Research on the planning and optimization model of regional integrated energy supply system

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Abstract. Integrated energy system is an important development trend of energy system in the future. As an important form of integrated energy system in local areas, regional integrated energy system has the complex characteristics of multi-energy supply. Therefore, this paper studied the planning model of regional integrated energy supply system. Firstly, the planning index system of regional integrated energy supply system was constructed. Secondly, based on the planning index system, considering the multiple constraints of power grid and heat grid, a regional energy supply system planning model was established to realize the minimum comprehensive cost of investment, operation, economy and environment. Finally, the example shows that the proposed planning model has better economic performance than the traditional planning scheme.

1. Introduction

As an important development trend of future energy system, integrated energy system is the technical support and implementation of multi-energy coordinated optimization. Regional integrated energy supply system (RIESS) is an important form of integrated energy system in local areas. The complex characteristics of multi-energy supply make the system planning and operation more complicated, and the traditional planning method cannot ensure an economic and efficient planning scheme. Therefore, it is an urgent problem to propose a better supply planning method for RIESS.

At present, the relevant research on the supply planning of RIESS is still in the early stage. The literature [1-2] makes a preliminary study on the planning and analysis technology of multi-energy system and regional integrated energy system, and puts forward a relatively complete theoretical framework. A microgrid planning method considering environmental benefits is proposed in literature [3]. Literature [4] proposed a dynamic planning scheme for micro grid containing distributed energy. Literature [5] is similar to the research idea of this paper, but the main research of this paper is the planning of electro-pneumatic system. To sum up, from the current research content at home and abroad, we can find that the research on multi-energy coordinated planning in regional integrated energy system is relatively limited.
In view of the above problems, this paper studies the planning model of RIESS. Firstly, a planning index system of RIESS is established. Secondly, the planning model of energy supply network is proposed, with the total cost minimum to be the objective function and the system load and system security to be the main constraints. Finally, the planning and analysis of energy supply network is carried out in the suburban city in north China. The conclusion shows that the planning model proposed in this paper is feasible, and has a better economic performance than the traditional planning scheme.

2. Regional integrated energy supply system

Within a certain region, the energy supply required by users is met by various energy producers in the region, and there is also a supply and demand relationship between energy producers. As the junction of energy flow, users and energy producers interconnect through a variety of energy transmission channels, including power grid and heat grid, forming a multi-level composite system, namely RIESS.

At present, users may need various forms of energy supply, including power supply and heat supply. However, with the deepening of the substitution of electric energy in China, the energy supply network will turn to take electric energy as the core and transfer most of the primary energy into electric energy to users. In terms of specific energy services, there may be various types of integrated energy services and more complex energy network coupling in the future [6]. Considering the practical significance, this model is based on the current situation in China, and focuses on the production and supply of electric energy and heat energy. The network coupling is mainly realized through the combined generation of heat and power and the electric heat transfer facility.

3. Planning index system of RIESS

In this paper, construction of regional integrated index system of energy supply system planning includes prospective index and binding index, the main idea is to "projects three low" integrated energy system of target decomposition, "projects were targets include the improvement of energy efficiency integrated system, the improvement of reliability of system running, the user can use the cost reduction, systems to cutting carbon emissions and other pollutants. In terms of supply planning, the system energy efficiency, system cost, system pollutant emission and total energy consumption of the system are decomposed into four first-level indicators and 15 second-level indicators, as shown in Table 1.

| primary index                  | secondary index                      | remarks     |
|-------------------------------|--------------------------------------|-------------|
| system energy efficiency       | primary energy ratio                 | Prospective index |
|                               | coefficient of energy conversion     | Prospective index |
|                               | efficiency                           | Prospective index |
|                               | energy consumption per capita         | binding index |
| system cost                    | investment cost                      | binding index |
|                               | operation cost                       | Prospective index |
|                               | investment income                    | Prospective index |
|                               | annual emission of smoke             | binding index |
|                               | annual emission of SO₂               | binding index |
| system pollutant emission      | annual emission of CO₂               | binding index |
|                               | annual emission of NOₓ               | binding index |
|                               | the proportion of cleaning energy    | binding index |
| system total energy consumption| consumption                         | binding index |
|                               | usage rate of renewable energy       | binding index |
|                               | Annual oil consumption               | binding index |
|                               | Annual coal consumption              | binding index |
|                               | Annual gas consumption               | binding index |
4. Regional integrated energy supply system planning model

