-zonal exchanges. [9] presented an innovative method for modeling energy hubs based on energy flow between its constituent elements, and the objective was to fulfill daily cooling, heating and electric demands of a hypothetical building with the maximum profit. In paper [10], a method of multi-model switching based predictive functional control was proposed and applied to the temperature control system of an electric heating furnace. In [11], an optimization model with the objective of minimizing the cost difference between ground source heat pump and water chilling unit with heat storage electric boiler was proposed to directly solve their boundary conditions. In [12], the energy efficiency ratio of high efficient ground source heat pump system was predicted by Artificial Neural Network (ANN), and the best operation mode of ground source heat pump system with energy saving and soil temperature field recovery was studied in [13]. Paper [14] proposed an optimization model for replacing coal with electricity, using the goal of minimal total annual cost and the constraints of coal consumption.

Most above mentioned research focused on how to reduce the operating cost of DEH system under certain scenario, failed to take the rural heating load growth and operating characteristics of BTH region into consideration. However, our research discussed how to achieve minimum total clean heat supply system cost based on optimized planning method of DEH system considering demand-side response and heating load characteristics. We also predicted the future DEH system capacity of BTH region and calculated its comprehensive benefits.

Methodology

To minimize the construction and operation cost of DEH system, we constructed the objective function of optimizing the layout of DEH system in BTH region as follows:

$$\min c = c_s(1 - y_s) f_s + c_t(1 - y_t) f_t + \sum_{t=1}^{T} [g_{e} + o_{t} + m_{t} f_{t}]$$  \hspace{1cm} (1)

where:
- \(c_s\) and \(c_t\) are the cost of DEH system investment and its electric distribution network investment;
- \(y_s\) and \(y_t\) are the salvage value ratio of DEH system and its electric distribution network investment at the end of planning period;
- \(f_s\), \(f_t\), \(f_{t}'\) are the uniform annual value coefficient of DEH system investment, its electric distribution network investment, and year \(t\) operation expenditure;
- \(T\) is the planning period;
- \(o_t\), \(o_{t}'\), \(m_{t}\) are year \(t\) DEH system operation cost, its electric distribution network operation cost, and demand-side response cost.

In which, DEH system investment cost:

$$c_s = w_s \cdot s \cdot p_e$$  \hspace{1cm} (2)

where:
- \(w_s\) is the capacity of DEH for unit heating area;
- \(s\) is the effective heating area;
- \(p_e\) is the procurement and installation cost for unit capacity of DEH equipment (such as electric radiator, carbon crystal floor heating, electric heating film, heating cable, air source heating pump, etc.).

In which, corresponding electric distribution network investment is:

$$c_t = w_{max} \cdot p_l$$  \hspace{1cm} (3)

where:
- \(w_{max}\) is the capacity of corresponding electric distribution network;
- \(p_l\) is the construction cost for unit capacity of corresponding electric distribution network.

The year \(t\) DEH system total operation cost at different scenarios was:
\[
\sigma_{\text{et}} = \sum_{i=1}^{N} (w_i \cdot h_i) \cdot s \cdot p_e
\]

\( w_i, h_i \) were heating demand and its duration for unit heating area in scenario \( i \); \( p_e \) was corresponding electricity price for heating; \( N \) were the total scenario numbers.

The year \( t \) electric distribution network total operation cost at different scenarios was:

\[
\sigma_{\text{et}} = w_{\text{max}} \cdot v + \sum_{i=1}^{N} (w_i \cdot h_i \cdot \eta_i) \cdot s \cdot p_e
\]

\( v, w_i \) were operation cost and electric energy loss rate for unit capacity of electric distribution network.

The year \( t \) demand-side response total cost at different scenarios was:

\[
m_{\text{ds}} = \sum_{i=1}^{n} [(w_i \cdot \text{wds}) \cdot h_i] \cdot s \cdot p_{\text{ds}}
\]

\( p_{\text{ds}} \) was the demand-side response electricity price;

\( n \) were the scenario numbers when heating capacity exceeded that of electric distribution network.

