Multi-objective Optimal Allocation of Regional Integrated Energy System

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Abstract. The integrated energy system (IES) can promote complementarity and efficient use of different energy by coupling with multiple energy resources, such as electricity, heat and cold. An optimal capacity configuration method of regional integrated energy system considering electricity and heat transaction is proposed in this paper, including the cost of energy interaction between IES and power/heating networks. The optimization objective is a multi-objective function considering the economy, environmental protection, reliability of the system and interacting power fluctuation factors. Based on the energy hub, this paper optimizes the capacity of every energy supply equipment within the region and the genetic algorithm is adopted combining with system economic operation on typical days. Finally, the proposed method is verified by an example of a certain park. The results show that the method can effectively reduce the cost of system and reasonably avoid the limitations caused by the single decision factor in the system planning stage, which provides a reference for the planning and design of actual IESs.

Introduction

With the rapid development of social economy, the problems of energy shortage and environmental pollution have become increasingly prominent. In traditional energy systems, energy subsystems such as electricity, heat, cold systems are independent of each other in the design, planning, operation and control process. The complementarity among different energy cannot be made full use, and the traditional energy systems cannot realize the overall harmonization, coordination and optimization of multi-energy equipment, causing low energy utilization rate and reduction of safety and reliability. In this background, integrated energy system (IES) arises through coupling multiple energy such as natural gas, electricity, hot, cold, etc., to realize the efficient utilization of renewable energy and satisfy the multiple energy requirement of users [1-2].

At present, there are some researches in optimal configuration of regional integrated energy system. In [3], a three-stage collaborative overall optimization design method for combined cooling heating and power(CCHP) system was proposed. The better economy and environmental-friendliness of CCHP system designed by this optimal method were proved by comparing two CCHP systems designed by “following the electric load (FEL)” “principle and allowing the thermal load (FTL)” principle. A capacity configuration model for stand-alone microgrid robust optimization based on Benders decomposition method to solve the problem by interactive iteration was established in [4]. An optimization planning framework of energy hub was presented to solve the capacity configuration problems of multi-energy system in [5]. The literatures above lack comprehensive consideration on economy, environmental protection, reliability and interaction of electric and heat energy, ignoring energy transaction factors and the types of equipment in energy system were relatively few.

This paper proposes an optimal capacity configuration method of regional integrated energy system considering electric and heat transaction. The optimization objective is a multi-objective function comprehensively considering the economic costs, environmental benefits, reliability and interacting power fluctuation. Based on system’s economic operation on typical days, the genetic algorithm is adopted to optimize the capacity configuration of the system.
Structure of Integrated Energy System

Integrated energy system (IES), a complex system combining many different energy resources, can realize the energy cascading utilization and promote the sustainable development of energy through the complementarity between energies (e.g., wind-solar complementary characteristics). In short, IES can be roughly divided into three levels including: 1) the energy input side: mainly an input of primary energy including wind, solar and natural gas. Primary energy from nature supports and guarantees the basic operation of system. 2) the energy coupling part: it includes many kinds of energy forms and energy links: energy production link such as wind turbine, gas turbine, etc., energy conversion link such as heat pump, absorption chiller, etc., energy collection and distribution link based on current, heat and cold collector. 3) the energy output side: the energy generated by system can be reasonably and efficiently transferred to end users to meet their energy needs of cooling, heating and electrical load through energy transportation network. The established framework of regional integrated energy system (RIES) based on energy hubs is shown in figure 1.

RIES is located in the lower level of energy bus which contains many kinds of energy such as electricity, heat, etc., realizing the interaction with the bus. It not only can absorb energy from the energy bus, but also provide energy through the bus. Due to the different energy demands of every operation time in RIES and the different market prices of energy, considering diversity and complementarity of electricity and heat interaction with energy bus in optimal configuration, it is beneficial to reduce the system operating cost and greatly promote the comprehensive optimal utilization of multiple energy. Energy interaction structure of IES with multi-energy network is established as shown in figure 2, considering the energy interaction between the system and energy bus, including the power and heat networks.

