IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 6, 2019, accepted July 26, 2019, date of publication July 30, 2019, date of current version August 15, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2932141

Coordination Scheduling Model of Multi-Type Flexible Load for Increasing Wind Power Utilization

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This work was supported in part by the National Natural Science Foundation of China under Grant U1766204, and in part by the Special fund for industrial innovation of Jilin Province Development and Reform Commission under Grant 2017C017-2.

ABSTRACT Wind curtailment of power grid is severe during heating period in the 'Three North'(northwest china, north china, and northeast china) area of China, and the 'wind-heat conflict' causes insufficient of power system peaking, which is one of the main reasons that impacts wind power consumption. To enhancing flexibility of power system by configuring flexible load is an effective means to improving wind power acceptance. This paper, based on the dispatch of the cogeneration unit, analyzed the composition and operation rules of battery energy storage–heat storage system. Considering the constraints of power system and thermal system, the coordinative dispatching model of battery energy storage and regenerative electric boiler is established. Based on a regional power grid in the 'Three North' area of China is used to simulate the acceptance of wind power under different modes of operation. The results show that in the way of power alternative, the regenerative electric boiler has the best effect of eliminating wind and abandoning wind, and the environmental benefits are obvious. When the thermal storage electric boiler is matched with an excessively large new adding heat load, the thermal power unit in the electric power for heating accounts for a relatively high amount of electricity, and the efficiency of energy utilization is low. Considering the battery storage price is greatly reduced, the peak shaving effect of battery energy storage and thermal storage electric boiler coordinated operation is the most obvious, and it is of great significance for the safe and stable operation of wind power and high-wind power infiltration grid.

INDEX TERMS Battery energy storage, optimized control, regenerative electric boiler, wind power consumption.

I. INTRODUCTION

As energy and environmental issues become more prominent, countries around the world have reached a consensus on changing energy structure and developing renewable energy [1]. In recent years, China's renewable energy has developed rapidly [2]. From January to June 2018, the newly added wind power grid-connected capacity of the country was 7.94 million kilowatts. By the end of June, the cumulative wind power grid-connected capacity reached 171.6 million kilowatts [3]. However, large-scale wind power access has also brought many problems [4], [5]. Among them, China's "Three North" region (referring to the Northeast, North China and Northwest) is located in the north latitude of 31°36'—53°33', and the average temperature in winter reaches −20° for about 170 days. Therefore, the demand for heating in winter in the "Three North" region is high, but due to the insufficient peak-shaving capacity of the system, the wind abandonment in the power grid is serious [6]–[8]. The wind abandonment and staying high has become the main bottleneck restricting the development of wind power.

Related research at home and abroad has proposed various measures to improve wind power consumption. Considering the characteristics of wind power to improve the level of

The associate editor coordinating the review of this manuscript and approving it for publication was Shantha Jayasinghe.

wind power consumption. In [9], a reciprocal peak-regulation trading improved method of inter-regional grids considering wind power uncertainty is established, which is robust to wind power fluctuations, which can effectively reduce wind abandonment and reduce total operating costs. Deyou *et al.* [10] put forward a rolling and dispatching control strategy with a BESS based on model predictive control (MPC), which can effectively stabilize wind power fluctuations, thereby enhancing system flexibility and improving wind power consumption. However, due to the randomness and volatility of wind power, the accuracy of wind power forecasting will affect the effectiveness of the method results.

From the consideration of the relationship between power and thermal systems to improve the level of wind power consumption, the current main solution is to install electric boilers, heat pumps and heating devices equipped with heat storage tanks. According to relevant reports, these measures can reduce power curtailment and improve operational efficiency [11]–[14]. In [15], the operational strategies are evaluated by comparing the market operation performance of heat pumps and electric boilers in different scenarios, and the relevant influencing factors are analyzed, but the coordinated operation strategies of heat pumps and electric boilers are lacking. Waite and Modi [16] established a model to evaluate the coupling effect of large wind turbines in New York State, and increased the use of electric heat pumps to meet the needs of some space heating and domestic hot water (DHW) in New York City. The analysis shows that with the use of heat pumps increasing, the utilization rate of wind power generation is significantly increased, which can increase the installed capacity of wind power generation. However, the continuous investment of heat pumps will inevitably lead to an increase in costs. Further research is needed to weigh the benefits and costs of heat pumps; In [14], [17]–[23], the coupling relationship between power system and thermal system is analyzed, and the electric-thermal joint scheduling model is established. By disposing the heat storage and electric boiler device in the thermal power plant to decouple the rigid coupling relationship between electricity and heat of the cogeneration unit, improve the system adjustment capability and increase the grid-connected space of wind power. However, the heat storage device does not match the wind power characteristics very well in the adjusting speed. The reason is that the heat storage device is limited by the mechanical parts of the electrode, and the adjusting times and speed are restricted by the performance of the device itself, so it can not suit the characteristics of wind power very well, resulting in a large part of abandoned wind power generation. In [24], a combined heat and power dispatch (CHPD) is formulated to coordinate the operation of electric power system (EPS) and district heating system (DHS). It proves the potential advantages of the combined operation of the combined heat and power system, wind power utilization and potential benefits of the actual system, but how to better solve the uncertainty of renewable energy still needs further research. Chen X *et al.* [14] proposed a linear model for centralized scheduling of power systems and thermal systems to improve system flexibility and reflect the effectiveness of centralized scheduling. Although the flexibility of cogeneration units can be improved by using heat storage devices and electric boilers separately, the strategy in the corresponding combination is lacking. Li *et al.* [25] proposes a decomposition coordination algorithm to optimize the location of energy conversion between electrical and thermal systems, and verifies that this method can not only reduce operating costs, but also reduce wind power, but ignores wind power costs. Nuytten T *et al.* [26] established a maximum flexibility model for combined cogeneration and heat storage systems, and considered the impact on system flexibility in both centralized and decentralized approaches. Although the above documents break the operation mode of the rigid coupling relationship between electricity and heat, and increase the flexibility of the system, due to the contradiction between the slow response speed of the heat storage device and the wind power characteristics, and the lack of detailed control strategy support, the abandonment of wind power is reduced. Further research is still needed on the issue of reducing wind abandonment.

