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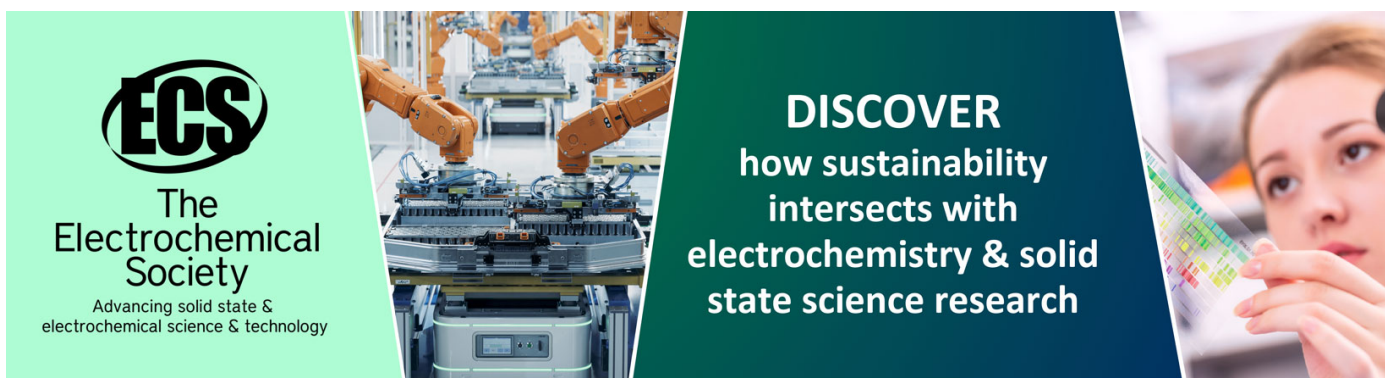
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Low-carbon economic dispatching model of electric-heating combined system considering multi-type energy storage

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Abstract. In order to reduce the wind abandonment rate during the winter heating period in the “Three North” region and the environmental pollution caused by carbon emissions during power generation, this paper proposes a low-carbon economic dispatching model that takes into account multiple types of energy storage for electric-heating combined systems. First, a multi-type energy storage model with electric boilers, electric energy storage, and heat storage as the core is proposed, and its internal energy conversion, storage, and output links are refined. Then, a carbon trading mechanism is introduced into electric heating. The combined system, taking into account the cost of carbon trading, and aiming at the lowest overall operating cost of the system, construct a low-carbon economic dispatching model for wind-power, conventional thermal power units, combined heat and power units, and multiple types of energy-storage combined heat and power systems. Yalmip/Gurobi solved the model and analysed the wind power consumption effect and carbon emission situation in the dispatching mode through numerical simulation. Simulation results show that under carbon trading, participation of multiple types of energy storage can effectively improve wind power utilization and the economic and environmental benefits of the system.

1. Introduction

With the exploitation and utilization of traditional fossil energy, the environmental pollution is becoming more and more serious. Therefore, the improvement of energy conservation and emission reduction in the power industry has attracted extensive attention from all over the world[1]. Most of the current studies only consider carbon trading or the impact of a single energy storage unit on wind power consumption and the system economic operation. Therefore, this paper proposes a low-carbon economic dispatching model that takes into account multiple types of energy storage for electric-heating combined systems.

2. Multi-type energy storage model

In order to make up for the deficiency of traditional electric energy storage effectively, a multi-type energy storage system including electric energy storage, electric heat storage and electric boiler units is constructed in this paper. The structure of the system is shown in Figure 1.



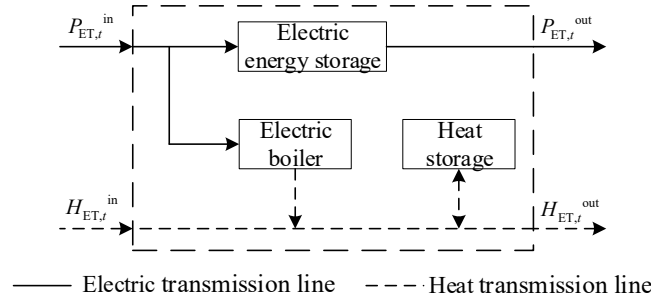


Figure 1. Multi-type energy storage system.

