Economic Dispatch of Combined Heat and Power Energy Systems Using Electric Boiler to Accommodate Wind Power

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ABSTRACT It is of significant economic value to use an electric boiler to coordinate the heating network and power grid to reduce wind curtailment during heating supply seasons in the north area. This paper presents an optimal economic dispatching model of combined heat and power energy systems to minimize the total operation cost and wind curtailment by using electric boilers. The proposed model comprehensively considers the thermal characteristics of buildings and the constraints of electric and thermal power balancing, combined heat and power (CHP) units, heat storage tanks, electric boiler power, and wind power. To address this model, a linearization optimization model is built, where different dispatch strategies under CHP only, CHP + HST (heat storage tanks), and CHP + HST + EB (electric boiler) different conditions are conducted. Thereafter, the relationship between indoor temperature and thermal power is analyzed with consideration of the temperature time-delay effect and the heat loss on heating balance. A 6-node combined heat and power energy system is used to validate the effectiveness of the proposed model and solution method. Furthermore, the case studies illustrate the impact of heat storage tanks and the electric boiler on wind power curtailment and coal consumption.

INDEX TERMS Power generation dispatch, energy storage, wind power generation, thermal analysis.

I. INTRODUCTION

Wind power, as a renewable energy source with high commercial value, has experienced fast growth over the last decades. However, wind power poses challenges to the economic dispatch of power systems due to its uncertainty and intermittency [1]–[3]. From January to June 2018, the wind power curtailment ratio in China reached 8.7% and the total wind power curtailment reached 18.2 billion kWh, which seriously affects the wind power industry [4]–[8]. Wind power curtailment is becoming an urgent problem to be solved since it not only reduces energy utilization but also brings economic losses to the enterprise.

The main reasons for wind power curtailment are as follows: i) the capability of the grid to accommodate wind power is insufficient in some areas [9]; ii) wind power has random volatility, and it is difficult to accurately predict[10]. At present, how to reduce the wind power curtailment ratio has become the research focus all over the world. Establishing a dispatch model of the integrated energy system and presenting the cooperation control method have become two important aspects in this field.

In integrated energy systems, reference [11] establishes a CHP dispatch model for better integration of wind power based on electric boilers and thermal storage equipment. A start-stop strategy is formulated that takes only abandoned wind as the heat source and the Newton-Raphson iterative method is applied to solve the model. Reference [12] proposes a detailed CHP dispatch model, where a three-stage heat transfer model of the extraction steam is used to describe the heating process. Then a joint dispatch model is developed, which contains CHP units, conventional thermal power units, and renewable energy source units. Reference [13] explores the opportunities of increasing the
flexibility of CHP units using electric boilers and heat storage tanks for better integration of wind power. A linear model is proposed for the centralized dispatch of integrated energy systems with detailed modeling of the charging processes of heat storage tanks. Electric boilers are more effective in reducing wind curtailment, whereas heat storage tanks can further improve the flexibility for heat and power energy conversion. Reference [14] presents a reliability-constrained optimization approach to determine the number and size of CHP system components, including CHP units, electric boilers and heat storage tanks. The load forecasting inaccuracy and random outages of CHP components are modeled as a Scenario tree by using the Monte Carlo sampling approach.

In cooperation control works, reference [15] presents an efficient algorithm for the static economic dispatch of cogeneration systems, and the solution procedure basically follows a two-level strategy. Reference [16] presents an improved genetic algorithm using novel crossover and mutation to solve the combined heat and power economic dispatch. Furthermore, a new solving method is proposed to repair the mutated offsprings and enable them to enter feasible regions easily. Reference [17] proposes a two-stage dispatch approach by combining optimization and decision making, and test results show that this approach manages to coordinate the relations between the economy and environment of CHP dispatch. Reference [18] applies a novel criss-cross optimization (CSO) algorithm to a large scale combined heat and power economic dispatch problem. CSO mainly has two interacting operators, horizontal crossover and vertical crossover. The two operators proceed alternatively in each iteration and generate moderation solutions in opposite directions. The method is effective in preserving the population’s diversity and overcoming premature convergence.

In most areas, the main reason for wind power curtailment in the heating supply season is that thermal power plants are affected by conventional thermo-electric constraints. When wind power is increasing, CHP units cannot reduce power generation in time because electricity generation is determined by heat load. Due to the priority of heat supply, CHP units need to have more heat output at night which will cause more wind power curtailment [19]. Currently, the installation of thermal storage tanks can help accommodate wind power, but the study on the control strategy for combined heat and power energy systems is still insufficient.

