



Coordinated dispatching strategy of multiple energy sources for wind power consumption

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Abstract Heat storage systems with multiple heat sources play an important role in consuming extra wind power. A reasonable scheduling strategy for a hybrid system with multiple heat and electric sources could provide greater economic benefits. However, the present scheduling methods primarily focus on extra wind power consumption alone. This paper aims to develop a coordinated dispatching method that targets the maximum extra wind power consumed and highest economic benefit of the hybrid energy system as the optimization objective. A two-step coordinated dispatching method is proposed, where the first step focuses on optimizing the extra wind power consumed by coordinating the consumption quota for different types of energy sources at the system level and distributes the consumption share for every unit within each type of energy source, thereby maximizing fuel savings and economic benefits in the second step. The effectiveness of the approach is demonstrated using simulation results for an electric-heat hybrid system. Compared with two existing

dispatching methods, the scheduling strategy presented in this paper could consume more extra wind power and provide higher fuel savings and economic benefits.

Keywords Coordinated dispatching, Wind power consumption, Combined heat and power (CHP), Primary heat circuit (PHC), Electric boiler, Heat storage tank (HST)

1 Introduction

During the cool seasons in the northern regions of China, the valley period of electric load is the key slot that maintains the frequency stability and power balance of the power grid. Meanwhile, with the vast integration of renewable energy, especially the wind power, higher demand at peak load regulation capacity leads to volatility, intermittency and anti-peak regulation of wind power. Therefore, wind power abandonment occurs frequently and the curtailed wind energy causes sorrow for stakeholders [1]. During the peak and medium load periods, the ordering power by heat (OPBH) policy does not significantly affect the operation of combined heat and power (CHP) units due to their relatively high electric power requirements. However, at night, the electric load declines and the heat load increases as the outdoor temperature drops. The opposite change between heat and electric load aggravates the contradiction between heat and electric power outputs from CHP units. Hence, due to the limits imposed on the OPBH policy, the heat output from CHP units must be kept at a higher level as well as the electric output. Therefore, some wind power sources must be abandoned to guarantee the stability and safety of the power grid [2].

An energy storage system (ESS) could shift energy generation and demand backward or forward in time. Thus,

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it becomes the primary approach for stabilizing power and energy fluctuations from renewable energy sources [3, 4]. Heat storage system is a type of ESS that contains several auxiliary heat sources such as electric boilers (EBs), heat pumps and heat storage tanks (HSTs). An approach that uses the heat storage capacity of a primary heat circuit (PHC) in a heat network to promote the consumption of wind power is introduced in [5]. As the range of heat and electric sources increases, the operation and control modes of those sources influence the economical efficiency of the hybrid energy systems and wind power consumption. Thus, an appropriate scheduling method for multiple energy sources is of importance.

Wind power is characterized by its nonlinearity and high dispersion, and researchers have developed a series of optimization algorithms for dispatching energy sources to address integration such as Lagrange relaxation method [6, 7], heuristic algorithms [8], dynamic programs [9, 10], and modern intelligent optimization algorithms [11]. Reference [12] introduces an approach for using compressed air energy storage for wind power consumption and optimizes the control technique based on its economic operation. Based on state quantity prediction technology, an optimized control technique for ESS using batteries in wind farms is presented in [13], which could improve the tracking of output power from wind farm and dispatching instructions. Reference [14] proposes an optimized control method for ESS based on the charge state feedback in the ESS. In order to decrease the charging/discharging frequency and prolong the service life of an ESS, a scheduling method for an ESS that takes the longest charging/discharging time and minimum power output volatility as the optimization objective is proposed in [15]. Reference [16] reviews the optimal allocation and control of multiple energy sources in a power system. The cooperation between EB and CHP could improve the flexibility of a power system and increase the consumption capacity of renewable energy. The peak regulation capacity of a CHP with an HST is evaluated and an electric-heat power dispatching model for a hybrid power system is built in [17] with the goal of minimizing coal consumption. In [18], it is proposed that the additional HSTs should be setup alongside CHPs to increase the capacity for wind power consumption. Reference [19] proposes an optimal operating strategy for HSTs that aims to minimize the operation cost of the power system. To summarize, most of prior research focuses on scheduling multiple energy sources. However, aiming at a large-scale power grid, the present research is primarily focused on a single energy storage technique. Furthermore, studies on coordinated dispatching among multiple energy sources are concentrated on microgrids [20, 21].

A multiple energy ESS that combines a high energy density technique could preferably accommodate a high

level of renewable energy integration. An appropriate scheduling method arranges the operation of energy storage units into different types and can accommodate different energy storage techniques, guaranteeing economic operation of the power system.

The main contributions of this research are as follows.