4.1. Description of basic problem

The problems and main conditions to be solved by this model can be qualitatively described as the following three elements: first, in a given region, there are given series of users and their corresponding demands; Secondly, the optimal calculation of the model is limited by the boundary conditions of power grid and heating specification. Thirdly, based on the above two aspects, a planning scheme is proposed to meet user needs, meet technical constraints and have the lowest comprehensive cost. One of the characteristics of RIESS is to consider the coupling and complementary relationship between multiple energy flows. In this paper, the substitution effect of electric load on thermal load is mainly considered, that is, electric heating, a form of energy conversion, is taken into account in the model design to improve the overall energy efficiency of the system.

4.2. Model construction

In the optimization decision of RIESS planning, the idea of model construction in this paper is to minimize the total cost of construction and operation under the constraints of meeting the demand and energy network security requirements.

The construction cost mainly includes three aspects, namely, the construction cost of the energy supply unit, the capacity expansion cost of the energy supply system and the construction cost of the energy supply system, as shown in formula (1).

$$C_1 = \sum_{i=1}^{n} \alpha_i U_i + \sum_{j=1}^{m} \beta_j N_j$$

In the formula, $n$ is the number of generator sets to be built; $\alpha_i$ is the unit capacity construction cost of type $i$ generator set; $U_i$ is the capacity of type $i$ generator set; $m$ is the number of generator sets to be built; $\beta_j$ is the unit capacity construction cost of type $i$ heating units; $N_j$ is the capacity of type $j$ heating unit. The capacity-expand cost of power supply system mainly refers to the construction or capacity-expand cost of substation. The cost of substation construction is expressed in formula (2).

$$C_2 = \chi S$$

In the formula, $\chi$ is the unit capacity construction cost of the substation; $S$ is the substation capacity. Energy transmission cost mainly includes the cost of laying power grid and heating network, as shown in formula (3).

$$C_3 = \sum_{i=1}^{n} \gamma_i D_i$$

In the formula, $n$ represents the number of energy supply lines to be built; $\gamma_i$ represents the unit construction cost of the type $i$ power supply circuit; $D_i$ represents the length of the energy supply circuit of type $i$. To sum up, the construction cost can be expressed by formula (4).

$$C = C_1 + C_2 + C_3$$

Operating costs mainly include power/heating costs and environmental costs. The generation/heating costs are shown in formula (5).

$$O_i = \sum_{t=1}^{T} \sum_{j=1}^{m} p_{i,t} \eta_{i,t} + \sum_{j=1}^{m} \sum_{t=1}^{T} q_{j,t} \gamma_{j,t}$$

In the formula, $n$ and $m$ are respectively the number of power supply units and heating units; $p$ and $q$ are the unit power supply cost and heating cost respectively; $P_{i,t}$ and $Q_{j,t}$ are respectively the output of the power supply unit $i$ and the heating unit $j$ at time $t$; $\eta_i$ and $\gamma_j$ are variables of $(0,1)$, representing the starting and stopping state of the unit. Where, the combined heat and power generation unit is tested as the superposition of heating unit and power supply unit, and its variables $(0,1)$ are given separately. System environmental cost is another operating objective function, which is reflected in the operating cost in the form of pollutant discharge fee or environmental management fee. At present, the emissions mainly considered include CO2, SO2, NOx and soot. The environmental cost of CO2 is converted by
referring to the carbon tax of foreign countries. To sum up, the environmental cost is shown in formula (6).

\[ O_2 = \sum_{s \in S} \sum_{g \in G} \phi_g E_{s,g} \mu_s \]  

(6)

In the formula, \( s \in S \) = \{all emission sources in the scheme\}; \( g \in G \) = \{CO\(_2\), SO\(_2\), NO\(_x\) and smoke\}; \( \phi_g \) is the unit environmental cost of type \( g \) emissions; \( E_{s,g} \) is the emission of emissions from source \( s \) and source \( g \). \( \mu_s \) is the variable \((0,1)\), representing the start and stop state of the unit. To sum up, the operating cost can be expressed by equation (7).