The internal energy conversion process is expressed as follows.

(1) Charged process

$$\begin{bmatrix} P_{ESS,t} \\ H_{ETT,t} \end{bmatrix} = \begin{bmatrix} a & 0 \\ (1-a)\eta_{EB} & 1 \end{bmatrix} \begin{bmatrix} P_{ET,t}^{in} \\ H_{ET,t}^{in} \end{bmatrix} \quad (1)$$

where $P_{ESS,t}$ is the operating power of the electric energy storage in time period t ; $H_{ETT,t}$ is the sum of the heating power of the electric boiler and the heat input power; $P_{ET,t}^{in}$ and $H_{ET,t}^{in}$ are the power input and thermal input of the multi-type energy storage system in time period t ; a is the dispatching coefficient of the energy storage device; η_{EB} is the electric heating conversion efficiency of the electric boiler.

(2) Release process

$$\begin{bmatrix} P_{ET,t}^{out} \\ H_{ET,t}^{out} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} P_{ESS,t} \\ H_{ETT,t} + H_{TES,t} \end{bmatrix} \quad (2)$$

where $P_{ET,t}^{out}$ and $H_{ET,t}^{out}$ are respectively the power and thermal output of the multi-type energy storage system in time period t ; $H_{TES,t}$ is the operating power of the electric heat storage in time period t .

Multi-type energy storage can be regarded as a virtual energy storage system with two inputs and two outputs. As an energy storage system, it has two working states of energy storage and energy output, and its external characteristics are expressed as follows:

$$\begin{cases} P_{ET,t} = P_{ET,t}^{out} - P_{ET,t}^{in} \\ H_{ET,t} = H_{ET,t}^{out} - H_{ET,t}^{in} \end{cases} \quad (3)$$

where $P_{ET,t}$ is the charge-discharge power of the multi-type energy storage system in time period t ; $H_{ET,t}$ is the heat storage and heat release power of the multi-type energy storage system in time period t . When $P_{ET,t}$ is positive, it means that the multi-type energy storage system releases electricity to the grid; when $P_{ET,t}$ is negative, it means that the system absorbs electricity from the grid. Similarly, when $H_{ET,t}$ is positive, it means that the multi-type energy storage system releases heat energy to the thermal network; when $H_{ET,t}$ is negative, it means that the system absorbs heat energy from the thermal network.

3. The carbon trading mechanism of the electric-heating combined system

The carbon trading cost of the system is mainly determined by carbon emission and carbon quota[2]. The carbon trading cost can be expressed as:

$$F = c_k (E_o - E_q) \quad (4)$$

where c_k is carbon trading price; E_o and E_q respectively refer to carbon emission and carbon quota.

In this paper, it is approximated that the unit carbon emission quota and the unit output are linearly related[3]. The carbon emission quota E_q calculated as follows:

$$E_q = \sum_{t=1}^T \lambda P_t \quad (5)$$

where λ is the carbon emission distribution coefficient per unit of electricity; P_t is the active output of all units in the system during period t .

As wind is a clean energy source, it can be considered that no carbon emissions are generated. The total carbon emission of the unit can be expressed as:

$$E_o = \sum_{t=1}^T \sum_{i=1}^n \mu_i P_{i,t} + \sum_{t=1}^T \sum_{i=1}^N \gamma_i P_{ZS,i,t} \quad (7)$$

where μ_i is the carbon emission intensity of unit output of the thermal power unit i ; γ_i the carbon emission intensity of unit output of the electric-heating combined unit i . $P_{i,t}$, $P_{ZS,i,t}$ are respectively the output of conventional thermal power units and thermal power units converted to pure condensing conditions during period t [4].