From the consideration of the characteristics of the heat network to improve the level of wind power consumption. In [27], [28], it is proposed to install an electric boiler on the secondary heat networks side for peak shaving, reduce the heat load of the cogeneration unit, increase the electric load, and provide more space for the wind power. In [29], pipeline heat storage is modeled in the combined heat and power dispatch (CHPD) model under the constant mass flow heating dispatch mode, a decentralized solution to the CHPD model is proposed, which verifies that the program can reduce the economic benefits of wind reduction, but the pipeline parameters are uncertain. In [30], transmission-constrained unit commitment (UC) with combined electricity and district heating networks (UC-CEHN) is formulated with a linear DHN model to coordinate short-term operation of electric power and district heating systems. The results show that the method has potential advantages in wind power integration and efficient operation, but the information exchange and privacy issues between the parties still need to be further explored. In [31], a new feasible region method is proposed for formulation of new district heating system (DHS) models, and a greedy method is developed to solve the new modified feasible region models by calculating a series of linear programming problems efficiently. The conclusions show that the scheme can reduce the total cost and the abandonment of wind power, but the bidding strategy of a district heating control centers (DHCC) in the electricity market can be further explored. Although the use of the heat network can increase system flexibility and reduce the amount of wind abandonment, the uncertainty of the parameters of the pipeline and the imperfection of the control strategy are further studied.

Considering the coordinated operation of heat storage electric boiler and energy storage battery. In [32], in order to solve the problem of wind power absorption, a coordinated dispatching model of abandon wind absorption based on regenerative electric boiler combined with energy storage battery is proposed from the viewpoint of decoupling thermoelectric coupling constraints and unit operation constraints. In [33], the coordination between regenerative electric boiler and energy storage battery under different operation modes is compared. The effectiveness of the coordinated energy storage battery system is verified by the analysis of the overall operation effect of the system with and without energy storage battery. In [34], [35], the influence of the number of electrode adjustments on the operation effect of the system is further analyzed, and the optimal operation strategy is proposed to further improve the operation effect of the battery energy storage coordinated regenerative electric boiler system.

In addition, various studies have also been optimized from the state of battery energy storage, super capacitors, etc. [36]–[39], however, most of the above studies enhance the operational flexibility of the system and improve the wind power consumption capacity from the power side or the load side. The research on the integration of battery energy storage and thermal storage in the electric-thermal joint dispatching system to improve wind power consumption is less. Most of them are to verify the operation effect of the energy storage battery coordinated regenerative electric boiler system, lack of further analysis of the control strategy of the system and the overall operation effect of different devices under different capacity configurations. Therefore, this paper takes the "Three North" regional power grid with more serious abandonment wind as the research object, formulates the control strategy of coordinated operation of battery energy storage and thermal storage. Then establishing a grid dispatching model including battery energy storage and regenerative electric boiler, and comparing the analysis of wind power acceptance under different operating modes.

The remainder of this paper is organized as follows: Section II introduces the composition of the battery energy storage and thermal storage system, and develops the corresponding control strategy for battery energy storage and thermal storage. Section III establishes a scheduling model for battery energy storage and thermal storage systems, considering the constraints of power and thermal systems, and the constraints of regenerative electric boilers and battery energy storage. Section IV studies and discusses the situation under different scenarios through the actual operation of a regional power grid in the "Three North" region of China. Finally, section V reports the relevant conclusions.

II. COMPOSITION AND CONTROL STRATEGY OF BATTERY ENERGY STORAGE AND HEAT STORAGE SYSTEM

A. ANALYSIS OF THE MECHANISM OF WIND ABANDONMENT

Wind power resources are abundant in the heating season in the "Three North" area, but in the period of low load, wind power often occurs frequently, while in the period of peak load, wind power often occurs less, which has the characteristics of reverse peak regulation. The heat-supply units in the "three-north" area are mainly cogeneration units with the operation mode of "heat-fixed electricity". That is to say, with the rising of thermal power, the regulation range of the unit's electric output is decreasing and the lower limit of the unit's electric output is rising. In order to meet the demand of heating load, the thermoelectric units have to increase their electric output, and then severely reduce the size of wind power available space in the system. It leads to the contradiction between wind and heat. The schematic diagram of the mechanism of wind abandonment in heating period is shown in Fig. 1. Among them, ΔP1 and ΔP2 are peak shaving capacity of heating and non-heating periods respectively, and the area of shadow area is abandoned wind power.