- 1) Clarification of the operation mode of energy sources: this work clarifies the control methods of EB, PHC, HST, and CHP. The differences among the control methods are analyzed to distinguish the utilization of energy sources for consuming extra wind power.
- 2) Problem formulation: the coordinated dispatching model is formulated as a two-step optimization problem. In the first step, extra wind power consumption is the optimization objective, where energy sources are adjusted at the system level to achieve a predefined goal. The fuel savings and economic benefits are maximized by considering the operation of energy sources in different working conditions. The dynamic programming algorithm is used to guarantee that the most economical unit could be properly utilized.
- 3) Performance evaluation: simulations are performed for an electric-heat hybrid system. Wind power abandonment could be dropped from 52.2% to 4.8%. Approximately, 890 MWh of surplus wind energy could be absorbed by the cooperation between multiple heat sources, comprising 214 MWh, 302 MWh, and 374 MWh for PHC, HST, and EB, respectively. Compared with the existing dispatching methods, the extra wind power consumed in the approach described herein is approximately 24% higher than that consumed under the equal distribution method (EDM) and is approximately 1.5% higher than that consumed under the equal proportion distribution method (EPDM). The corresponding economic benefits which are brought by fuel savings are 17.3% and 6.7% higher than that under EDM and EPDM, respectively.

2 Operation of heat sources

2.1 Control method for additional heat sources

2.1.1 Control method of EB

The adjustment rate of an EB is fast and could be continuously controlled within the full operation range, thus the EB has remarkable traceability to the net load power of the grid. Compared with other additional heat sources, the EB has the largest wind power consumption capacity because it could promote wind power

consumption by increasing the electric demand and reducing heat required by the CHP unit. The total operation power of the EB in the grid is based on the surplus wind power capacity. Each EB has a corresponding HST. Thus, the workload of each EB is determined by the storage in the HST, and the destination of heat transformed from electricity will depend on whether the surplus wind power could be absorbed by the increased electric load alone. Figure 1 illustrates the control method of EB.

When the wind power could not be consumed by the power grid, the stored heat in the HST and PHC should be checked. If the extra wind power could be consumed by the released heat from the HST and PHC, then the EB would not function. Otherwise, the EB starts increasing the electric load to consume extra wind power. The extra wind power could be consumed by boosting the electric load applied to the EB and the generated heat could be stored in the HST when the HST is not full or the heat should be sent to the heat network. If the extra wind power could not be consumed by only increasing the electric load, heat from the EB should be sent directly to the heat network to reduce

the heat load of the CHP, followed by decreasing its electric power output.

2.1.2 Control method of HST

If the power balance in the power grid could be maintained, no wind power would be curtailed, and the state of storage (SOS) of the HST should be determined. If sufficient heat energy is stored in the HST, then the HST will not absorb heat from the heat network. Otherwise, the HST should store more heat from the CHP or EB.

If more wind power is generated and could be integrated into the grid or consumed by PHC, the HST should release its storage to reduce the heat demand of the CHP and then decrease its electric power output, thereby creating extra consumption capacity of wind power. The control method of HST is shown in Fig. 2.

2.1.3 Control method of PHC

The PHC could be considered as a heat storage facility with huge storage capacity, thus the control method is similar to that for the HST. In order to maximize the stored heat, the heat medium in the PHC should remain at a relatively high temperature before the valley load period. If no wind power abandonment occurs, the temperature and flow velocity of the heat medium in the PHC could be kept constant. The temperature differences between each heat exchanger are constant when the input heat approaches that transmitted to the secondary heat circuit. When wind power abandonment occurs, the PHC could provide additional