Multi-objective Optimal Configuration Model

Considered system, as is shown in figure 1, consists of wind turbine, solar PV, combined heating and power systems with gas turbines as a core, auxiliary energy supply equipment such as gas boiler, electric heat pump, absorption chiller and electrical chiller.
Objective of Optimal Configuration

The optimal configuration model established comprehensively considers four factors: system economy, environmental protection, reliability and interacting power fluctuation. The objective function includes equipment investment costs, operation and maintenance costs, energy transaction costs, pollutant emissions costs and so on.

\[
\text{Min } G_{\text{IES}} = G_{\text{ECO}} + G_{\text{ENV}} + G_{\text{REL}} + G_{\text{STD}}
\]

1) Economic objective

The economic objective include three parts: the initial investment costs, the operation and maintenance costs, and the costs of electricity and heat transaction.

\[
G_{\text{ECO}} = C_{\text{INV}} + C_{\text{OM}} + C_{\text{DJ}} + C_{\text{RJ}}
\]

a. Initial investment costs

\[
C_{\text{INV}} = \sum_{m} C_{\text{inv,m}} \lambda_{m} \frac{r(1+r)^Y}{(1+r)^Y - 1}
\]

where, \( C_{\text{inv,m}} \) is the investment cost of unit capacity for equipment \( m \) and \( \lambda_{m} \) is the installation capacity for equipment \( m \); \( Y \) is the service life for equipment; \( r=6.7\% \).

b. Operation and maintenance costs

\[
C_{\text{OM}} = \sum_{m} d_{n} \sum_{t} \left( C_{\text{om,m}} P_{t,m} T + \frac{c_{\text{gas}} F_{t,m}}{Q_{\text{gas}}} \right)
\]

where, \( C_{\text{om,m}} \) is the operation and maintenance cost of unit output energy for equipment \( m \); \( P_{t,m} \) is the output power of equipment \( m \) at period \( t \); \( F_{t,m} \) is the gas consumption of equipment \( m \) at period \( t \); \( d_{n} \) is duration of each scene; \( c_{\text{gas}}=¥3.45/m^3; Q_{\text{gas}}=9.73 \text{ kW·h/m}^3; \Delta t=1\text{h} \).

c. Costs of electricity and heat transaction

The interaction of IES with power and heating network is taken into account in optimal configuration to realize the optimal allocation of energy. Transaction cost represents the expense of energy interaction between RIES and power as well as heating networks, including the power purchase cost from the main power network and the return of selling electricity to it, heat purchase cost from the heating network and the return of selling heat to it.

\[
C_{\text{gas}} = \sum_{t} \left[ \frac{(C_{\text{Dbuy,m}} - \alpha C_{\text{Dsell,m}})}{2} P_{t,\text{DJ}} + \frac{(C_{\text{Dsell,m}} + \beta C_{\text{Dbuy,m}})}{2} P_{t,\text{DJ}} \right]
\]

\[
C_{\text{heat}} = \sum_{t} \left[ \frac{(C_{\text{Rbuy,m}} - \alpha C_{\text{Rsell,m}})}{2} H_{t,\text{RJ}} + \frac{(C_{\text{Rsell,m}} + \beta C_{\text{Rbuy,m}})}{2} H_{t,\text{RJ}} \right]
\]

where, \( C_{\text{Dbuy}} \) and \( C_{\text{Dsell}} \) are, respectively, the prices system buy and sell electricity from and to the main network at time of \( t \); \( C_{\text{Rbuy}} \) and \( C_{\text{Rsell}} \) are the prices system buy and sell heat from and to the heating network respectively; \( P_{t,\text{DJ}} \) is the power system interacts with power grid at time \( t \), which represents electricity purchased from the main network when its value is above 0, electricity sold to the main network when the value is below 0 and having no power trade with the main network when the value equals to 0. Similarly, \( H_{t,\text{RJ}} \) is the power system interacts with upper heating network at time \( t \); \( \alpha \) and \( \beta \) are variables which are 0 or 1.

2) Environmental protection objective

The emissions of CO\(_2\) and NO\(_x\) are taken as the environmental protection indexes of RIES in this paper.

\[
G_{\text{ENV}} = \xi_{\text{CO}_2} + \xi_{\text{NO}_x}
\]
\[ \xi_{CO_2} = \sum_n \sum_{i=1}^{24} (k_i F_{i,GT} + k_i F_{i,GB}) + \sum_n \sum_{i=1}^{24} k_i P_{t,DI} \]

\[ \xi_{NO_x} = \sum_n \sum_{i=1}^{24} k_i \sum_m P_{m,\Delta t} \]

where, \( k_a, k_b \) and \( k_c \) are the pollutant emission coefficients of natural gas, electricity and system equipment\(^3,6\).