4. Low-carbon economic dispatching model of electric-heating combined system

The structure configuration and energy flow of the electric-heating combined system containing multiple-type energy storage are shown in Figure 2.

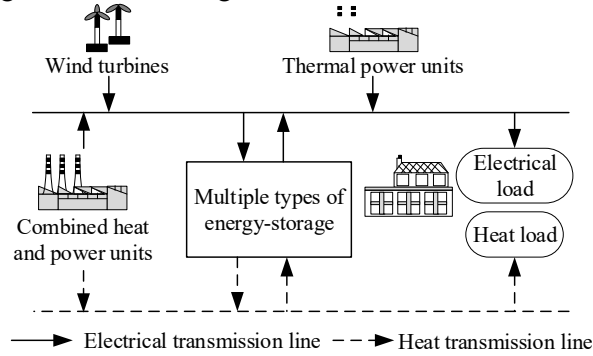


Figure 2. Structure of a combined electrothermal system with multiple types of energy storage.

4.1. Objective function

(1) Operating cost of conventional thermal power units

$$F_c = \sum_{i=1}^n \sum_{t=1}^T (a_i P_{i,t}^2 + b_i P_{i,t} + c_i) \quad (8)$$

where n is the number of units; a_i , b_i and c_i are fuel cost coefficients.

(2) Operating cost of electric-heating combined units

$$F_{CHP} = \sum_{i=1}^N \sum_{t=1}^T (a_{m,i} P_{ZS,i,t}^2 + b_{m,i} P_{ZS,i,t} + c_{m,i}) \quad (9)$$

where N is the number of combined electric and heat units; $a_{m,i}$, $b_{m,i}$ and $c_{m,i}$ are the generating cost coefficients of the combined electric and heat unit i .

(3) Operation and maintenance cost of wind turbines

$$F_{wl} = k_m \sum_{t=1}^T P_{w,t} \quad (10)$$

where k_m is the operation and maintenance cost coefficient of the wind turbine.

(4) Cost of curtailed wind power punishment

$$F_{w2} = c_{mq} \sum_{t=1}^T (P_{WF,t} - P_{w,t}) \quad (11)$$

where $P_{WF,t}$ is the predicted output of the wind turbine at time t ; c_{mq} is the wind curtailment punishment coefficient.

(5) Operating cost of multi-type energy storage

Multi-type energy storage system is composed of electric boiler units, electric power storage devices and electric thermal storage devices. The operating cost is expressed as:

$$F_{EF} = c_{ESS} \sum_{t=1}^T P_{ESS,t} + c_{TES} \sum_{t=1}^T H_{TES,t} + c_{EB} \sum_{t=1}^T P_{EB,t} \quad (12)$$

where F_{EF} is the operating cost of multi-type energy storage; c_{ESS} , c_{TES} and c_{EB} are the operating cost coefficients of electric power storage device, thermal storage device and electric boiler device; $P_{EB,t}$ is the electric boiler device operating power in time period t .

To sum up, the objective function with the lowest comprehensive operation cost of the system can be expressed as follows:

$$\min F = F_c + F_{CHP} + F_{w1} + F_{w2} + F_{cq} + F_{ET} \quad (13)$$

where F is the comprehensive operation cost of electric-heating combined system.

4.2. Constraints

(1) Electrical and thermal balance constraints

$$\sum_{i=1}^n P_{i,t} + \sum_{i=1}^N P_{CHP,i,t} + P_{w,t} + P_{ET,t} = P_{load,t} \quad (14)$$

$$\sum_{i=1}^N H_{CHP,i,t} + H_{ET,t} = H_{load,t} \quad (15)$$

where $P_{load,t}$ and $H_{load,t}$ are the electrical load and thermal load demand of the system at time t respectively.

(2) Thermal power unit constraints

$$P_{min,i} \leq P_{i,t} \leq P_{max,i} \quad (16)$$

where $P_{min,i}$, $P_{max,i}$ are the lower limit and upper limit of the output of thermal power units.