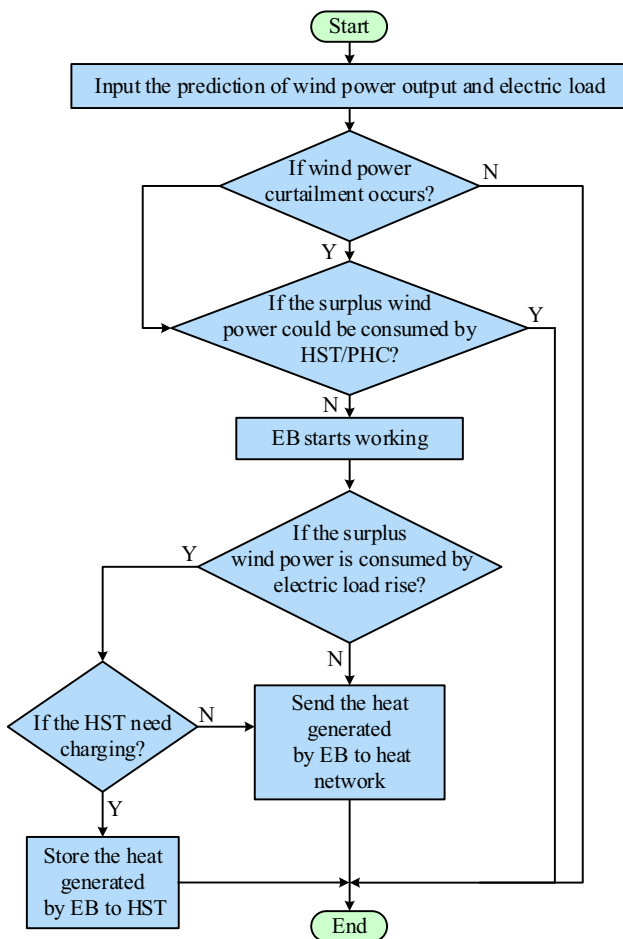


Fig. 1 Control method of EB

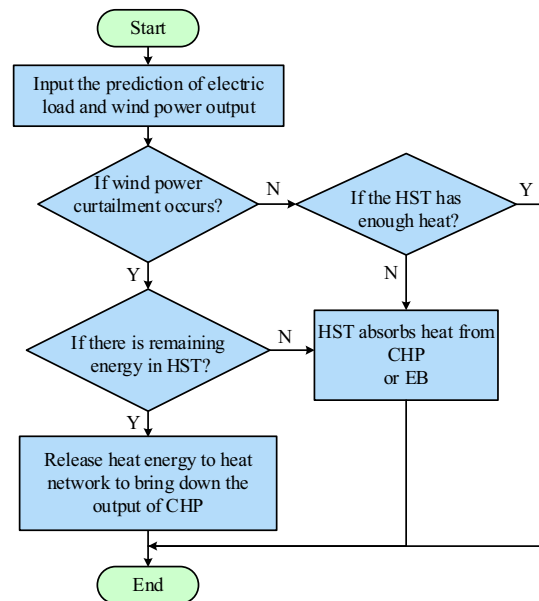


Fig. 2 Control method of HST



heat to the heat load and the electric power output of CHP could be reduced to integrate surplus wind power when the heat medium in PHC is hotter than the lower limit. Otherwise, the PHC could not increase wind power consumption as heat storage becomes exhausted. Figure 3 shows the control method of PHC.

2.2 Control method of CHP

The control method of CHP is shown in Fig. 4.

The CHP unit is an electric power source for an electric system and the main heat source for a heat network. Hence, when adjusting its electric power output, the heat output must be coordinated with additional heat sources and the heat network. Similar to other energy sources, wind power consumption will be initially determined. If available wind power could not be fully consumed, then the heat stored in the PHC and HST will be determined, followed by calculating the additional heat supplied by the PHC, HST, and EB. The electric power and heat output from the CHP are confirmed and the allowed power output reduction is subsequently determined. The electric power output from the CHP can then be decreased, allowing the consumption of extra wind power in the grid. If the PHC and HST could not consume extra wind power, the electric power input to the EB will increase and provide additional heat to the heat network.

2.3 Comparison of control methods

Table 1 shows a comparison of the control methods, from which one finds that only the EB consumes extra wind power by increasing its electric load and decreasing

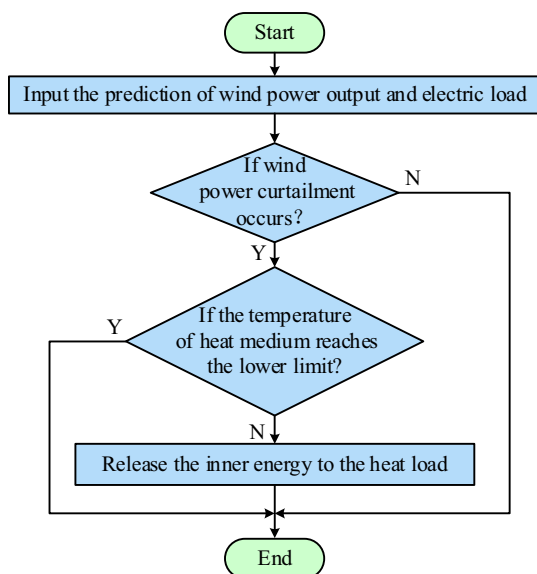


Fig. 3 Control method of PHC

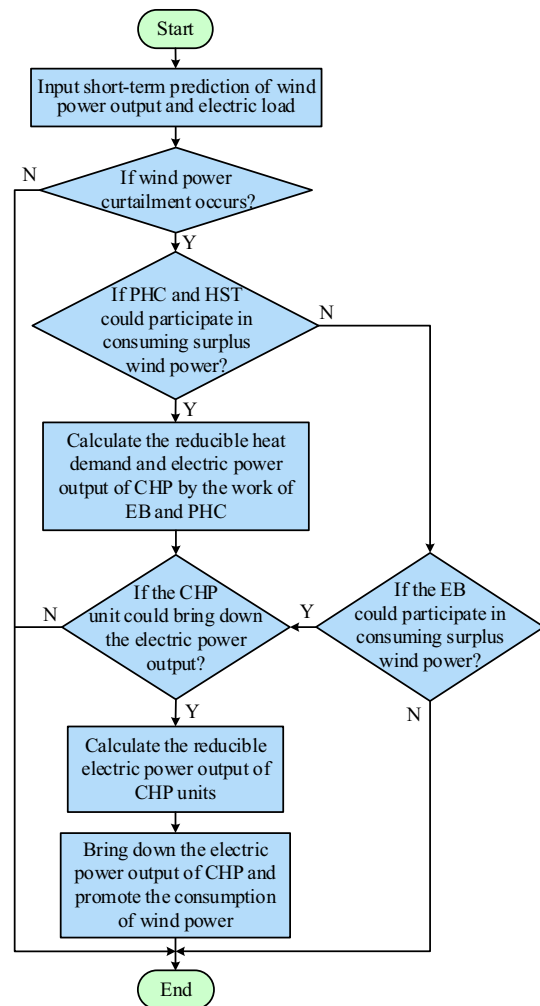


Fig. 4 Control method of CHP unit

Table 1 Comparison of various control methods

Item	EB	HST	PHC	CHP
Increasing electric load	Yes	No	No	No
Regulating speed	Fast	Slow	Slow	Slow
Storage capacity	None	Medium	Huge	None
Acting position	ES&HS	HS	HS	ES&HS

the heat load of the CHP. However, other methods involve decreasing the heat load of the CHP and decreasing the electric power output from the CHP. The regulating speed of the EB is as high as its power capacity adjustment. Meanwhile, other methods influence the electric system (ES) by affecting the electric power output from the CHP, thus their regulation speed is relatively slower than that of the EB. The EB and CHP have no heat storage capacity, thus a significant amount of heat medium is contained in

the PHC, endowing the PHC with huge heat storage capacity. While the heat storage capacity of an HST depends on the tank volume. The EB could act as an electric load and a heat source, and a CHP is both an electric and heat source. Therefore, the EB and CHP are electric and heat systems. The HST and PHC consume extra wind power by affecting the heat load of the CHP, thus the HST and PHC are only HSs.