2) Reliability objective

Energy supply reliability indexes (including power interruption rate and heating interruption rate) are employed to measure the reliability level of the system. Power grid is only the backup power source of system when the wind-solar output is relatively low and the load demand cannot be satisfied at the peak of load. When failure happens in external power grid such as the interruption of power supply caused by tie-line fault, the power outage rate reflects the ability of continuous power supply when failure happens. As such, heat supply interruption rate reflects the ability of continuous heating supply. The smaller the \( R_{LPSP} \) and \( R_{LHSP} \) are, the higher the reliability is.

\[ G_{REL} = R_{LPSP} + R_{LHSP} \]

\[ R_{LPSP} = \frac{\sum_n (P_{PL} - (P_{WT} + P_{PV} + P_{GT} - P_{AC} - P_{AB}))}{\sum_n P_{PL}} \]

\[ R_{LHSP} = \frac{\sum_n (H_{HL} - (H_{WH} + H_{GB} + H_{GB} - H_{AC}))}{\sum_n H_{HL}} \]

3) Interacting power fluctuation objective

The energy fluctuation will happen when the RIES is connected into the power and heating networks as an energy terminal unit, which affects the safe and stable operation of the system. Therefore, the fluctuation of electricity-heating interaction is needed to be considered in the optimal configuration of the system.

\[ G_{STD} = R_{PSTD} + R_{HSTD} \]

\[ R_{PSTD} = \frac{1}{\sqrt{N-1}} \left( \sum_{i=1}^{N} (P_{i,DI} - \overline{P}_{DI}) \right)^2 \]

\[ R_{HSTD} = \frac{1}{\sqrt{N-1}} \left( \sum_{i=1}^{N} (H_{i,RJ} - \overline{H}_{RJ}) \right)^2 \]

where, \( \overline{P}_{DI} \) and \( \overline{H}_{RJ} \) are the mean power interacted with the power and heating networks respectively. The smaller the \( R_{PSTD} \) and \( R_{HSTD} \) are, the smaller the interacting power fluctuation is. The dimensions of calculated data are different, and the levels of quantitative unit differ comparatively as well, so normalization processing is needed.

Constraints

\[ P_{WT} + P_{PV} + P_{GT} + P_{DI} = P_{PL} + P_{AC} + P_{AB} \]

\[ H_{WH} + H_{GB} + H_{WH} + H_{RJ} = H_{HL} + H_{AC} \]

\[ Q_{AC} + Q_{EC} = Q_{CL} \]

\[ 0 \leq \lambda_m \leq \lambda_{m,max} \]
Here, $P_t,P_{HP},H_t,H_{CL}$ and $Q_t$ are, respectively, the electrical, heating and cooling load of system at period $t$. The energy balance constraints on current, heat and cold collector are given respectively in formula (16), (17) and (18). The formula (19) and (20) are limitations on installed capacity and constraints on output for equipment $m$. As such, the formula (21) and (22) represent constraints on power the system interacts with the power and heating networks respectively.

**Case Analysis**

This paper takes a region in northern China as the research object. The calculated curve of WT and PV and the typical daily curves of electrical, heating and cooling loads are shown in Fig. 3. The prices of electricity and heating price can refer to literature [2]. This case adopts the genetic algorithm to solve the problem and the parameters in the algorithm are given as follows: taking the population size $N$ and iteration number $k_{max}$ as 100. To verify the advantage of IES (System 3) considering electricity and heat transaction, the System 1 and System 2 are introduced in this paper to make comparison. The System 1 is traditional separation production system (SP), that is, the electrical load is only supplied by power grid, heating load is satisfied by gas boiler and cooling load is supplied by electrical chiller. The System 2 is the integrated energy system that only interacts with the power grid. The optimization results of each system are shown in table 1.

![Figure 3. The curve of WT, PV and electrical/heating/cooling demand of RIES on typical days.](image)

From table 1, the devices are few in System 1 and electricity is only provided by the power grid, therefore, the cost of power transaction is relatively high which results in high total cost and the pollutant emission is relatively high as well, showing that the economy, environmental protection and reliability of the separation production system are relatively terrible.