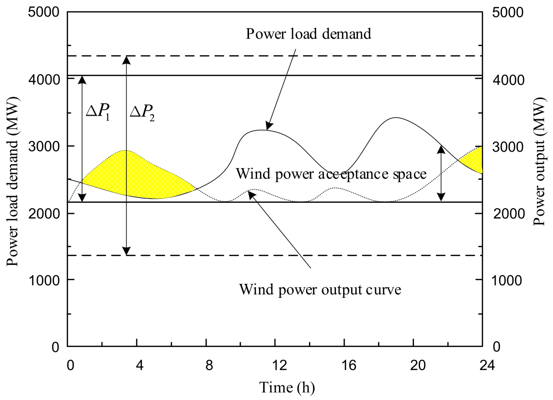


FIGURE 1. Schematic diagram of the mechanism of wind abandonment in power network during heating period.

B. BATTERY ENERGY STORAGE AND HEAT STORAGE SYSTEM

The regenerative electric boiler is equipped with a heat storage device, meeting the heat supply while storing heat during the abandonment period, storing and releasing heat during the non-abandonment period, which realize the transfer of energy in time. Due to its fast response and two-way flow of energy, the system of battery energy storage can respond to grid dispatching commands in real time for charging and discharging.

This paper mainly introduces the coordinating effect of regenerative electric boilers and battery energy storage to enhance the flexibility of system operation and improve the wind power acceptance. The structure of the battery energy storage and regenerative electric boiler system is shown in Fig. 2.

As shown in the above figure, the heat storage electric boiler on the load side can increase the power load and eliminate the wind load by increasing the electric load level during the load valley period of the heating period. The system of battery energy storage improves the peak shaving ability of the whole system through the operation mode of peak load shifting, thereby reducing the amount of wind power.

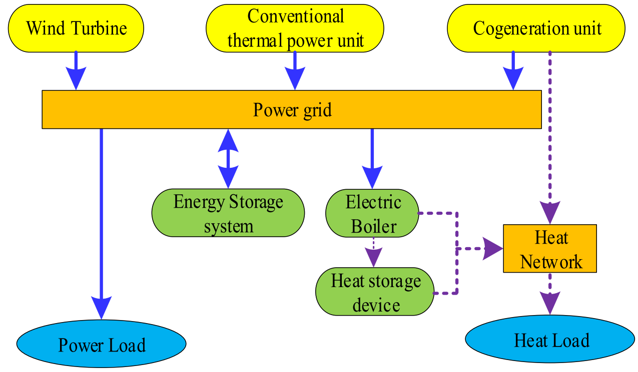


FIGURE 2. The composition of flexible load system to consume wind power.

C. BATTERY ENERGY STORAGE AND HEAT STORAGE SYSTEM CONTROL STRATEGY

At present, in order to promote the clean energy consumption of wind power and nuclear power, the northeast region has introduced relevant peak shaving assistance to serve the market operation rules and provide certain compensation under the premise of meeting operational rules [40]. Regenerative electric boilers mainly use electricity in the low-valley period of the power grid. The power grid shall compensate for peak shaving according to the contract power of the load valley and may also negotiate bilateral transactions with wind power enterprises. The peak shaving by battery energy storage mainly absorbs power in load valley or discarded nuclear period, releases power in other periods, and cannot be charged in peak period or discharged in load valley period, otherwise no compensation will be given.

Therefore, the time-division operation control strategy of the battery energy storage coordinated regenerative electric boilers is formulated, as shown in the following figure.

Because of the heat supply constraints of the regenerative electric boilers, therefore, it is used as the main body of wind power consumption, and the battery energy storage coordinates its action. As shown in the figure above, this paper takes 22:00-22:00 the next day as a dispatching cycle, and the initial dispatching time starts at 22:00 on the previous day, i.e. load trough period. The operating mechanism is as follows: in the initial period of load valley, the electric boiler operates to heat and store heat at the same time to absorb the wind power and heat supply. When the abandoned wind power does not meet the demand of heating, the conventional power is absorbed; when there is abandoned wind in the system, the battery energy storage starts to act to charge to eliminate the abandoned wind. During periods of gradual load, the heat storage begins to operate to meet the demand of the heat load, and the battery energy is used to increase the difference in the peak-valley price, which is mainly discharged to the initial state of charge during the peak period.

III. BATTERY ENERGY STORAGE AND HEAT STORAGE SCHEDULING MODEL

A. OBJECTIVE FUNCTION

The economic dispatch model of wind power grids is based on the minimum power generation cost of the system, which will cause serious wind abandonment. Therefore, in order to improve the level of wind power consumption, a penalty function that considers the cost of abandoned wind and the pollution discharge of conventional units is added to the objective function, which are referenced in the literature [41]; this objective function is of great significance to environmental protection while increasing wind power consumption. Therefore, the objective function is as follows:

$$S = \min \sum_{t=1}^{T}\Big(\sum_{i=1}^{M} S_c(i,t) + \sum_{k=1}^{N} S_e(k,t) + \lambda \cdot P_{w,qf}(t) + \beta \cdot S_p(t)\Big), \qquad (1)$$

where, $S_c(i,t)$ is the power generation cost function of thermal power units. $S_e(k,t)$ is the power generation cost function of cogeneration units. S is the objective function. M and N are the number of units of various types. λ is the penalty factor of abandoned wind cost. β is the penalty factor of pollution emission. $P_{w,qf}(t)$ is the abandoned wind power at time t. $S_p(t)$ is the discharge penalty function at time t. T is the scheduling time.

