Operation control and capacity configuration optimization of CCHP system based on high temperature phase change heat storage

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Abstract—The existing regional integrated energy system with thermal storage electric boiler as the main body cannot solve the cooling problem. In this paper, LiBr refrigerators were added on its basis to realize an energy supply mode that integrates heating and cooling. Established a multi-party win-win mechanism to ensure the minimum risk and obtain the maximum benefit. The results shown that the power grid load reduction ratios in winter and summer were 39% and 31%, respectively. When the subsidy price was 0.1CNY/kWh, the spending gap between sensitive and insensitive users reached 40%. A case of 100 office buildings in Beijing shown that the optimal capacity of phase change heat storage was 80MWh.

1. Introduction
In order to achieve the goal of “carbon peak” in 2030 and “carbon neutrality” in 2060, China, as the world's largest energy producer and consumer, urgently needs to meet the huge energy demand and adjust the energy structure [1]. China is rich in wind resources. As of the end of 2020, the cumulative installed capacity of power generation in the country is 2 billion kW, ranking first in the world, but the phenomenon of wind curtailment is very serious [2].

If the multi-energy complementary form is adopted, that is the comprehensive utilization of non-renewable energy and renewable energy. Complementarity of the power grid and new energy sources would greatly improve the reliability and sustainability of energy supply of the load side [3]. Taking wind power as the main energy source of the distributed energy system can reduce the amount of wind curtailment, improve the utilization rate of renewable energy and the flexibility of the power system. Electric heating is adopted as a clean and environmentally friendly heating method on the load side. The energy source is electric energy, which is released in the form of heat energy after conversion to meet the heating demand. At present, many researchers have carried out research on renewable energy power consumption [4].

Xianzheng Huang et al. [5] provided a method for cogeneration load dispatch. They proposed to introduce electric boilers into the district heating system, integrate additional wind power into the grid within an optimized time period, and convert wind power into thermal energy for heating. Electric boilers replace traditional coal-fired boilers for heating which reduces environmental pollution, increases the utilization space of wind power and the utilization rate of wind energy. Quan Lu et al. [6] established relevant models for evaluating coal-saving effects and national economic efficiency. They
compared three wind abandonment schemes: thermal storage, wind power heating and pumped storage, indicated that thermal storage solution provides the least investment per unit capacity of wind power receiving space, the highest coal saving efficiency (the amount of coal saved when consuming and absorbing a unit of wind abandonment power) and the strongest ability to withstand the uncertain risk of wind abandonment. Quan Lu et al. [7] used wind power instead of cogeneration units for power and heating supply and solved the problem of wind abandonment by electric boilers. In addition, the coal-saving benefits and economics are analyzed: according to the different situations of wind curtailment in various places, there is an optimal plan for the installation scale and annual utilization hours of electric boilers. Bing Qi et al. [8] established a regional comprehensive energy optimization dispatch model with thermal storage electric boilers as the main body. The results showed that under different working modes, it is more economical to use thermal storage electric boilers during low electricity prices and more flexible for the operation of system. However, its consideration of distributed renewable energy and other energy storage equipment is not sufficient, such as the impact of renewable energy volatility on system operation. Yuanhang Dai et al. [9] proposed a dispatching model for thermal power plants with thermal storage which uses thermal storage devices of thermal power plants and existing heat supply pipe networks. They fully considered the operational effects of eliminating and curtailing wind, In order to obtain the most profitable scheduling strategy of wind farm and cogeneration joint optimization operation.

In this paper, we added LiBr refrigerators on traditional regional integrated energy system based on thermal storage electric boilers which was difficult to solve the problem of cooling. LiBr refrigerators were driven by thermal energy during operation, absorbing the heat of the surrounding environment to achieve the effect of refrigeration. In addition, a multi-party win-win mechanism by the introduced load aggregators was established, so that all parties involved in high-temperature phase change heat storage can obtain corresponding benefits. And in order to ensure the minimum risk of four subjects, the safety of electricity use was ensured through the method of risk restriction.

2. Introduction to the device

2.1. Overall design of model

In this paper, information interaction models for new energy, power grids, load aggregators and regenerative thermal users are constructed. The model is located in Beijing, with 100 office buildings as the demand side thermal users, and the load aggregator as the market intermediary to complete the interaction with the power grid, wind power plant and thermal users, to maximize the overall benefit. At time i, the information interaction structure between the four groups is shown in Fig.1.
2.2. **Constraint condition**

To ensure the minimum risks, it is necessary to ensure the safety of electricity consumption through risk constraints.

2.2.1. **System equipment constraints**

(1) Capacity constraint of the heat storage body

\[
0 \leq S_t \leq S_{\text{max}}
\]

Where \( S_t \) denotes capacity status of heat; \( S_{\text{max}} \) denotes the maximum capacity of heat storage.