3 Coordinated dispatching model of multiple heat sources

3.1 Optimization objective of coordinated dispatching

The total operation cost of the hybrid system with the coordinated dispatching scheme is minimized when wind power consumption is maximized. The total operation cost includes the operation cost of the CHP, EB, and HST. The PHC is an inherent facility within a heat network, and its operation cost could be ignored. The objective function for coordinated dispatching can be defined as:

$$\min C_{dis} = C_{CHP} + C_{EB} + C_{HS} \tag{1}$$

where C_{dis} is the total operation cost; and C_{CHP} , C_{EB} , and C_{HS} are the operation costs of the CHP, EB, and HST, respectively.

The operation cost of CHP is:

$$C_{CHP,i}^t = b_{coal}\alpha_i(P_{i,e}^t)^2 + \beta_i P_{i,e}^t + C_i + \theta_i(P_{i,h}^t)^2 + \delta_i P_{i,h}^t + \xi_i P_{i,h}^t P_{i,e}^t \tag{2}$$

where $C_{CHP,i}^t$ is the operation cost of CHP i at moment t ; $P_{i,e}^t$ and $P_{i,h}^t$ are the electric and heat power provided by CHP i at moment t , respectively; b_{coal} is the price of coal; and α_i , β_i , C_i , δ_i , θ_i , ξ_i are the CHP operation cost coefficients, which could be derived from economic coefficients.

The operation cost on EB is mainly determined on the electricity price for EB working. The electricity used by EB could be equivalent to the surplus wind energy, thus, the holder of EB could negotiate with wind farm for a much lower electricity price. The operation cost on EB is:

$$C_{EB,i}^t = \tau_i P_{EB,i}^t \tag{3}$$

where $C_{EB,i}^t$ and $P_{EB,i}^t$ are the operation cost and working power of EB i at moment t , respectively; and τ_i is the electricity price for EB i .

The operation cost of HST includes the cost of heat source and the cost of the accessory equipment.

$$C_{HS,i}^t = C_{sto,i}^t + C_{ope,i}^t = \lambda_i P_{sto,i}^t + \eta_i (P_{sto,i}^t + P_{release,i}^t) \tag{4}$$

where $C_{HS,i}^t$ is the operation cost of HST i at moment t ; $C_{sto,i}^t$ and $C_{ope,i}^t$ are the costs of the heat source and accessory equipment of HST i ; λ_i is the heat price; η_i is the operation cost of the accessory equipment; and $P_{release,i}^t$, $P_{sto,i}^t$ are the release and store power HST i at moment t , respectively.

3.2 Operation constraints of coordinated dispatching

The operation constraints of coordinated dispatching among the electric and heat sources contain the energy balance limit, the coupling relationship between electric and heat output of CHP, the ramping rate of CHP and the operation limits of EB and HST.

4 Two-step optimal model of coordinated dispatching

The optimization of the dispatching strategy among the heat sources proceeds via two steps as shown in Fig. 5. The first step is on the system level, which confirms the consumption capacity of surplus wind power for each heat source (EB, HST, PHC, and CHP). The optimization objective at this level is to maximize the consumption of surplus wind power. The second step is at the unit level, which determines the consumption quota for each unit with various heat sources. The optimization objective at this level is to minimize the total operation cost of the hybrid system.

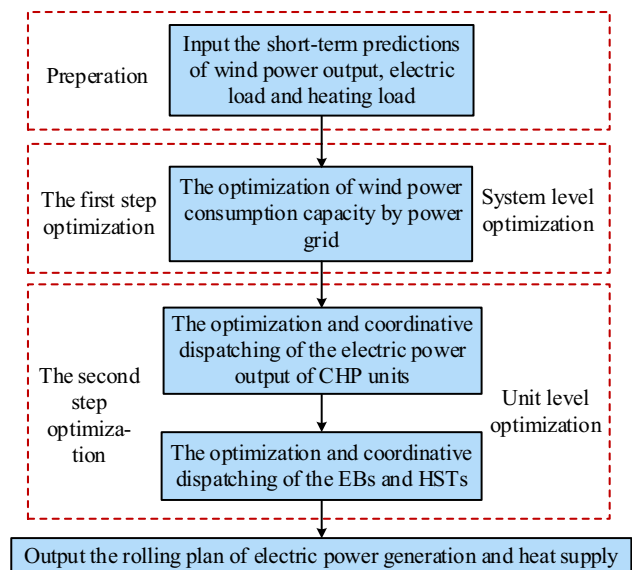


Fig. 5 Two-step optimization algorithm for coordinated dispatching of multiple heat sources

4.1 System level optimization

The surplus wind power consumption, and heat compensation from the EB, HST, and PHC are determined at each time step during the first optimization step. The surplus wind power consumption could be divided into 2 parts: the increased electric load from the EB and the reduced CHP electric power output:

$$\Delta P_{\text{curt},wt} = \sum_{i=1}^{N_{\text{CHP}}} P_{\text{CHP},i,t}^{\text{down}} + \sum_{j=1}^{N_{\text{AHS}}} P_{\text{EB},j,t} \tag{15}$$

where $\Delta P_{\text{curt},wt}$ is the surplus wind power consumption; $P_{\text{CHP},i,t}^{\text{down}}$ is the reduced electric output of CHP i ; and $P_{\text{EB},j,t}$ is the power input to EB j at moment t .