\[ O = O_1 + O_2 \]  

(7)

Thus, the objective function with the minimum total cost is shown in formula (8).

\[ \min \{C + \sum_{i=1}^{T} \left[ \frac{1}{(1+k)^1} \cdot 5\% \right] \cdot C \times \frac{1}{(1+k)^1} \} \]  

(8)

In the formula, the first item is the construction cost of fixed assets, and the present value is directly taken; The second item is the operating cost of the system, which needs to be accumulated after discounting the operating cost of each year in the planning period \( T \), and \( k \) is the discount rate. The third item is the residual value of fixed assets at the end of the planning period, which needs to be converted into the present value and recovered. Therefore, it needs to be deducted from the cost, and the residual value rate of fixed assets is 5%.

Constraints mainly include the following six aspects:

1) node voltage constraint

\[ V_{\min} \leq V_{k,t} \leq V_{\max} \]  

(9)

In the formula, \( V_{\min} \) and \( V_{\max} \) are the lower limit and upper limit of node voltage respectively; \( V_{k,t} \) represents the real-time voltage of node \( k \).

2) branch capacity constraint: the current on each circuit shall not be higher than the upper limit of branch capacity. At present, only branch capacity constraints of power network are considered and branch capacity constraints of heating network are ignored. The constraint relationship is expressed in formula (10).

\[ I_l \leq I_{l,\max} \quad l = 1, 2, \ldots, L \]  

(10)

In the formula: \( I_l \) is the real-time current on line \( l \); \( I_{l,\max} \) is the upper power limit of line \( l \); \( L \) is the total number of branches.

3) considering the thermal load constraint of nodes with complementary energy: in this paper, the energy flow in the heating network is simplified, and the thermal load constraint requires that the remaining heat when the heat flow flows through any node is not less than 10% of the rated load. In this paper, it is required that the total amount of all thermal load nodes lower than the load requirement is not greater than the converted value of the part of the real-time power supply unit whose output is greater than the electrical load, which is expressed by formula (11).

\[ \sum_{i,j} \Delta R_{i,j} \leq \sum_{i=1}^{n} P_{i,j} - \sum_{i,j} U_{i,j} I_{i,j} \]  

(11)

In the formula, \( \Delta R_{i,j} \) is the values at time \( t \) of node \( k \) that the energy obtained by the heating network is lower than that required by the load.

4) thermoelectric coupling constraint: first, the state point of thermal and electric output of cogeneration unit is limited by the boundary of the unit; Second, as required by the state on cogeneration units, the average annual thermo-electric ratio of each unit must be greater than the reference value, as shown in formula (12).

\[ \frac{\sum_{i,j} Q_{i,j}}{\sum_{i,j} P_{i,j}} \geq \tau \]  

(12)

In the formula, \( \tau \) is the average annual thermoelectric ratio of a cogeneration unit, which is usually 50%.
5) constraint of output power range: the power supply unit must meet the minimum load rate requirement, and it cannot exceed the upper limit of unit capacity. The constraint relationship is expressed in formula (13).

\[
\begin{align*}
&wU_i \leq P_{i,t} \leq U_i \\
&rn_j \leq Q_{j,t} \leq N_j
\end{align*}
\]  

(13)

In the formula, \(P_{i,t}\) is the output of the power supply unit \(i\) at time \(t\); \(U_i\) is the power supply capacity of unit \(i\); \(w\) is the minimum power supply load rate of the unit; \(Q_{j,t}\) is the output of the heating unit \(j\) at time \(t\); \(N_j\) is the heating capacity of unit \(j\); \(r\) is the minimum heating load rate of the unit.