(3) Combined heat and power units constraints

$$\begin{cases} P_{CHP,i,t} \geq \min \{ c_{mi} H_{CHP,i,t} + K_{c,i}, P_{CHP,min,i} - C_{v,i} H_{CHP,i,t} \} \\ P_{CHP,i,t} \leq P_{CHP,max,i} - C_{v,i} H_{CHP,i,t} \end{cases} \quad 0 \leq H_{CHP,i,t} \leq H_{max,CHP,i} \quad (17)$$

where $P_{CHP,min,i}$ and $P_{CHP,max,i}$ are the minimum and maximum electrical output of the unit i under pure condensing conditions; c_{mi} is the elastic coefficient of the unit under back pressure conditions; $H_{max,CHP,i}$ is the upper limit of the thermal output of the unit.

(4) Wind turbine constraints

$$0 \leq P_{w,t} \leq P_{WF,t} \quad (18)$$

(5) Operating power constraints of electricity storage

$$\begin{cases} 0 \leq P_{cha,t} \leq \varepsilon_{cha,t} P_{cha,max} \\ \varepsilon_{dis,t} P_{dis,max} \leq P_{dis,t} \leq 0 \\ \varepsilon_{cha,t} + \varepsilon_{dis,t} = 1 \end{cases} \quad (19)$$

where $P_{cha,max}$ and $P_{dis,max}$ are the upper limit of the charging and discharging power of the energy storage device (charging is positive and discharging is negative); $\varepsilon_{cha,t}$ and $\varepsilon_{dis,t}$ are charge and discharge signs, and their values are 0-1 variables. The above formula indicates that when $P_{ESS,t} \geq 0$, $P_{cha,t} = P_{ESS,t}$, the energy storage is working in the charging state; In the same way, when $P_{ESS,t} \leq 0$, $P_{dis,t} = P_{ESS,t}$, the energy storage is working in the discharge state.

(6) Operating power constraints of thermal storage device

$$\begin{cases} 0 \leq H_{cha,t} \leq \varepsilon_{hcha,t} H_{cha,max} \\ \varepsilon_{hdis,t} H_{dis,max} \leq H_{dis,t} \leq 0 \\ \varepsilon_{hcha,t} + \varepsilon_{hdis,t} = 1 \end{cases} \quad (20)$$

where $H_{cha,max}$, $H_{dis,max}$ is the upper limit and release power of the thermal storage device (heat storage is positive, heat release is negative); $\varepsilon_{hcha,t}$, $\varepsilon_{hdis,t}$ is the thermal storage and thermal release sign. When $H_{TES,t} \geq 0$, $H_{cha,t} = H_{TES,t}$, then the thermal storage device is working in the heat storage state; In the same way, when $H_{TES,t} \leq 0$, $H_{dis,t} = H_{TES,t}$, the thermal storage device is working in the heat release state.

(7) Operating power constraints of electric boilers

$$0 \leq P_{EB,t} \leq P_{EB,max} \quad (21)$$

Where $P_{EB,max}$ is the upper limit of the operating power of the electric boiler.

5. example analysis

5.1. Results and analysis

Take a region in northeast China as an example to build model. In order to simplify the analysis and calculation, all the generator sets in the test system are set up with one set[5]. In this paper, the Yalmip toolbox is used to establish electro-thermal combined system low-carbon economic dispatch model, which include multiple types of energy storage, and the Gurobi commercial optimization software is called to solve the model.

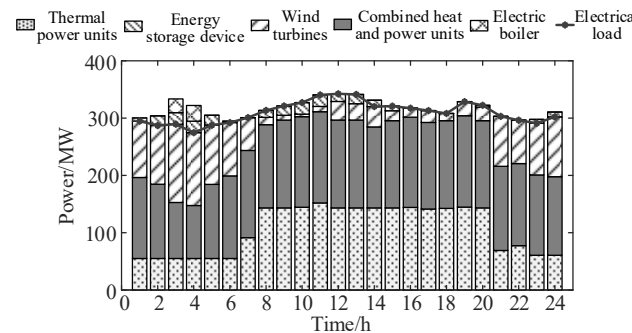


Figure 3. Electric power optimization results of each unit.