1) GENERATION COST FUNCTION OF CONVENTIONAL THERMAL POWER UNITS

For condensing turbine, the generation cost function $S_c(i,t)$ is as follows:

$$S_c(i,t) = F_1(P_{e,i}^t) + F_2(u_i^t), \qquad (2)$$

where, F_1 is the operation cost function of thermal power unit. F_2 is the unit commitment cost function of thermal power unit. The operation cost and commitment cost of thermal power units are mainly the coal consumption cost. Therefore, the operation cost function of thermal power units is similar to the coal consumption function, which is the quadratic form of power generation output [20].

$$\begin{cases} F_1 = a_i(P_{e,i}^t)^2 + b_i P_{e,i}^t + c_i \\ F_2 = u_i^t(1-u_i^{t-1})S_i. \end{cases} \qquad (3)$$

where, a_i, b_i, and c_i are the generation cost coefficients of unit i. u_i^t is the start-stop state of unit i at time t.

2) GENERATION COST FUNCTION OF COGENERATION UNITS

China's cogeneration unit is mainly based on pumping units, and the power generation cost function $S_e(i,t)$ is as follows:

$$S_e(k,t) = a_k(P_{e,k}^t + c_{v,k}P_{h,k}^t)^2 + b_k(P_{e,k}^t + c_{v,k}P_{h,k}^t) + c_k, \qquad (4)$$

where, a_k, b_k, and c_k are the cost coefficients of k generation of thermal power units. $P_{h,k}^t$ is the thermal output of k generation of thermal power unit. $P^t_{e,k}$ is the electric output of the thermal power unit k.

3) PENALTY FUNCTION

The penalty function mainly includes the cost of abandoning wind and the cost of governance costs of conventional unit pollution emissions. The penalty term of the objective function is added to improve the level of wind power absorption. Pollution discharge penalty is mainly related to unit coal consumption, that is, power generation and heat supply.

B. OPERATIONAL CONSTRAINTS

1) POWER SYSTEM CONSTRAINTS

a: POWER BALANCE CONSTRAINT

$$P^t_{e,z} + P^t_{wind} + P^t_{ESS,dis} = P^t_{gl} + P^t_{load} + P^t_{ESS,cha}. \tag{5}$$

where, $P^t_{e,z}$ is the total output of thermal power units and cogeneration units at time t. P_t wind is the grid-connected power of wind power at time t. $P^t_{ESS,dis}$ is the discharge power of the energy storage system at time t. P^t_{gl} is the power of the electric boiler at time t. P_t load is the demand of the power load at time t. $P^t_{ESS,cha}$ is the charging power of the energy storage system at time t.

b: UNIT OUTPUT CONSTRAINT

Pumping unit k output force constraint:

$$\begin{cases} P^t_{e,k} \geq \min\left(c_{m,k}P^t_{h,k} + K_k, P_{e,\min,k} - c_{v,k}P^t_{h,k}\right) \\ P^t_{e,k} \leq P_{e,\max,k} - c_{v,k}P^t_{h,k}. \end{cases} \tag{6}$$

where, $P_{e,min,k}$ and $P_{e,max,k}$ are the minimum and maximum electric output of the pumping unit under condensation condition. $c_{m,k}$, $c_{v,k}$, and K_k are the unit parameters.

Condensing turbine i output force constraint:

$$P_{e,\min,i} \leq P^t_{e,i} \leq P_{e,\max,i}. \tag{7}$$

c: UNIT RAMP RATE CONSTRAINT

$$-P_{down,i} \leq P^t_{e,i} - P^{t-1}_{e,i} \leq P_{up,i}. \tag{8}$$

where, $P_{up,i}$ and $P_{down,i}$ are the up and down ramp rates of unit i. The output change of thermal power unit is realized by changing the boiler state, so the rate constraints of electric and thermal output climbing are converted to electric power constraints under pure condensation condition.

2) THERMAL SYSTEM CONSTRAINTS

a: HEAT BALANCE CONSTRAINTS IN THERMAL SYSTEMS

$$P^t_{h,z} + \eta_{eh}P^t_{gl} - P^t_{TES,in} + P^t_{TES,out} = P^t_{h,load,z}. \tag{9}$$

where, $P^t_{h,z}$ is the total heating power of the heating unit. $P^t_{TES,in}$ is the heat storage power of the heat storage device. $P^t_{TES,out}$ is the heat release power of the heat storage device. $P^t_{h,laod,z}$ is the total demand of heat load. η_{eh} is the efficiency of the electric boiler, taking 0.98.

b: THERMAL OUTPUT CONSTRAINTS OF UNITS

$$0 \leq P^t_{h,k} \leq P^t_{h,\max,k}. \tag{10}$$

where, P^t_h is the thermal output of the thermal power unit. $P^t_{h,max}$ is the maximum thermal output of the thermal power unit.