6) substation capacity constraint: the substation capacity should be greater than the sum of the real-time unit output, and meet the reliability requirements, should have more than 10% reserve capacity. The constraint relationship is expressed in formula (14).

\[
S \geq 110\% \times \sum_{i=1}^{r} P_i \eta_i
\]  

(14)

7) unit climbing constraint: there is a limit to the upward and downward change rate of the output power of coal and gas units in unit time, which will affect the system's response ability to load changes. The constraint relationship is expressed in formula (15).

\[
\begin{align*}
&P_{i,t} = P_{i,(t-1)} \leq P_{i,asc} \\
&P_{i,(t-1)} - P_{i,t} \leq P_{i,dsc}
\end{align*}
\]  

(15)

In the formula, \(P_{i,asc}\) and \(P_{i,dsc}\) are respectively the maximum rise and fall values of unit output in a fixed period.

5. Case study

5.1. Parameters

The regional energy planning of a suburb in north China is selected as a case for example analysis. According to the average thermoelectric load in this region, the time-by-time unit curve of thermal and electric load is shown in figure 1. The initial grid structure of the region is shown in figure 2. The solid line part in the figure is the existing power grid, and the dotted line part is the line allowed to be built in the power grid control regulations. There is no buried heating network in the area, and it is assumed that all parts of the figure allow buried heating network. A, B and C represent the site of the newly added energy supply facilities. A 110kV substation and a 20MVA main transformer has been built at location A and it is connected to the urban power grid. There are no facilities at location B and location C. The number in the figure is the load bus. The example assumes that the hourly electric and thermal load curves of each load point are consistent with figure 1. The hourly load of each bus can be obtained by setting different load peaks. In addition, this example requires that the planning results must meet the growth of thermal and electric load during the 10-year planning period.

![Figure 1. Hour-traced power and heat load curve of a suburb in North China (per unit value)](image)

The peak value and growth rate of heat and electric load at each bus are shown in Table 2. The cost data related to the calculation example are shown in Table 3. The seasonal price of electricity purchased from the main network is shown in Table 4. The pollutant emission level of various units refers to the
literature [7], and the limit of thermoelectric characteristics and the minimum load rate of power supply and heating for cogeneration units refers to the literature [8]. Other data are shown in Table 5.

![Figure 2. Structure of initial grid in planning area.](image)

Table 2. Three scheme comparing.

| load bus | peak value of heat load /MW | peak value for electric load /MW | average annual growth rate of heat/electric load (%) |
|----------|-----------------------------|---------------------------------|-----------------------------------------------|
| 1        | 1.2                         | 1.1                             | 3                                             |
| 2        | 1.1                         | 1.2                             | 4                                             |
| 3        | 1.3                         | 1.1                             | 2.5                                           |
| 4        | 1.3                         | 1.1                             | 3                                             |
| 5        | 1.2                         | 1.2                             | 4                                             |
| 6        | 1.7                         | 1.8                             | 3.3                                           |
| 7        | 2.1                         | 1.6                             | 2.7                                           |
| 8        | 1.9                         | 1.3                             | 2.5                                           |
| 9        | 2.2                         | 2.0                             | 3.8                                           |
| 10       | 1.7                         | 1.3                             | 4.1                                           |
| 11       | 0.9                         | 2.7                             | 4.7                                           |
| 12       | 1.3                         | 1.5                             | 5.2                                           |
| 13       | 1.9                         | 1.7                             | 1.9                                           |

Table 3. Construction & operation cost of energy service supply network

| Project                                      | Cost                        | Project                                      | Cost                        |
|----------------------------------------------|------------------------------|----------------------------------------------|------------------------------|
| coal-fired thermoelectric unit               | 4.3 million ¥/MW            | Environment cost of CO₂                      | 0.01 ¥/kg                  |
| gas-fired thermoelectric unit                | 5.1 million ¥/MW            | Environment cost of SO₂                      | 0.42 ¥/kg                  |
| Cost of the expansion of the substation      | 0.23 million ¥/MVA          | Environment cost of NOₓ                      | 0.63 ¥/kg                  |
| capacity                                     |                              | Environment cost of Smoke                    | 0.15 ¥/kg                  |
| Cost of grid laying                          | 2.517 million ¥/km          | Cost of thermal generation                   | 0.22 ¥/kWh                 |
| Cost of heating Network laying               | 0.21 million ¥/km           | Cost of gas power generation                 | 0.75 ¥/kWh                 |
| Cost of heating                              | 50.8 ¥/GJ                   |                                              |                              |
Table 4. Seasonal price that the main suburbs buying electricity from the main grid

| Month | Electric price /(¥/kWh) | Month | Electric price /(¥/kWh) |
|-------|-------------------------|-------|-------------------------|
| Jan   | 0.7                     | Jul   | 0.88                    |
| Feb   | 0.7                     | Aug   | 0.88                    |
| Mar   | 0.55                    | Sep   | 0.75                    |
| Apr   | 0.55                    | Oct   | 0.55                    |
| May   | 0.55                    | Nov   | 0.55                    |
| Jun   | 0.75                    | Dec   | 0.7                     |