Motivated by this research gap, an electric-thermal scheduling model focused on both time delay in the heating system and computational complexity in solving the optimization problem is developed in this work. A joint operation mode through electric boiler and heat storage tanks is proposed for the economic dispatch problem. Firstly, this paper analyzes the heating network balance under the following Scenarios: i) heating provided by CHP unit, ii) heating provided by CHP unit with heat storage tank, and iii) heating provided by CHP unit with heat storage tanks and electric boiler. Then, an economic dispatch optimization model of a CHP unit with a heat storage tank and electric boilers is constructed. Finally, this paper compares the effectiveness of thermal storage tanks and electric boiler in reducing wind power curtailment and coal consumption in different Scenarios.

Compared to previous work, the main contributions of this work include the following two aspects: i) the cost of wind curtailment is built as the penalty factor of economic dispatching for combined heat and power energy system; ii) a single-order linear dynamic system for evaluating the thermal behavior of CHPs is converted into algebraic equations considering thermal slow-response profiles for building thermal inertia and heat network inertia.

## II. COMBINED HEAT AND POWER ENERGY SYSTEM

The traditional form of the energy system is limited to a single electric/thermal energy source, and the synergies and complementary advantages between various energy sources cannot be fully utilized. A single form of energy can no longer meet green and efficient energy requirements. Thus it is imperative to develop a safe and economical combined heat and power energy system.

In order to reduce the output of the conventional CHP and improve the utilization of wind power, the combined heat and power energy system can couple the independent power system and the thermal system. This system mainly includes coal-fired units, wind turbines, CHP units, thermal storage tanks, and electric boilers, which is shown in Fig. 1. In this system, the electric load is supplied by coal-fired units, wind turbines and CHP units; the heat load is supplied by CHP units, thermal storage tanks, and electric boilers. The heat storage tanks have two working states: endothermic working state and exothermic working state. Electric boilers can convert electric power into thermal power during operation.

![FIGURE 1. The structure diagram of combined heat and power energy system.](image-url)

## III. ECONOMIC DISPATCHING MODEL OF COMBINED HEAT AND POWER ENERGY SYSTEM

This section develops a novel framework for the economic dispatch of combined heat and power energy systems. Specifically, the associated mathematical models of the coal-fired thermal power unit are first revisited. Then, the models are built for combined heat and power energy systems.
A. MODEL OF COAL-FIRED POWER UNIT

During the working process, the steam generated by the boiler is lost due to condensation, resulting in a large part of heat energy is hard to supply to the heat load, so coal-fired thermal power unit has low energy efficiency [20]. In the coal-fired thermal power unit, the equation between coal cost and generated power can be approximated as

$$f_G = aP_{i,G}^2 + bP_{i,G} + c$$

where $f_G$ and $P_{i,G}$ are respectively the coal cost and electric power output of the thermal power generator set. $a$, $b$, $c$ are cost coefficients of the coal-fired thermal power unit.

B. MODEL OF CHP UNIT

1) OPERATION CHARACTERISTICS OF CHP UNIT

a: CHP UNIT WITHOUT THERMAL STORAGE TANK

The coupling relationship between electrical power output and thermal power output in the CHP units is called the electric-thermal characteristics [21]. The electric-thermal characteristic of the CHP units without a thermal storage tank is shown as area ABCD in Fig.2.

The electricity output of the CHP is restricted by the thermal power output. As the thermal power output increases, the adjustment range of the electric power gradually decreases. If the thermal output of the CHP unit is $H_L$, the adjustable range of the electric power will be limited to $[P_F, P_E]$. To ensure more wind power consumption, the CHP unit generally maintains the minimum output power.

b: OPERATION CHARACTERISTIC OF THE THERMAL STORAGE TANK

The water-based thermal storage tank can solve the contradiction between electric power and thermal power, but its output is affected by the thermal requirement obviously. It is necessary to predetermine whether the thermal storage tank is in an endothermic state or an exothermic state. Considering the non-simultaneity of heat absorption and heat release, $X(t) \in \{0, 1\}$ is introduced as the state variable. When the total heat load is more than the sum of the maximum output power of each CHP unit, the thermal storage tank releases heat, $X(t) = 0$; when the heat load is less than the sum of the maximum output power of each CHP unit, the thermal storage tank will absorb heat, $X(t) = 1$ [22]. The thermal storage tank model can be described as

$$S_{hsi,t} = S_{hsi,t-1} + \left( q_{hsi,t} - q'_{hsi,t} \right) \cdot \Delta t$$

where $S_{hsi,t}$ and $S_{hsi,t-1}$ are the stored thermal energy of the thermal storage tank at time $t$ and at time $t - 1$, respectively; $q'_{hsi,t}$ is the endothermic power of the thermal storage tank at time $t$; $q_{hsi,t}$ is the heat exothermic power of the thermal storage tank at time $t$. In this paper, the initial stored energy of the thermal storage tank is 300MWh.