3) CONSTRAINTS ON REGENERATIVE ELECTRIC BOILER SYSTEM

a: POWER CONSTRAINTS OF ELECTRIC BOILERS

$$0 \leq P^t_{gl} \leq P_{gl,\max}. \tag{11}$$

where, $P_{gl,max}$ is the maximum operating power of electric boilers.

b: OPERATION CONSTRAINTS OF HEAT STORAGE DEVICES

$$\begin{cases} 0 \leq P^t_{TES,out} \leq P^t_{TES,out,\max} \\ 0 \leq P^t_{TES,in} \leq P^t_{TES,in,\max}, \end{cases} \tag{12}$$

where, $P^t_{TES,out,max}$ and $P^t_{TES,in,max}$ are the maximum heat storage and discharge power of the heat storage device.

c: OPERATION STATUS OF HEAT STORAGE DEVICE

$$\begin{cases} 0 \leq S^t_h \leq S_{h,\max} \\ S^t_h = S^{t-1}_h + \eta_{TES,in}P^t_{TES,in} - \dfrac{1}{\eta_{TES,out}}P^t_{TES,out} \\ P^t_{TES,in} \cdot P^t_{TES,out} = 0, \end{cases} \tag{13}$$

where, $S_{h,maxs}$ the maximum heat storage capacity of the heat storage device. S^t_h is heat storage state of heat storage device at time t. $\eta_{TES,in}$ is the efficiency of the heat storage, taking 0.92. $\eta_{TES,out}$ is the efficiency of the heat storage and release, taking 0.92. Because the total heat loss of the heat storage tank is less than 1% in a day, the heat loss of the heat storage device is not considered in this paper.

Constraints on the start and end state of heat storage:

$$S^0_h = S^T_h, \tag{14}$$

where, S^T_h is the end state of the heat storage scheduling period.

4) BATTERY ENERGY STORAGE SYSTEM CONSTRAINTS

a: POWER CONSTRAINTS OF ENERGY STORAGE OPERATION

$$\begin{cases} 0 \leq P^t_{ESS,dis} \leq P_{ESS,\max} \\ 0 \leq P^t_{ESS,cha} \leq P_{ESS,\max}, \end{cases} \tag{15}$$

where, $P_{ESS,max}$ is the maximum power of heat storage and heat dissipation of the heat storage device.

b: THE RELATIONSHIP BETWEEN SOC AND TERMINAL VOLTAGE IS SHOWN IN THE FOLLOWING FIGURE

The fitting function is as follows:

$$U_{oc}(SOC) = -1.031 * e^{-35*SOC} + 3.185 + 0.2156 * SOC \\ -0.1178 * SOC^2 + 0.3201 * SOC^3 \tag{16}$$

where, U_{oc} is terminal voltage, which referenced in the literature [42].

c: STATE OF CHARGE OF ENERGY STORAGE SYSTEM

$$SOC^t = SOC^0 - \frac{\int_0^t i(\tau)d\tau}{C} \tag{17}$$

where,C is the capacity of the battery.SOC^t is the state of charge of energy storage at time t. SOC^0 is the charging state at the initial time of energy storage. $i(\tau)$ is charging and discharging current. The formula is referred to in the literature [43].

d: POWER CONSTRAINTS OF ENERGY STORAGE OPERATION

$$SOC_{\min} \leq SOC^t \leq SOC_{\max}, \tag{18}$$

where, SOC_{max} and SOC_{min} are the upper and lower limit constraints of energy storage charging state.

The state of charge at the beginning and end of energy storage:

$$SOC^0 = SOC^T, \tag{19}$$

where, SOC^T is the state of charge at the end of the energy storage scheduling period.

C. MODEL SOLUTION

This paper uses the popular CPEX to solve the above-mentioned dispatching model of combination unit. CPLEX is IBM's software. This software has the advantages of improving efficiency and fast implementation strategy, which can effectively solve combination of complex unit problems. The version of CPLEX used in this paper is 12.7.

IV. CASE ANALYSIS

A. CASE CONDITION

According to the actual operation of a regional power grid in the "Three North" area of China, the power supply structure is simplified, the above model is solved and verified, and the power supply installation situation is simplified as shown in Table 1.

TABLE 1. Installed capacities of unitsc.

Unit type	Installed Capacity / MW	Proportion / %
condensing turbine	600	12.17
thermal power unit	2400	64.97
wind power	700	19.96

Assuming that the thermal load in the area is basically unchanged, the value is 2150 MW, in which the thermal power plant 1 supplies the 500 MW heat load to the A area. the thermal power plant 2 supplies the 850 MW heat load to the B area, and the thermal power plant 3 supplies the 800 MW heat load to the C area; Power plant 4 is a thermal power plant; schematic diagram of the regional power grid structure, as shown in Figure 4.

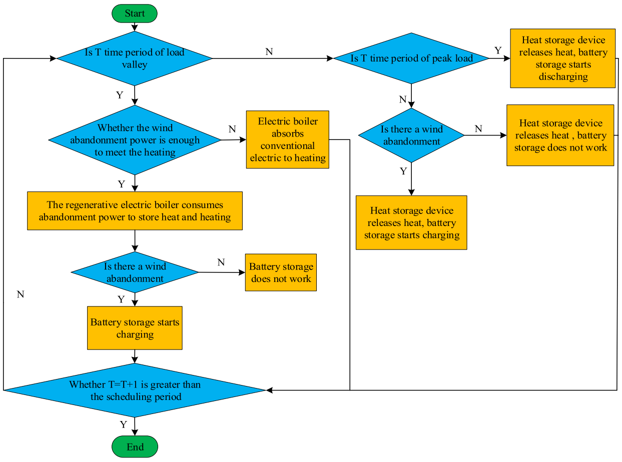


FIGURE 3. Flow chart of flexible load control strategy.