However, because this study is fully using electric boiler for heating, in order to ensure the thermal comfort of power off, the heat can not be completely released in the peak heat, need to retain a certain safety capacity. The Adjusted capacity constraint is:

\[
S_{\text{min}} \leq S_t \leq S_{\text{max}}
\]

(2) Storage or heat power constraints

\[
0 \leq \sum_{n=1}^{M} N_{m,i} (L_{m,i} - L_{\text{X,mi}}) + (aL_{\text{DC}} + bL_{\text{C,i}}) \leq \Delta t \cdot HP_{\text{max}}
\]

Where \( HP_{\text{max}} \) denotes the maximum heating power; \( \Delta t \) denotes the time step; \( a, b \) denotes the indication coefficient to ensure that the simultaneous storage or heat discharge operation is not performed.

(3) Start state constraint of heat storage body capacity Operational optimization of thermal storage systems generally requires that the capacity state return to the initial state after running one cycle:

\[
S_{\text{start}} = S_{\text{end}}
\]

Where \( S_{\text{start}} \) denotes the initial heat storage of the heat storage cycle; \( S_{\text{end}} \) denotes the end of the phase transition heat storage cycle.

(4) Electric thermal conversion constraints of heat storage electric boiler:

\[
L_i = \eta \cdot \Delta t \cdot HP_i
\]

Where \( L_i \) denotes supply heat for the electric boiler \( i \), \( HP_i \) denotes power for the electric boiler \( i \); \( \eta \) denotes electric thermal conversion efficiency.

2.2.2. **Safety operation constraints of the power grid**

According to the previous analysis, the main purpose of the grid participation in thermal storage electric heating is to reduce the peak load and thus reduce the peak valley difference may cause operating risk. The resulting risk constraint is to ensure that the load reduction ratio is not zero, combined with the revenue model of the grid, the constraint is:

\[
\theta \geq \varepsilon
\]

Where \( \varepsilon \) represents an acceptable minimum reduction.

2.2.3. **Income and risk constraints of wind power plants**

In this study, the load aggregation conducted heat storage during periods of low night electricity prices, and only when the price of wind power was lower than the municipal valley electricity price. Although the wind power plants have the pricing power and the income increases with the rising price, the wind power plants will not benefit if the bundling electricity price is higher than the municipal valley electricity price. According to the risk constraints of wind power plants for their own pricing, combined with the revenue model.

According to the above formula, in the operation process of heat storage electric heating, the four parties need to operate under the corresponding risk constraints to ensure that the risks occur while obtaining benefits for themselves.
3. Test Results and Discussions

Figure 1 (a) and (b) are the original load power, load power, heat storage power and electricity price curves within 24 h of a design day in winter and summer, respectively. During the valley electricity price period (from 0 to 8 o'clock) on a design winter day and a summer design day, the user does not participate in load reduction. The system uses wind power to accumulate heat from the heat storage device until the heat storage power reaches 0, indicating that the heat is stored at this time. The device is fully charged. From 8 o'clock to 13 o'clock and 17 o'clock to 22 o'clock, the load power is lower than the original load power, which is due to the load reduction of the thermal users. From 10 o'clock to 13 o'clock and 18 o'clock to 20 o'clock, the heat release power of the heat storage device coincides with the heat load curve of the heat user, indicating that the heat storage device can fully meet the load demand of the user. The heat storage devices also participate in partial heat supply from 8 o'clock to 10 o'clock, 13 o'clock to 18 o'clock, and 20 o'clock to 22 o'clock, and the insufficient heat is supplied by electric boilers (take winter design days as an example).

The income of aggregators, wind power plants and peak shaving within 24 hours is shown in Table 1. The grid load reduction ratios in winter and summer are 39% and 31%, respectively. In addition, comparing the user's expenditure when participating or not participating in the response respectively, it is calculated that the proportions of cost savings in winter and summer are 26.8% and 24.3%.
Table 1. Benefits in winter/summer

|                                | Winter income/CNY | Summer income/CNY |
|--------------------------------|-------------------|-------------------|
| Load aggregator                | 85594.9           | 150233.4          |
| Wind power plant revenue       | 44892.4           | 68484.8           |
| Peak cut income                | 2418.3            | 4763.9            |

Figure 2 is a graph showing the change in the cost of a single user with the subsidy price. It can be seen from Figure 2 that since the No. 1 user is price-sensitive, when the subsidy price is less than 0.1 CNY/kWh, the response ratio of the No. 1 user increases with the increase in the subsidy price, and its expenditure is affected by the response ratio and the subsidy price. The influence of the two factors has a significant decreasing trend as the subsidy increases, and the No. 2 user does not participate in the response when the subsidy price is less than 0.1 CNY/kWh, so its total expenditure remains unchanged. When the subsidy price is greater than 0.1 CNY/kWh, user No. 1 fully participates in the response, and its response ratio reaches the maximum. Its cost is only a monotonic function of the subsidy price, and its changing trend slows down; while user No. 2’s spending is affected by the response ratio. With the increase of subsidies, the influence of the two factors, the price of subsides and subsidies, has a significant decreasing trend. At the same time, through comparison, when the subsidy price is 0.1 CNY/kWh, the difference between the cost of No. 1 and user No. 2 can reach 40%; when the subsidy price is 0.2 CNY/kWh, the difference in expenditure between the two is 7.7%.