c: CHP UNIT WITH THERMAL STORAGE TANK

Compared with the CHP unit without a thermal storage tank, the electric-thermal characteristic of the CHP units with a thermal storage tank is shown as AEFGHI in Fig.2. If the conventional CHP unit is equipped with a thermal storage tank, the electric-thermal characteristics will change greatly. The electric-thermal characteristic operation interval has changed from the original area ABCD to the new area AEFGHI. Under the same heating power, the adjustable performance of electric power is changed from $[P_F, P_E]$ to $[P_N, P_M]$, and the adjustment range is improved. The operation characteristic breaks the conventional operation mode, and the thermal regulation capability of the CHP unit is improved by the thermal storage tank in Fig. 2.

2) OPERATION COST OF CHP UNIT

According to the electric-thermal characteristics of the CHP unit, the operation cost is related to the electric output and heat output, which can be expressed as

$$f_{chp} = \eta_1 + \eta_2 P_{i,chp} + \eta_3 Q_{i,chp} + \eta_4 P_{i,chp}^2 + \eta_5 Q_{i,chp}^2 + \eta_6 P_{i,chp} Q_{i,chp}$$

where $f_{chp}$ is the coal consumption cost of the CHP unit; $P_{i,chp}$ and $Q_{i,chp}$ are the electric output and heat power output of the CHP units respectively; $\eta_1 \sim \eta_6$ are the power generation cost coefficients of the CHP unit.

C. PUNISHMENT CHARACTERISTIC OF WIND POWER CURTAILMENT IN INTEGRATED ENERGY SYSTEM

The output power of the wind turbine is uncertain, which is determined by the average wind speed. It can be expressed as

$$P_w = \begin{cases} 0 & v < v_i \\ \frac{v^3 - v_i^3}{v_n^3 - v_i^3} P_{wn} & v_i < v < v_o \\ P_{wn} & v_n < v < v_o \\ 0 & v \geq v_o \end{cases}$$

where $v_i, v_o, v_n$ respectively represent the cut-in wind speed, cut-out wind speed and rated wind speed of the wind turbine, $P_{wn}$ represents the rated power of the wind turbine.
The wind power curtailment cost can be formulated by

\[ F_W = \alpha \sum_{t=1}^{T} \sum_{i=1}^{N_W} (P_W - P_{W,i,t}) \]  

(5)

where \( P_W \) is the wind power prediction output of the wind turbine \( i \) at time \( t \); \( P_{W,i,t} \) is the actual wind power output of wind turbine \( i \) at time \( t \); \( \alpha \) is the penalty factor for wind power curtailment; \( N_W \) is the number of wind turbines.

D. THE OBJECTIVE FUNCTION

The objective of this energy system is to minimize wind power curtailment and total operational cost of the system, which can be expressed as

\[ F = \min \sum_{t=1}^{T} \left( \sum_{i=1}^{N_w} f_G(P_{G,i,t}) + \sum_{i=1}^{N_{chp}} f_{CHP}(P_{chp,i,t}, Q_{chp,i,t}) \right) + F_W \]  

(6)

E. THE CONSTRAINTS

1) EQUALITY CONSTRAINTS

a): Electric load balancing constraint is given by

\[ \sum_{i=1}^{N} P_{G,i,t}^1 + \sum_{i=1}^{N_{chp}} P_{chp,i,t} + \sum_{i=1}^{N_w} P_{W,i,t} = P_{EB} + P_{LD} \]  

(7)

where \( P_{G,i,t}^1 \) is the electric power of coal-fired thermal power unit \( i \) at time \( t \); \( P_{chp,i,t} \) is the electric power of the CHP unit \( i \) at time \( t \); \( P_{W,i,t} \) is the electric power of wind turbine \( i \) at time \( t \); \( P_{EB} \) is the absorbed electric power of electric boiler \( i \) at time \( t \); \( P_{LD} \) is the electric load power of the system at time \( t \).

b): Thermal load balancing constraint is given by

\[ \sum_{i=1}^{N_{chp}} Q_{chp,i,t}^1 + Q_{EB}^1 + Q_{HS}^f = Q_{LD} \]  

(8)

where \( Q_{chp,i,t}^1 \) is the thermal power of CHP unit \( i \) at time \( t \); \( Q_{EB}^1 \) is the thermal power of electric boiler \( i \) at time \( t \); \( Q_{HS}^f \) is the thermal power of the thermal storage tank at time \( t \); \( Q_{LD} \) is the heat load of the system at time \( t \).