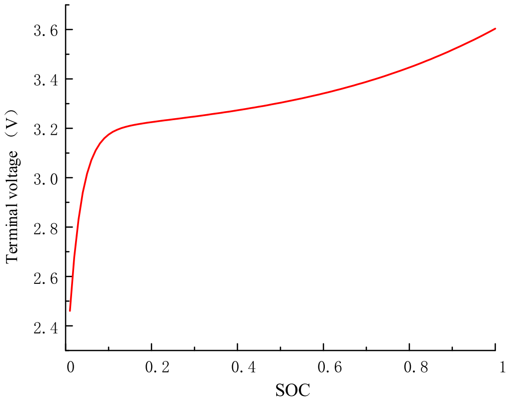


FIGURE 4. Relation diagram between SOC and terminal voltage.

Detailed parameters of a single unit are referenced in the literature [13]; The electric load data is the actual load demand of the grid in the region, and the wind power output is obtained from the historical wind speed data. It is assumed that there is no energy exchange between the regional grid and the external grid, and the scheduling time is 24 hours. The examples use the following different modes of operation to improve wind power consumption:

Mode 1: The regenerative electric boiler and energy storage do not participate in the power grid dispatching. The phenomenon of wind abandonment is more serious.

Mode 2: The regenerative electric boiler participates in the power grid dispatching. The electric load level in the power grid increases, and the heat storage can improve its operational flexibility. Under the premise of satisfying the heating, the wind abandonment should be consumed as much as possible for heating.

Mode 3: Battery energy storage participates in grid dispatching. By configuring the battery storage energy to cut the

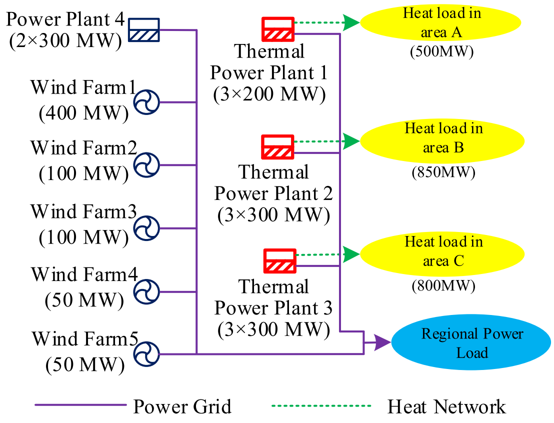


FIGURE 5. Schematic diagram of regional grid structure.

peak and fill the valley, increase the wind power consumption during the low valley period.

Mode 4: The heat storage electric boiler and energy storage are all involved in grid dispatching. Improve wind power consumption by leveraging their respective advantages.

Consider the economics of battery energy storage and heat storage electric boilers, in which the energy storage cost of the battery is 900,000 yuan/MW and 800,000 yuan/MWh, and the cost of the regenerative electric boiler is 500,000 yuan/MW and 50,000 yuan/MWh. Assume that the system adds heat load or electric energy to 60MW, and needs to be separately configured with about 230MW/1100MWh of regenerative electric boiler; when the battery energy storage is separately configured 40MW/160MWh. When the capacity of the battery energy storage is 30MW/120MWh and the regenerative electric boiler is configured at 80MW/360MWh, the cost is the same as that of the separately configured regenerative electric boiler.

The different effects of the example analysis are as follows:

Operation pattern 1: Add heating load. By renovating the users of coal-fired heating, the regenerative electric boiler is used for heating.

Operation pattern 2: Consider the replacement of electrical energy. Reduce the heat load level of the cogeneration unit and replace the heating with a regenerative electric boiler.

However, the replacement of electric energy does not have policy support (reducing the heating income of thermal power plants), and the provinces have introduced corresponding policies for the conversion of fuel into electricity.

B. MODEL SOLVING AND ANALYSIS

1) EFFECT OF ELIMINATING WIND ABANDONMENT UNDER DIFFERENT MODES OF ACTION

a: ADD HEATING LOAD

Through the transformation of coal-fired heating users, the wind power acceptance under different operating modes is shown in Figure 5.

TABLE 2. Effect of different operation mode.

Operating Mode	Consume Wind Power / MWh	Coal Saving / t
regenerative electric boiler	1354	433
battery energy storage and regenerative electric boiler	613	196
battery energy storage	158	50

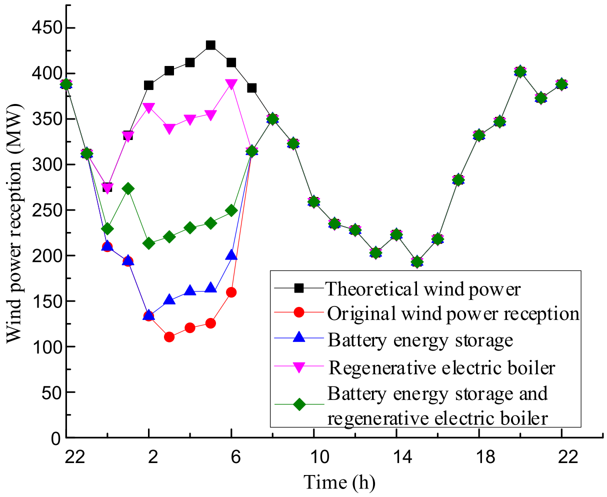


FIGURE 6. Wind Power Acceptance Under the Effect Way of Increasing New Electric Load.

Table 2 shows the different operating modes to eliminate the abandonment of wind power and coal saving.

It can be seen from the above operation results that under the same cost, and the regenerative electric boiler has the best effect of eliminating wind power under the different operation modes participating in power grid dispatching, however the battery storage energy alone receives less wind power.

b: CONSIDER THE REPLACEMENT OF ELECTRICAL ENERGY

Heating is replaced by electric energy to replace the cogeneration units, the wind power is accepted in different modes of operation as shown in Fig. 6.