Exterior heat is supplied by 3 sources: the discharged heat from HST $H_{j,t}^{\text{HS}}$, the transformed heat from EB $H_{j,t}^{\text{EB}}$, and the heat released from PHC $H_{X,t}^{\text{PHC}}$:

$$H_{\text{AHS},t} = \sum H_{j,t}^{\text{HS}} + \sum H_{j,t}^{\text{EB}} + \sum H_{X,t}^{\text{PHC}} \tag{16}$$

where $H_{\text{AHS},t}$ is the exterior heat.

4.2 Unit level optimization

4.2.1 Coordinated dispatching of CHP

Dynamic programming is used to optimize the de-rating quota among CHP units and minimize the total operation cost of CHPs.

Dynamic programming is used to divide the global problem into several sub-problems and solve them in sequence. Every local solution for the sub-problems is listed, and the optimal solution is chosen as the sub-solution according to the problem constraints. The sub-solution for the last sub-problem has an influence on the next sub-problem. The remaining sub-problems can be solved in the same manner. The sum of the sub-solutions could be considered as the optimal solution for the global problem. Figure 6 shows a flowchart of the dynamic programming algorithm used in this paper.

The total decreased electric power output from the CHP is chosen as the global optimization problem. And the total power output is divided into several parts, where each part is a sub-problem. All possible combinations of CHP unit outputs are listed as local solutions, then the lowest dispatching cost for all CHP units is used as the determining criterion to confirm the optimal share quota for each CHP unit, which is the sub-solution for the sub-problem. After optimizing all sub-problems, the global optimal solution is equal to the sum of the sub-solutions, yielding the optimal electric power output for each CHP unit.

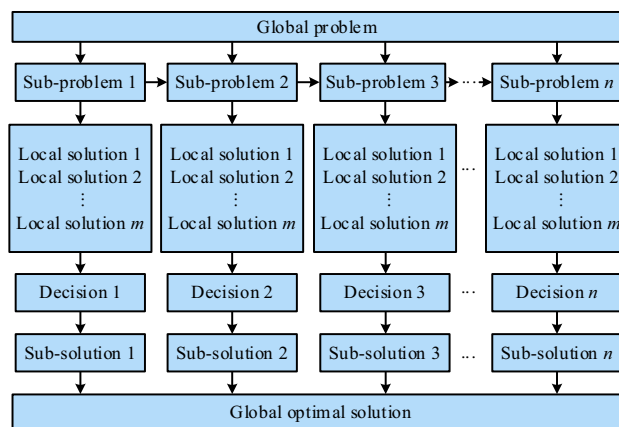


Fig. 6 Flowchart of dynamic programming algorithm

4.2.2 Coordinated dispatching of EB and HST

The heat input to each EB and HST is determined using the reduced heat supplied by their corresponding CHP:

$$\Delta H_{\text{CHP},j,t}^{\text{down}} = H_{\text{HS},j,t} + H_{\text{EB},j,t} \tag{17}$$

where $\Delta H_{\text{CHP},j,t}^{\text{down}}$ is the reduced heat output from CHP j at moment t ; and $H_{\text{HS},j,t}$, $H_{\text{EB},j,t}$ are the heat input to HST j and EB j , respectively.

Comparing the heat costs for an EB, HST, and PHC, the heat stored in an HST and PHC come from the heat system, while it is transformed from electricity for EB. Therefore, the heat cost for an EB should be higher than that for an HST or PHC. Therefore, the heat in an HST and PHC should be preferentially utilized.

The EB could absorb surplus electricity directly as an electric load, or it could supply additional heat to a CHP, allowing the CHP to reduce its electric power output. Therefore, the surplus wind power consumption capacity of an EB is higher than that of an HST or PHC. Meanwhile, the heat generated by an EB is transformed from electricity. The heat cost of an EB depends on the price of electricity. Generally, the heat cost for an EB is higher than that for an HST or PHC, thus the EB should be used when surplus wind power could not be fully consumed by HST and PHC.

5 Case study

5.1 Simulation model

The heat and electric hybrid system introduced in [22] is used as a simulation model with certain modifications. The CHP units and their economic parameters are shown in Table 2.