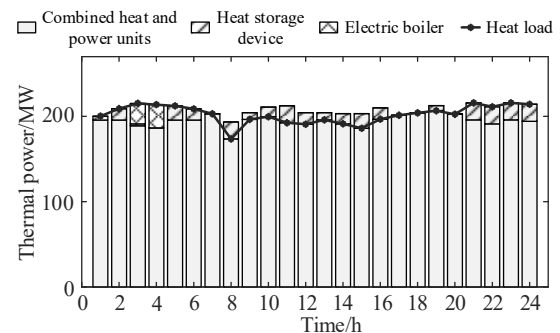


Figure 4. Thermal output optimization results of each unit.

The electric power optimization results of each unit in the dispatch cycle are shown in Figure 3. It can be seen that during the night time period when the electrical load demand is low, the output of the power supply can be appropriately increased, and the part that exceeds the electrical load is stored in the energy storage device; while during the day when the electrical load demand is high, the power output can be appropriately reduced, and the output shortage is compensated by the electricity stored before the energy storage releases.

The thermal output optimization results of each unit in the dispatching period are shown in Figure 4. It can be seen that the heat storage device only realizes the translation of the heat load From 8:00 to

16:00, the system heat load level is low, and the thermal output of the thermal power unit can store excess heat in the heat storage device when the thermal load condition is met. When the thermal load level is high at night, the thermal output of the thermal power unit can be appropriately reduced. The shortfall in heat supply can be compensated by the heat storage device and the electric boiler.

5.2. Optimal dispatching model comparison

In order to verify the effectiveness of the proposed model for wind power consumption and economic and environmental benefits, the following two scheduling modes are set:

Method 1 is a multi-type energy storage dispatching method considering carbon trading. Method 2 is a dispatching mode of electric energy storage system considering carbon trading.

The effect of wind power consumption under different dispatching methods is shown in Figure 5. It can be seen that Method 1 achieves wind power consumption completely. This dispatching method realizes the collaborative optimization of electrical storage device, heat storage device and electric boiler, thereby improving the overall flexibility of the system and effectively promoting the integration of wind power.

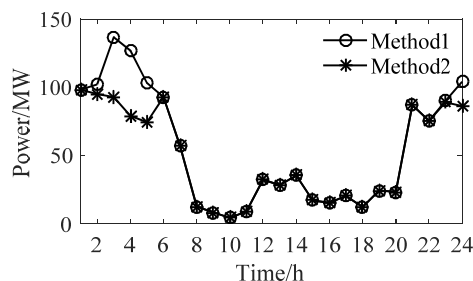


Figure 5. Comparison of wind power consumption effects.

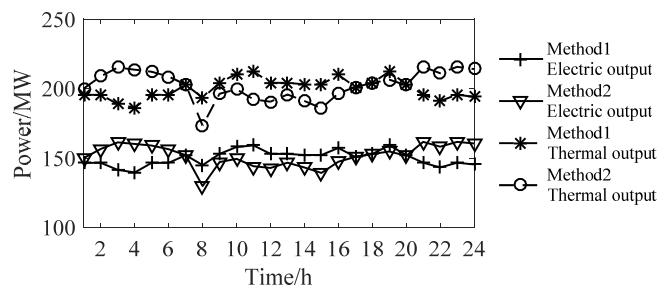


Figure 6. Comparison of output of thermoelectric units.

Figure 6 shows the output of the thermoelectric unit under different dispatching methods. As can be seen from the figure, the thermal output of the thermal power unit of Method 2 needs to be balanced with the thermal load at all times, so its regulation ability is limited.