According to the results of the above operation results, the different operation modes participate in the grid dispatching. The regenerative electric boiler absorbs wind power of 1580 MWh, the battery energy storage consumes 158 MWh of wind power, and the battery energy storage and regenerative electric boiler absorbs wind power of 732 MWh.

It can be seen from the above operation results that under the mode of electric energy substitution, the mode of elimination of the wind is relatively large, but the heating users of the cogeneration units is reduced, and the conditions for large-scale application are not currently available. The reason for this situation is that the replacement of electric energy does not have policy support (reducing the heating income of thermal power plants).

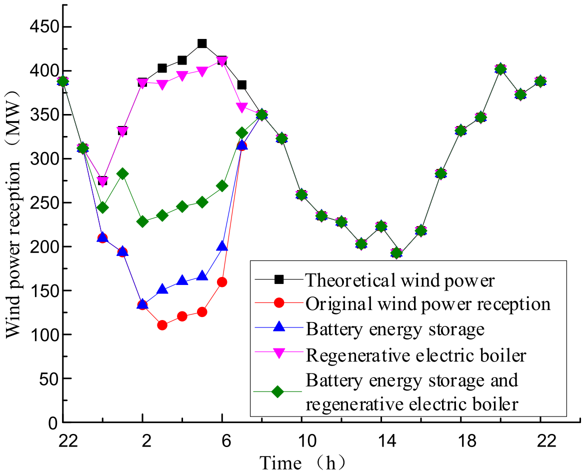


FIGURE 7. **Wind power acceptance under the effect way of electric power replacement.**

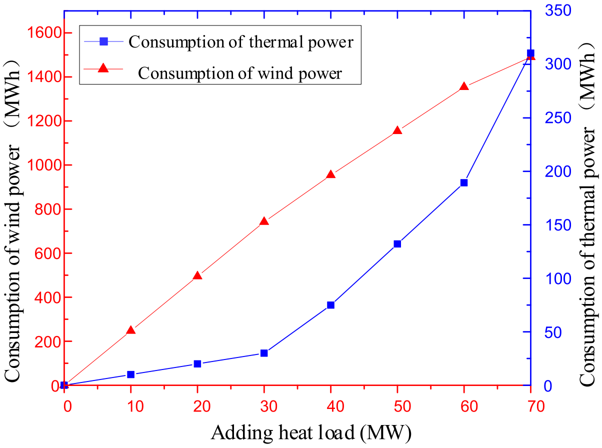


FIGURE 8. **The output of cogeneration units under the effect way of increasing new electric load.**

2) INFLUENCE OF HEAT LOAD LEVEL ON WIND POWER CONSUMPTION

In order not to affect the heating users and benefits of cogeneration units, only the impact of different thermal load levels on wind power acceptance under the new electric load mode is analyzed, as shown in Figure 7 below.

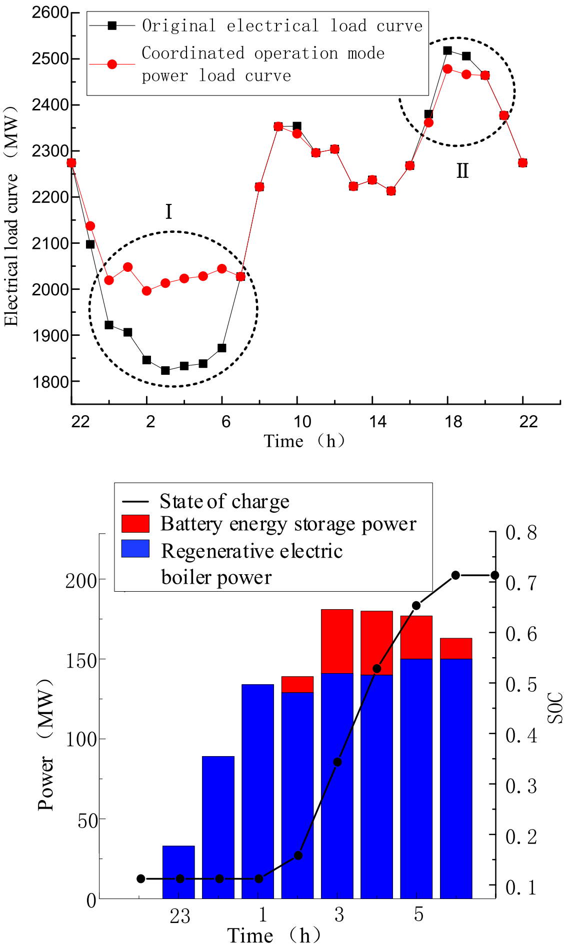
As shown in the above figure, when the new thermal load is 0, both the abandonment wind and the thermal power are both 0. when the new thermal load is 70 MW, the abandoned wind is 1490 MWh, which can reduce about 89% of the wind, but At the same time, 17.3% of the electricity used for heat supply comes from the thermal power unit, and the energy utilization efficiency is low. Therefore, the matching new heat load level should not be too large. From the above curve, when the new thermal load is 40MW, about 954MWh of wind is reduced, and about 7% of the electricity used for heating is from the thermal power unit. The new heat load level is reasonable.