System 2 and System 3 are the integrated energy systems which use multi-energy complementary to make comprehensive planning. Many devices increase the investment, operation and maintenance costs in System 2, 3. However, energy trading can reduce the total cost significantly and improve economic efficiency of the system, and the consumption of distributed generation can effectively reduce the emissions of pollutants.
Compared with System 2, System 3 makes optimal configuration considering interaction of heat energy and heat reliability. Based on different energy demands and different prices in energy market in each operation time, the system further reduces the total cost, improves the utilization rate of renewable energy and promotes the comprehensive optimal utilization of multiple energy through electricity and heat interaction. System 3 reduces the total cost by 4.4191 million yuan, reduces emissions of pollutants by 222.46 tons, and lowers power interruption rate and interaction power fluctuation at failure by 0.008 and 4.5.

Table 1. Comparison of the optimization results of each system.

<table>
<thead>
<tr>
<th>Optimization Results</th>
<th>Economic objective[¥10^3]</th>
<th>Environmental protection objective[t]</th>
<th>Reliability objective</th>
<th>Interacting power fluctuation objective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Investment, operation and maintenance costs</td>
<td>Cost of Electricity and heat transaction</td>
<td>Total cost</td>
<td>Emission of CO₂ and NOₓ</td>
</tr>
<tr>
<td>System 1</td>
<td>958.79</td>
<td>4571.9</td>
<td>5530.69</td>
<td>44365.62</td>
</tr>
<tr>
<td>System 2</td>
<td>4309.76</td>
<td>-287.92</td>
<td>4021.84</td>
<td>15268.12</td>
</tr>
<tr>
<td>System 3</td>
<td>4031.38</td>
<td>-451.45</td>
<td>3579.93</td>
<td>15045.66</td>
</tr>
</tbody>
</table>

The results above show that System 3 has better economy, environmental protection and reliability. The results of capacity configuration of every equipment in System 3 are shown in table 2:

Table 2. Capacity configuration for equipment in System 3.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>2160</td>
<td>—</td>
<td>9960</td>
<td>149.4</td>
<td>20</td>
</tr>
<tr>
<td>Photovoltaic system</td>
<td>1830</td>
<td>—</td>
<td>27460</td>
<td>412</td>
<td>25</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>13062</td>
<td>0.6</td>
<td>6000</td>
<td>0.6</td>
<td>30</td>
</tr>
<tr>
<td>Waste heat boiler</td>
<td>6966</td>
<td>0.8</td>
<td>340</td>
<td>0.03</td>
<td>15</td>
</tr>
<tr>
<td>Gas boiler</td>
<td>1409</td>
<td>0.9</td>
<td>400</td>
<td>0.04</td>
<td>20</td>
</tr>
<tr>
<td>Electrical heat pump</td>
<td>179</td>
<td>4.5</td>
<td>3000</td>
<td>0.07</td>
<td>20</td>
</tr>
<tr>
<td>Absorption chiller</td>
<td>2000</td>
<td>1.3</td>
<td>1100</td>
<td>0.08</td>
<td>20</td>
</tr>
<tr>
<td>Electrical chiller</td>
<td>701</td>
<td>4</td>
<td>970</td>
<td>0.097</td>
<td>10</td>
</tr>
</tbody>
</table>

Summary

This paper proposes an optimal capacity configuration method of equipment in RIES considering electricity and heat transaction to realize the maximum of the economy, environmental protection and reliability goals of the system. The energy interaction between the system and energy bus (i.e. upper power grid and heating network) is taken in account and the reliability indexes are established. Based on the genetic algorithm, The validity and practicability of the proposed method are verified, and the results are shown as follows:

1) Compared with traditional separation production system, the proposed model can make full use of cooperativity between conventional energy and renewable energy and complementarity of multi-energy equipment, so that effectively improve the economy and environmental properties of the system. 2) Energy transaction between the system and the power grid as well as heating network is included in optimal configuration, which can effectively reduce the operation cost, avoid waste of energy and greatly promote the optimal utilization of equipment. 3) The reliability objective and the
interacting power fluctuation objective reduce the influence the system complexity have on the safety of the RIES, which guarantees the reliability of the power supply.

However, there are relatively many uncertainties in actual planning, the impact that the wind-solar fluctuation and sensitivity of energy price fluctuation have on the optimal configuration method need to be further studied in the future.

Acknowledgement

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References