Figure 4 shows the revenue of aggregators, wind power costs, and electricity costs under different heat storage device capacities. It can be seen that with the increase of capacity, the revenue and cost of the system are showing a gradual increase trend. In order to optimize the capacity configuration of the heat storage device, the dynamic investment payback period under different schemes is calculated, and the optimal scheme is selected.
Calculation formula for dynamic investment payback period:

\[ \sum_{t=0}^{n_p} \frac{f_{in} - f_{out}}{(1+i)^t} = 0 \]  

(6)

Where \( f_{in} \) is the annual income; \( f_{out} \) is the annual expenditure; \( i \) is the discount rate. Costs include investment costs, operation and maintenance costs, wind power costs and electricity costs. Revenue includes revenue from aggregators and revenue from cooling and heating users. The calculation results are shown in Table 2:

Table 2. Dynamic investment payback period under different schemes

| Option   | Device capacity | Dynamic payback period |
|----------|-----------------|------------------------|
| Option A | 70 MWh          | 5.5 year               |
| Option B | 80 MWh          | 5.0 year               |
| Option C | 90 MWh          | 5.7 year               |
| Option D | 100 MWh         | 6.1 year               |

4. Conclusion

This article adds LiBr refrigerators on the basis of the traditional regional integrated energy system with thermal storage electric boilers as the main body to solve the problem of difficult cooling. In order to ensure the minimum risk, the safety of electricity use is ensured through the method of risk restraint. At the same time, load aggregators are introduced to establish a multi-party win-win mechanism, so that the four parties can obtain corresponding benefits. This article draws the following conclusions through analysis:

(1) The multi-party win-win mechanism makes the benefits of all parties obvious. The reduction ratio of grid load in winter and summer is 39% and 31%, respectively. When users participate in the response, they save 26.8% and 24.3% in winter and summer respectively.

(2) The sensitivity of users' response to load reduction and the impact of subsidy prices on user spending are explored. High subsidies can encourage users to participate in the response, and insensitive users will spend more on electricity than sensitive users. When the subsidy price is 0.1 CNY/kWh, the cost gap can reach 40%.

(3) Taking the shortest dynamic investment payback period as the optimization goal, the capacity allocation strategy of the combined cooling and heating system is analyzed. Taking 100 office buildings in Beijing as an example, the optimal capacity of the phase change heat storage device is 80 MWh.
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References
[1] Yujing Huang. Energy optimization management and control of regional integrated energy system based on demand response [D]. North China Electric Power University (Beijing), 2019.
[2] Jianlin Li, Zhijia Xie, Dexin Li, et al. Research on key technologies of regenerative electric boilers to improve wind power consumption and absorption capacity [J]. Electrical Appliances and Energy Efficiency Management Technology, 2018 (01): 1-7.
[3] Xuxuan Jiang. Research on mathematical modeling and optimized operation of a distributed cooling and heating system based on multi-energy complementation [D]. South China University of Technology, 2014.
[4] Yingnan Fu. Optimal control and configuration of thermoelectric hybrid energy storage system to improve wind power consumption [D]. Northeast Dianli University, 2020.
[5] Xianzheng Huang, Zhaofeng Xu, Yong Sun, et al. Heat and power load dispatching considering energy storage of district heating system and electric boilers [J]. Journal of Modern Power Systems and Clean Energy, 2018, 6(5): 992-1003.
[6] Quan Lv, Yongcheng Liu, Le Liu, et al. Research on the coal-saving effect and optimal configuration of wind power heating projects considering the characteristics of wind curtailment [J]. Proceedings of the Chinese Society for Electrical Engineering, 2017, 37(16): 4699-4711.
[7] Quan Lv, Hao Jiang, Tianyou Chen, et al. Thermal power plants based on electric boilers to absorb wind power and its national economic evaluation [J]. Automation of Electric Power Systems, 2014, 38(01): 6-12.
[8] Bing Qi, Chengyu He, Bin Li, et al. Optimal dispatch of regional integrated energy system based on different working modes of thermal storage electric boilers [J]. Modern Electric Power, 2019, 36(6): 45-51.
[9] Yuanhang Dai, Lei Chen, Yong Min, et al. Optimal dispatch of combined operation of wind farm and cogeneration with heat storage [J]. Proceedings of the Chinese Society of Electrical Engineering, 2017, 37(12): 3470-3479+3675.