Table 2 Number and economic parameter of CHP

Heat zone	CHP No.	Rated power (MW)	a	b	c	c_m
A	1	240	0.000076	0.2716	18.822	0.75
	2	240	0.000076	0.2716	18.822	0.75
B	3	330	0.000072	0.2292	14.618	0.75
	4	240	0.000171	0.2705	11.537	0.75
C	5	240	0.000171	0.2705	11.537	0.75
	6	240	0.000171	0.2705	11.537	0.75

Table 3 Configuration of heat source

Heat zone	Storage in PHC (MWh)	CHP No.	Rated power of EB (MW)	Rated heat output of HST (MW)	Rated storage of HST (MWh)
A	120	1	30	30	30
		2	30	30	30
B	110	3	35	35	35
		4	20	20	20
C	80	5	20	20	20
		6	20	20	20

The total installed power capacity of EBs in the hybrid system is 155 MW with no heat storage capacity. The total installed charging/discharging power of an HST 155 MW, and the total installed storage capacity of the HST is 155 MWh. The energy stored in an HST is limited from 30% to 90%. The available heat storage in the PHCs are 120 MWh, 110 MWh, and 80 MWh, respectively. The configuration of the heat source is shown in Table 3.

The heat load data for the No. 2 Thermal Power Corporation of Changchun, China in three consecutive days and the hourly average heat load are in the simulation model, as illustrated in Fig. 7. It is assumed that the heat load is stable during each hour. The EB has an outstanding

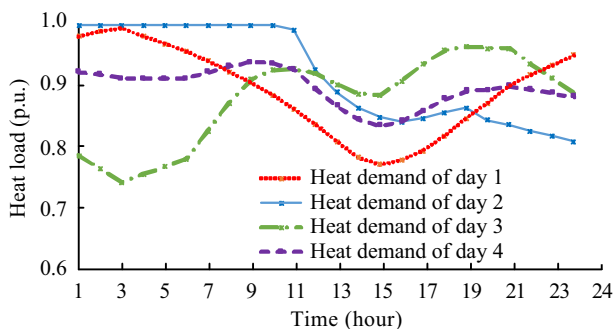


Fig. 7 Hourly heat load

power adjusting ability, and it could play an important role in tracing errors in the predicted wind power. Before each adjusting interval, if the predicted extra wind power does not exceed the consumption capacity of the EB, some EB power capacity will be reserved according to the predicted wind power and its maximum negative errors. Therefore, the extra wind power caused by prediction error could be consumed by rapidly adjusting the input power of the EB.

5.2 Analysis of coordinated dispatching at system level

Rolling electricity and heat generation plans for the CHP, EB, HST, and PHC could be formulated using the two-step coordinated dispatching approach. The optimal result at the system level is shown in Fig. 8. Coordinated cooperation among electric and heat sources consumes a significant amount of surplus wind energy. Before 01:20 am, the PHC plays the most important role in providing the reduced heat supply from the CHP, while the EB consumes the remaining surplus wind power. This limit the CHP ramping rate by taking advantage of the quick net load tracking ability of the EB. After 01:20 am, the heat stored in the PHC is exhausted, thus it could not consume more wind power. Thereafter, the EB and HST inherit duty to supply additional heat energy to the heat load. Up to 04:10 am, the HST retreats from wind power consumption as the remaining heat stored in the HST reaches its lower limit. The EB accounts for the additional heat supplied for the remaining valley period. In summary, wind power could be curtailed from 52.2% to 4.8% throughout the valley period, i.e., approximately 890 MWh surplus wind energy could be absorbed through the cooperation of multiple heat sources. 214 MWh, 302 MWh, and 374 MWh are consumed by the PHC, HST, and EB, respectively.

Figure 9 shows the heat output from each heat source during the valley electric load period. Wind power abandonment is not that serious before 00:00, and the additional

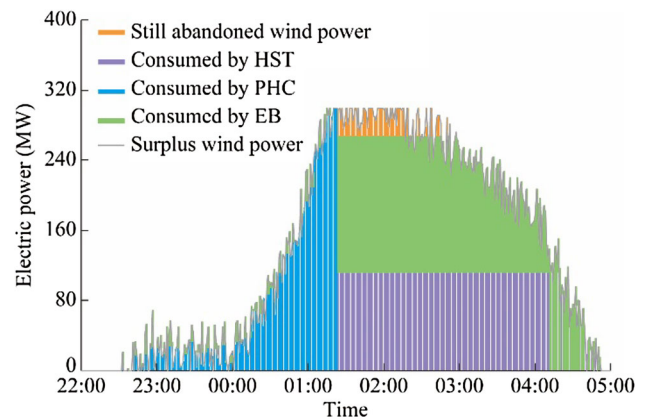


Fig. 8 System level wind power consumption



heat supply is relatively less involved. The heat is primarily supplied from the CHP, while the PHC affords additional heat when the generated power exceeds demand. From 00:00 to 01:20 am, the surplus power starts to increase, and the engagement of the PHC increases. The EB takes charge in absorbing the remaining surplus electricity that could not be consumed due to the limit of the CHP's ramping rate. The surplus electric power remains steady at a high level from 01:20 am to 04:10 am, where the EB and HST act the major additional heat sources to assist the CHP and guarantee heat demand. After 04:00 am, the additional heat is principally provided by the EB due to the use of heat stored in the HST. The surplus electricity wears off after 05:00 am, where the EB rarely operates and the CHP bears the heat supply.

5.3 Analysis of coordinated dispatching among heat sources

Considering the two-step optimization model, the dispatching scheme among heat sources should be undertaken in the first step. The second step establishes the coordinated dispatching scheme among units within each kind of heat sources.