(1) Advantages of coordinated operation of battery energy storage and regenerative electric boiler

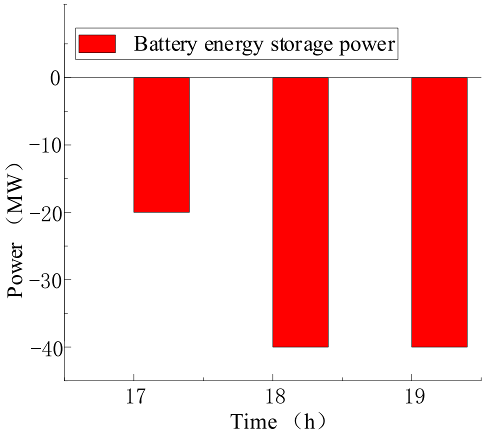
When the battery energy storage participates in the operation, the reduction of the abandonment wind is mainly affected by the expensive cost. Assuming that the cost is reduced by about 2/3 as the battery technology progresses, the new 40MW thermal load is required to be equipped with a 150MW/720MWh regenerative electric boiler. The configuration of battery energy storage 40MW/160MWh is the same as the above analysis cost, in this operation mode can eliminate the abandoned wind power is 1096MWh. The energy storage energy of the battery can flow in both directions, and it is important to reduce the peak-valley difference of the power load to improve the stability of the power system, as shown in Figure 8 below. Among them, Fig. 8 (I) and Fig. 8 (II) are enlarged diagrams of I and II in Fig. 8 respectively. Regenerative electric boilers use abandon wind power at night for heating and heating. In the daytime, they use the heat in the storage tank for heating. But at night, when only abandon wind power can not meet the heating demand, the electric boilers will purchase electricity from the power grid. Therefore, in a sense, regenerative electric boilers are also equivalent to electrical equipment and can be used as electrical load, so at night, the electric load curve is obviously improved. Storage batteries store excess wind power at night, discharge at peak hours during the day, and increase the profit of load peak-valley price difference.

Considering the adding heat load mode, when the regenerative electric boiler is configured, only the power consumption during the load low valley is increased. At this time, the original electric load peak-valley difference can be reduced to 204MW; when the battery energy storage coordination function, the peak-valley difference can be reduced to 213MW, and the effect of peak regulation is better than the regenerative electric boiler. However, due to the high cost of energy storage battery, this paper configures a relatively small capacity, just to verify that the installation of energy storage battery on the basis of regenerative electric boiler can bring benefits to the overall operation of the system. Therefore, the system can reduce the peak value to a certain extent after configuring the battery energy storage, but the effect is not very prominent because of the limitation of the capacity of the battery installed. With the continuous development of energy storage battery technology and the gradual reduction of cost, the economy of energy storage battery configuration will be further improved, and the application prospects will be broader. Therefore, as battery storage prices decrease, the coordinating operation of battery energy storage and regenerative electric boilers has potential advantages.

In summary, under the condition of considering economic factors, the regenerative electric boiler participates in the grid dispatching effect best, but with the increase of its configured capacity, the thermal power unit in the heating power is relatively large, and the energy utilization efficiency is low. Not conducive to solving the current serious haze problem; When considering the reduction of the battery storage price, coordination of regenerative electric boilers and energy storage



(I) 23:00-6:00



(II) 17:00-19:00

FIGURE 9. Pre-and post-load curve of battery energy storage and regenerative electric boiler.

batteries is the most obvious way to reduce the peak-valley difference of electric load.

V. CONCLUSION

This paper takes the "Three North" regional power grid with more serious abandonment wind as the research object, and improves the system operation flexibility by arranging battery energy storage and regenerative electric boiler to promote wind power consumption. Based on the analysis of the composition of the wind power system and the formulation of the control strategy, a grid-dispatching model including battery energy storage and regenerative electric boilers is established to analyze the wind power acceptance in different modes. The main conclusions are as follows:

(1) Under the three different operating modes of battery energy storage and heat storage, whether the regenerative electric boiler considers the adding heat load or the electric energy replacement, the wind power consumption of the regenerative electric boiler reaches 1354 MWh and 1580 MWh respectively. The effect is more than twice that of battery energy storage operation mode, coordination of battery energy storage and regenerative electric boiler, and it has reached more than twice of other operation modes in energy saving and emission reduction, and has better operation effect;

(2) When the configuration of the regenerative electric boiler is too large, more thermal power will be consumed. When the new 70MW heat load is added, 17.3% of the electricity used for heat supply comes from the thermal power unit, which affects the energy utilization efficiency;

(3) When battery energy storage and regenerative boiler are coordinated, peak-valley difference can be further reduced, peak-valley difference can be reduced to 213MW, and peak-shaving effect can be improved. The peak-valley difference of the original electric load can be reduced to 204MW by configuring the electric boiler with heat storage only.

Because the development of related technology is not mature enough, there are demonstration projects such as Datang Taonan Thermal Station Boiler Project. With the continuous innovation of technology and the investment of related pilot projects, the research and analysis of this paper can provide some reference value for the construction of practical projects. The utilization quality of battery energy storage is high. When the price of the battery energy storage is greatly reduced, the battery energy storage coordinated operation has the same capacity of peak load shifting as the regenerative electric boiler. Although the elimination of abandoned wind power is reduced, it is of great significance for the future safety and stability of high-permeability power grids.

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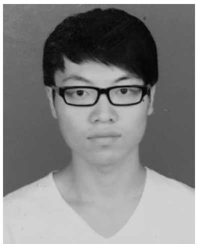

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