Table 5. Other data used in case study

| Parameter                        | Value    | Parameter                        | Value    |
|----------------------------------|----------|----------------------------------|----------|
| Ramp rate of gas generator unit  | 20%/min  | Ramp rate of coal-fired unit     | 10%/min  |
| Electrical heating efficiency    | 90%      | Branch capacity                  | 250A     |
| The upper limit of node voltage  | 311.1V   | The lower limit node voltage     | 155.6V   |

5.2. Results and analysis

Three comparison schemes are specifically designed for the calculation example, as shown below.

Plan 1: Pure main network power supply. According to the principle of radiant power supply, press A-1-2-3-4; A-1-2-6; A-5-7-9-10; A-8; A-11-12-13 for grid planning. The power demand is completely satisfied by the main network, and the thermal demand is satisfied by the load point using electric heating equipment. The scheme is used as the benchmark scheme.

Plan 2: Pure coal cogeneration. The power network planning is the same as the first scheme, and the heating network planning is consistent with the power grid line; The coal-fired thermal power station at point A meets the thermal power load in the planning area. This scheme is a representative planning scheme under an extensive planning idea commonly used in the past [10].

Plan 3: The planning scheme proposed by the model built in this paper. Substitute the relevant parameters in the example into the model. Programming by MATLAB, and Gaussian Quantum-behaved PSO (G – QPSO) are applied to get the answer. Let the termination condition be that the number of iterations reaches 100. Run the program ten times, Take the optimal output of ten times as the optimization result, as shown below.

1) Energy service network planning is shown in figure 3

2) The unit and substation capacity planning of each site is as follows.

Location A: build A new 8MW gas-fired thermoelectric unit; No expansion of transformer;
Location B: new 12MW coal-fired thermal power unit; 110kV transformer with a newly built capacity of 12MW;

Figure 3. Planning of energy supply service grid.
Location C: new 7MW gas-fired thermoelectric unit; Newly built 110kV transformer with a capacity of 7MW.

Table 6 shows the economic comparison of each scheme.

| Plan   | Initial investment /million yuan | Average annual value of the planning period /million yuan | Expensive present value /million yuan |
|--------|---------------------------------|----------------------------------------------------------|--------------------------------------|
| Plan 1 | 42.79                           | 14.8136                                                  | 1376.17                              |
| Plan 2 | 162.46                          | 12.4921                                                  | 1287.21                              |
| Plan 3 | 208.39                          | 9.6013                                                   | 1072.01                              |

It can be seen from table 6 that after financial discount, the planning method proposed in this paper can make the cost of meeting users' demand for heat and electricity in this area decrease obviously. Compared with the benchmark scheme (plan 1), it is 22% lower. Compared with the common plan (plan 2), it decreases 16.71%. In addition, the calculation process of plan 1 and plan 2 is mainly based on estimation without considering constraints, so the cost will be higher in practical application. Therefore, it can be considered that the model and algorithm proposed in this paper can effectively plan the regional energy supply network, and can significantly reduce the planning cost while meeting the system constraints compared with the existing planning.

6. Conclusion

In this paper, a regional energy supply system planning and optimization model considering coal power supply, gas power supply and heat power supply is established. Through the analysis of calculation examples, it is proved that the model proposed in this paper can satisfy the regional thermal and electric loads and significantly reduce the total cost of the system by considering the coupling and substitution relationship between the thermal and electric loads. It is noted that the planning model in this paper only considers the coordinated planning of CCHPs of coal and gas as well as thermal load and electric load, which is a relatively simplified system form. More and deeper researches are needed in the future.

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