1) Dispatching of PHCs

Early in the valley load period, the heat stored in the PHC is used primarily for its low cost. In order to take full advantage of the stored heat, the ratio of the power released among the PHCs is fixed and is connected with their storage capacity. The remaining heat stored in each PHC continuously decreases, and the heat in each PHC is exhausted by 01:20 am.

2) Coordinated dispatching of CHP units

The electric power outputs from the CHP units during the valley load period are determined using the dynamic

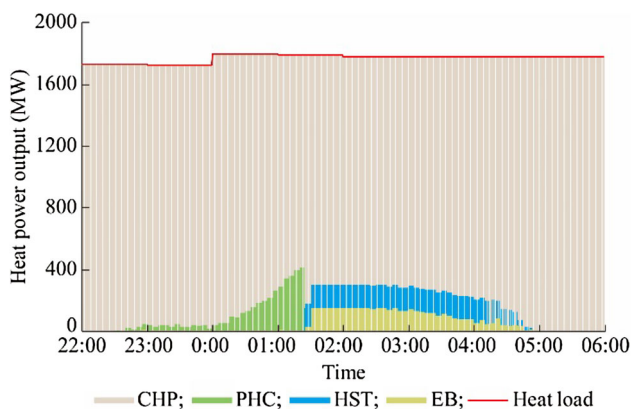


Fig. 9 Heat power output from various heat sources during electric valley period

programming algorithm presented earlier, and the results are shown in Fig. 10.

The CHP and PHC are the major heat sources before 01:20 am. Thus, the electric power output from the CHP units decreases in proportion with the heat released from the corresponding PHC. By 01:20 am, the heat stored in 3 heat zones is exhausted. From then on, the CHP units arrange their electric and heat output according to the dynamic programming results. The operation cost of CHP3 is the highest most of the time, followed by CHP2, 1, 6, 5, and 4. If the surplus electricity could not be consumed with a single CHP, other CHP units could participate in the order listed above.

3) Coordinated dispatching of EB

Figure 11 shows the working power for each EB during the valley load period. Before 01:20 am, the additional heat is primarily provided by the PHC. The EB absorbs the remaining surplus power that could not be consumed due to the limited CHP ramping rate. During this period, the HST reaches its heat storage capacity, and the heat in the EB is sent to the heat network. EB3 primarily operates alone because CHP3 has the highest operation cost. After 01:20 am, the EB and HST offer additional heat on account of the high wind power abandonment and limited heat that can be released from the HST. All EBs operate at full power until 02:45 am, at which the surplus power decreases. The HST is exhausted by 04:10 am, and the EB provides additional heat. The working order of EB is relevant to the operation cost of its corresponding CHP, thus the utilization ratio of EB 3 is the highest, followed EB1 and 2. EB4, 5, and 6 only operate during high wind power abandonment periods.

4) Coordinated dispatching of HST

During the early stage of the valley load period, the additional heat is primarily provided by PHC, while the HST rarely operates. From 01:20 am, the PHC depletes its