2) INEQUALITY CONSTRAINTS

a): Active power output inequality constraints of the coal-fired thermal power unit can be expressed as

\[ P_{min,G}^{i,t} \leq P_{G}^{i,t} \leq P_{max,G}^{i,t} \]  

(9)

where \( P_{min,G}^{i,t} \) and \( P_{max,G}^{i,t} \) are respectively the minimum and maximum active power output of the coal-fired thermal power unit \( i \).

b): Active power output ramp rate constraints of the coal-fired thermal power unit can be expressed as

\[ -\eta_{r,down}^{i,t} \Delta T(t) \leq P_{i,t} - P_{i,t-1} \leq \eta_{r,up}^{i,t} \Delta T(t) \]  

(10)

where \( \eta_{r,down}^{i,t} \) and \( \eta_{r,up}^{i,t} \) are respectively the descending and ascending ramp rates of the active power output of the coal-fired thermal power unit \( i \); \( \Delta T(t) \) is the time interval.

c): Active power output constraints of the CHP unit can be expressed as

\[ P_{min, chp}^{i,t} \leq P_{chp}^{i,t} \leq P_{max, chp}^{i,t} \]  

(11)

where \( P_{min, chp}^{i,t} \) is the active power output of the CHP unit \( i \) at time \( t \); \( P_{min, chp}^{i,t} \) and \( P_{max, chp}^{i,t} \) are respectively minimum and maximum active power output of the CHP unit \( i \).

d): Active power output ramp rate constraints of the CHP unit can be expressed as

\[ -D_{R}^{max} \Delta t \leq P_{i,t}^{chp} - P_{i,t-1}^{chp} \leq U_{R}^{max} \Delta t \]  

(12)

where \( U_{R}^{max} \) and \( D_{R}^{max} \) are respectively the up and down ramp rates of the CHP unit \( i \).

e): Thermal power output constraints of the CHP unit can be expressed as

\[ Q_{min, chp}^{i,t} \leq Q_{chp}^{i,t} \leq Q_{max, chp}^{i,t} \]  

(13)

where \( Q_{min, chp}^{i,t} \) and \( Q_{max, chp}^{i,t} \) are the minimum and maximum thermal power output of the CHP unit \( i \).

f): Thermal power output ramp rate constraints of the CHP unit can be expressed as

\[ \left( Q_{chp}^{i,t} - Q_{chp}^{i,t-1} \right) / \Delta t \leq R_{chp}^{down} \]

\[ \left( Q_{chp}^{i,t} - Q_{chp}^{i,t-1} \right) / \Delta t \leq R_{chp}^{up} \]  

(14)

where \( R_{chp}^{up} \) and \( R_{chp}^{down} \) are respectively maximum up rate and maximum down rate of the thermal output of the CHP unit \( i \), MWh.

g): Electric-thermal power constraints of the electric boiler can be expressed as

\[ P_{EB, min}^{i,t} \leq P_{EB}^{i,t} \leq P_{EB, max}^{i,t} \]

\[ Q_{EB}^{i,t} = \eta_{i} P_{EB}^{i,t} \]  

(15)

where \( P_{EB, min}^{i,t} \) and \( P_{EB, max}^{i,t} \) are respectively the maximum and minimum absorbed electric power of the electric boiler; \( Q_{EB}^{i,t} \) is the thermal power output of the electric boiler at time \( t \); \( \eta_{i} \) is the electric-thermal conversion efficiency.

h): Constraints of the thermal storage tank can be expressed as (16) and (17)

\[ Q_{HS, min}^{i,t} \leq Q_{HS}^{i,t} \leq Q_{HS, max}^{i,t} \]  

(16)

where \( Q_{HS, min}^{i,t} \) and \( Q_{HS, max}^{i,t} \) are the maximum and minimum thermal power of the thermal storage tank, respectively.

\[ 0 \leq S_{HS,c}^{i,t} \leq S_{max, HS} \text{c}(x(t)) \]

\[ 0 \leq S_{HS,f}^{i,t} \leq S_{max, HS} \text{f}(1 - x(t)) \]  

(17)

where \( S_{HS,c}^{i,t} \) and \( S_{HS,f}^{i,t} \) are the stored heat energy and released heat energy of the heat storage tank respectively; \( S_{max, HS} \text{c} \) and \( S_{max, HS} \text{f} \) are the maximum capacity of heat energy storage; \( x(t) \) is the proportion of heat absorption at time \( t \).
IV. MODEL SOLUTION PROCEDURE

In the combined electric-thermal energy system, with the aim of minimizing the wind power curtailment and coal consumption, the essence of optimizing economic dispatch is to solve the problem of coordinated control under the electric-thermal coupling relationship. The electric-thermal characteristics of the CHP can be expressed by the six limit values of the electric-thermal output in Fig. 3, AEFGCHI area is the coordinated control feasible area.