For the central township or residential area, the main constraint condition of DEH system construction were the restriction of distribution network corridor, DEH equipment selection constraints (for example, carbon crystal floor heating was applicable to existing buildings, electric heating film and heating cable were suitable for new buildings, air source heat pump operating efficiency was low under low temperature), and capacity constraints of existing electric distribution network.

Case Study

We conducted our case study at a village in Hebei Province with 20 households and a total heating area of 3,200 m². The demographic profile showed that the permanent resident is 28 during weekday, mostly elderly and children. During the weekend, the total population was 60 with some transient population, and the population peaked at 90 during the Spring Festival. The daily electricity heating price was 0.3 RMB/kWh during the heating season from Nov 15th to Mar 15th. And the off-peak heating price was 0.1 RMB/kWh from 21:00 to 6:00. According to local Demand-Side Response Electricity Financial Incentive Policy, any household actively reduced the electricity usage during peak time through demand-side response, would be rewarded based on the duration (24 hours, 4 hours, 0.5 hours) at 80 RMB/kW, 100 RMB/kW, 120 RMB/kW. We took the maximum heating demand at 70W/m² with heating load rate distribution as Table 1.

<table>
<thead>
<tr>
<th>Heating Load Rate</th>
<th>&lt;0.3</th>
<th>[0.3, 0.4)</th>
<th>[0.4, 0.5)</th>
<th>[0.5, 0.6)</th>
<th>[0.6, 0.7)</th>
<th>[0.7, 0.8)</th>
<th>[0.8, 0.9)</th>
<th>[0.9, 1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possibility</td>
<td>0.11</td>
<td>0.12</td>
<td>0.13</td>
<td>0.15</td>
<td>0.18</td>
<td>0.14</td>
<td>0.12</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Refer to Guide for planning and design standard for distribution network (Q/GDW 1738-2012), we took domestic electrification and distribution network reserve capacity into consideration. If we conducted the calculation with peak heating load without demand-side response (Solution One), the village needed to install two 315kVA transformers with 224kW heating equipment capacity.

In Solution Two, if the percentage of demand-side response management reduced the peak load at 10%, 10%, and 20% with duration of 24 hours, 4 hours, and 0.5 hours respectively, the village only needed to install two 160kVA transformers with 180kW heating equipment capacity based on the optimization results from simulation software MATLAB.

The comparative analysis showed that Solution Two reduced 17.6k RMB heating equipment procurement cost and 62k RMB transformers investment, with a total saving of 79.6k RMB compared to Solution One.
Based on heating supply operation simulation in typical scenario and its possibility, the result showed that, Solution One needed 187.7 MWh electric energy to meet heating demand for the entire heating season.

Solution Two reimbursed 3407.2 RMB when 182.1 MWh electricity was consumed for heating purpose. If the IRR is 8%, then Solution Two was much more economical than Solution One.

The household survey organized by electric companies indicated that coal-to-electricity plan would expand to 5.3m household in BTH region during year 2018-2020. When the plan was fully executed, additional 41.57 TWh would be consumed during a heating season and the demand-side response related electricity would rise to 1.21 TWh. According to current Demand-Side Response Electricity Financial Incentive Policy of different regions, we could reserve 11.19b RMB investment in electric distribution network with only 486m RMB compensation to residents. Based on current typical emission level of heating-purpose bulk coal burning, the coal-to-electricity could reduce PM 2.5 emission about 5500 tons.

Summary
Our research discussed how to achieve minimum total clean heat supply system cost based on optimized planning method of DEH system in Northern China considering demand-side response and heating load characteristics. The comparison analysis confirmed the rationality of the proposed method. According to the implementing plan of BTH region clean heating, we predicted the developing scale of DEH system and calculated the comprehensive benefit of the DEH system adoption. Considering demand-side response and heading load characteristics, the planning method could dramatically decrease the total investment of clean heating system with a small amount of heating demand loss. DEH system would be extensively used in BTH region in the foreseeable future, therefore, the stakeholders should vigorously promote Demand-Side Response Electricity Financial Incentive Policy to reduce the emission of heating-purpose bulk coal burning.

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References