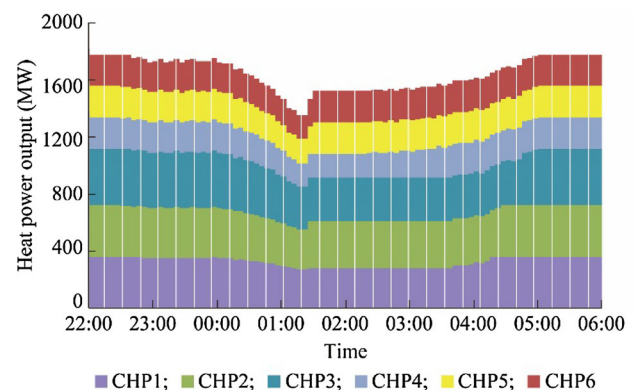


Fig. 10 CHP operation during electric valley period

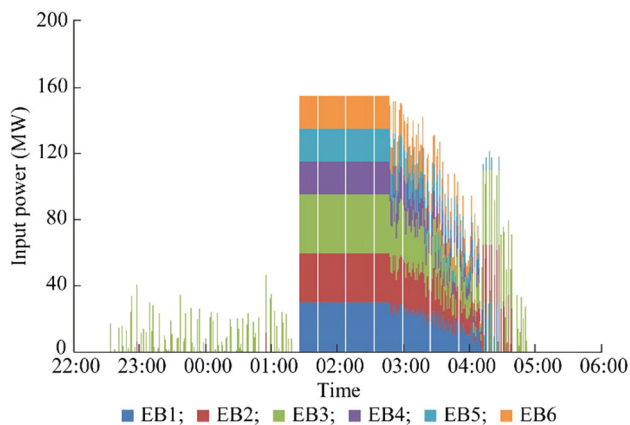


Fig. 11 Electric power input to EBs during electric valley period

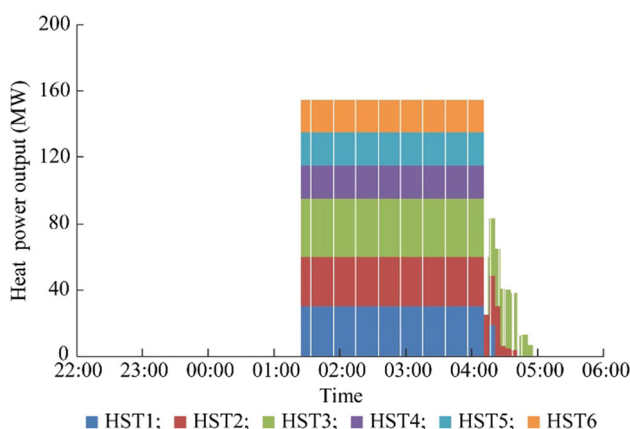


Fig. 12 Heat power output of HST

stored heat and the HST starts providing additional heat. Figure 12 shows the released heat power during the valley load period. 01:20 am to 04:10 am is a period of high wind power abandonment, and every HST operates at the highest release rate to provide maximum surplus power consumption. After 04:10 am, the heat stored in the HST is used up. According to the analysis in Section 5.3.1, CHP3 has the highest operation cost, thus surplus heat energy should store in HST3. The storage order for HSTs should follow the order for EBs, which is relevant to minimizing the CHP operation cost.

The remaining capacity in the HST is connected to its stored and released heat. If the release rate is higher than the storage rate, the remaining heat decreases, otherwise the remaining heat increases. Before 01:20 am, additional heat is provided by the PHC and EB, and the heat stored in each HST is maximized. Thereafter, the HST starts supplying heat as the PHC is exhausted due to high wind power abandonment. The HSTs release heat at the maximum rate, and the remaining heat stored in each HST drops

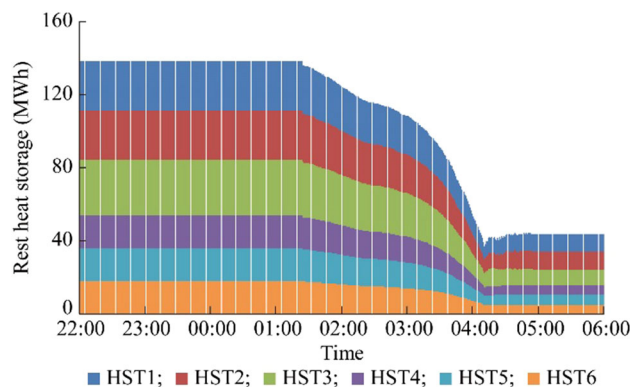


Fig. 13 Remaining capacity of HST during electric valley period

rapidly. This continues until 04:10 am, when the heat stored in the HST reaches the lower limit as is shown in Fig. 13.

5.4 Comparison with other dispatching methods

The EDM and EPDM are the primarily dispatching strategies consuming surplus wind power with multiple energy sources. The extra wind power consumption quotas are distributed to each unit of one energy source with the same quantity by EDM. In contrast, EPDM is used to distribute consumption quotas in proportion to the installed capacity of the energy source unit. The extra wind power consumption and fuel savings provided by EDM and EPDM are compared with the dispatching method presented herein. The results are shown in Table 4. The coordinated dispatching strategy provides the greatest fuel savings and extra wind power consumption. The EDM dispatching strategy divides the extra wind power into equal consumption quotas for every EB and HST, despite the fact that they have different installed capacities, and the maximum quota for each unit depends on the unit with the minimum installed capacity. Thus, the capability of consuming surplus wind power in units with large installed capacity could be optimized, and the consumed surplus wind power, saved fuel, and economic benefits provided by

Table 4 Comparison of different dispatching methods

Item	This work	EDM	EPDM
Extra wind power consumption (MWh)	890	718	877
Consumed by PHC (MWh)	214	172	213
Consumed by EB (MWh)	374	301	273
Consumed by HST (MWh)	302	245	291
Fuel saving (ton)	109.38	93.24	102.51
Economic benefits (\$)	10455	8912	9799



this dispatching method are the least desirable among the dispatching methods. The extra wind power consumption quota is distributed according to the installed capacity of each energy source unit. The surplus wind power consumption capacity could be improved, but the economic characteristics are considered. The fuel savings and economic benefits provided by EPDM are less desirable than those provided by the coordinated dispatching strategy proposed in this paper.

6 Conclusion

Renewable energy, especially wind power, will play a more important role in the future power grid thanks to its sustainability. Meanwhile, the high wind power abandonment rate is unacceptable. The coordinated dispatching scheme among multiple energy sources presented here aims to consume surplus wind power during valley electric load periods in the hot season on the background of heat demand during winter in northern China. The technological character and control method of CHP, EB, HST, and PHC are presented. A two-step optimization model is proposed in this paper, in which surplus wind power could be minimized by determining the wind power consumption quota among the EB, HST, and PHC in the first step. More economic benefits could be obtained by reasonably allocating the consumption quota among units within each type of energy source with the support of a dynamic programming algorithm in the second step. A case study is used to demonstrate the effectiveness of this approach. Wind power abandonment could be reduced from about 980 MWh (without ESS) to 90 MWh during a valley load period with the coordinated dispatching scheme, and the abandonment rate could be decreased from 52.2% to 4.8%. Compared with two existing dispatching methods, the extra wind power consumed in the dispatching model presented here is approximately 24% and 1.5% higher than that provided by EDM and EPDM, respectively. Meanwhile, the economic benefits are 17.3% and 6.7% higher than that provided by EDM and EPDM, respectively. These results show that the proposed coordinated dispatching model with multiple energy sources is effective for consuming surplus wind power.

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