Figure 7 is a comparison of the system's carbon emissions under different dispatching methods. It can be seen that the carbon emissions of Method 1 are significantly lower than Method 2 at night, and slightly higher than Method 2 during the day. This is because the heat storage device's heat storage results in a higher output of the combined electric and heat unit than Method 2. However, in the entire dispatch cycle, the carbon emission reduction effect of Method 1 is more advantageous than Method 2.

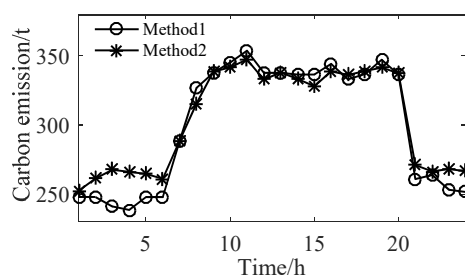


Figure 7. Comparison of carbon emissions.

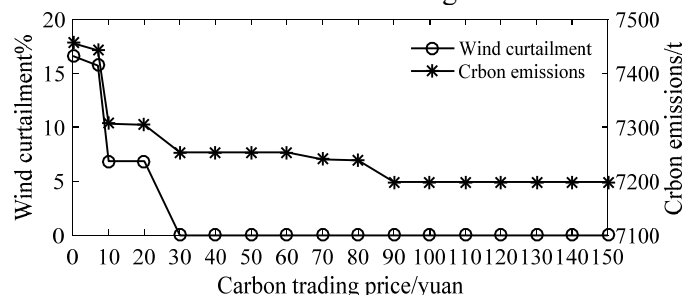


Figure 8. Impact of carbon trading price on system scheduling results.

From the comparison results of the economic and environmental benefits of the two dispatching methods, it can be seen that the total cost of Method 1 is reduced by 15600 yuan compared with Method 2, the amount of wind curtailment was reduced by 11.06%, achieve complete wind power consumption; carbon emissions have been reduced by 103.57t. Therefore, the dispatch method mentioned in this chapter can further improve the system's wind power consumption and economic and environmental benefits.

5.3. The influence of carbon trading price on dispatching results

Whether a power generation company can profit in the carbon trading market can be determined by the carbon emissions it generates and the allocated carbon quotas. But the weight of carbon trading costs in economic dispatch is affected by the carbon trading price. Therefore, this paper further explores the impact of different carbon trading prices on the system's wind curtailment and carbon emissions on the basis of considering multiple types of energy storage. The simulation results are shown in Figure 8.

It can be seen that the carbon trading price is higher than 30 yuan, the system can completely consume wind power. This is because after considering the carbon trading cost, the operating cost of the wind turbine is lower than that of the coal-fired unit. The system will give priority to the wind power to connected the grid. If the carbon trading price continues to increase beyond RMB 90, the carbon emissions of the system will reach the minimum and remain the same. Taking into account the carbon trading costs, although the operating costs of thermal power unit and combined heat and power unit are increasing, the growth rate is different. When the carbon trading price increases to a certain level, the operating cost of the thermal power unit will be lower than that of the combined heat and power units, which will change the dispatching order of the thermal power and combined heat and power units, that is, the system will prioritize the generation of thermal power units with low carbon emission intensity.

6. Conclusions

The results of calculation examples show that compared with the integrated operation cost of dispatching mode considering single electric energy storage operation, the cooperative operation cost of the multi-type energy storage system is reduced by 15,600 yuan, the wind abandoning capacity is reduced by 11.06%, the carbon emission is reduced by 103.57 t, and wind power generation is completely consumed. Therefore, the dispatching method proposed in this paper can effectively improve the system's wind power consumption and economic and environmental benefits.

The carbon trading price has a great influence on the low-carbon economic dispatching results of the system. The low price of carbon trading will lead to the failure of carbon trading to fully play its role in the optimization of system power supply structure. However, the high price of carbon trading will increase the operating cost of the system. The high price will also discourage power producers from participating in the carbon market. Therefore, it is necessary to set a reasonable carbon trading price according to the local conditions.

Acknowledgments

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