![Electric-thermal characteristics of the CHP unit.](image)

For any convex polygon, there is such a property that any point within the convex polygon can be linearly represented by the extreme points of the convex polygon [23]. In Fig. 3, the electric-thermal adjustment area AEFGCHI is a convex polygon, therefore, any operation point in the feasible area of the cogeneration characteristic can be linearly expressed by equations (18)-(20).

\[
P^{i,t}_{\text{chp}} = \sum_{j=1}^{n} \gamma_{i,j,t} P^{j}_{\text{chp}} \quad (18)
\]

\[
Q^{i,t}_{\text{chp}} = \sum_{j=1}^{n} \gamma_{i,j,t} Q^{j}_{\text{chp}} \quad (19)
\]

\[
\sum_{j=1}^{n} \gamma_{i,j,t} = 1 \quad (20)
\]

where \(i\) is the number of CHP units; \(j\) is the number of feasible areas extreme points; \(\gamma_{i,j,t}\) represents the combination coefficient of the \(j\)th extreme point of the \(i\)th CHP unit’s feasible region at time period \(t\); the \(P^{i,t}_{\text{chp}}\) and \(Q^{i,t}_{\text{chp}}\) are respectively the electric power output and thermal power output of the \(i\)th CHP unit at time period \(t\); both \(P^{j}_{\text{chp}}\) and \(Q^{j}_{\text{chp}}\) are respectively the electric power and thermal power at the \(j\)th extreme point of the \(i\)th CHP unit.

In the feasible operation region, the electric power output \(P^{i,t}_{\text{chp}}\) and the thermal power output \(Q^{i,t}_{\text{chp}}\) of the CHP unit can be represented by the six feasible area extreme points A, E, F, G, C, H and I. Thus, we can use equations (18) ~ (20) to transform the nonlinear programming model into a linear programming model, and the linear operation cost function of the CHP unit can be rewritten as.

\[
f^{i,t}_{\text{chp}} = \sum_{j=1}^{n} \gamma_{i,j,t} f^{j}_{\text{chp}} \quad (21)
\]

where \(f^{i,t}_{\text{chp}}\) is the operation cost of the \(i\)th CHP unit at time period \(t\); \(f^{j}_{\text{chp}}\) is the operation cost at the \(j\)th extreme point of the \(i\)th CHP unit.

This model belongs to the mixed-integer quadratic programming problem. We can use MATLAB and CPLEX solver to solve the optimization model.

V. THERMAL BALANCE CONSTRAINTS CONSIDERING TIME-DELAY AND HEAT ATTENUATION

The thermal balance of the heating system is similar to the electric balance of power system, which is necessary to ensure the dynamic balance between the heat energy supply and the heat user demand at all times. However, different from electricity, the heat transfer medium mass of the thermal system is steam or hot water, so the heating network has time-delay and heat attenuation characteristics [24], [25]. The time-delay characteristics of both the heating network and building temperature are mainly caused by the flow rate and the conveying distance of the heat transfer medium. The heat attenuation of the heating network is mainly caused by the external temperature and the structure of the heating pipeline. In this section, the heating network inertia and building thermal inertia are analyzed, then the improved thermal balance equation considered time-delay and heat attenuation is given.

For reflecting the effect of time-delay and heat attenuation on thermal balance, the relationship between indoor temperature and thermal power is analyzed firstly. At the heat-exchange station, the heat is transferred from the transmission network to the distribution network to provide adequate heat for residential heating requirements. Thus the heat-exchange station can be modeled as heat load. The indoor temperature of heat users can be used to measure whether the heat demand is qualified [26]. The relationship between the average indoor temperature and the heat power of the heat-exchange station can be expressed as

\[
Q^{BE}_{t} + Q^{in}_{t} + Q^{Ven}_{t} + C_{M} M_{L} (T^{in}_{t+\Delta t} - T^{in}_{t}) / \Delta t = H_{t} \quad (22)
\]

where \(H_{t}\) is the heat exchange power of heat exchange station at period \(t\); \(Q^{BE}_{t}\) is the basic heat loss through building envelopes at period \(t\); \(Q^{in}_{t}\) is the infiltration heat loss at period \(t\); \(Q^{Ven}_{t}\) is the ventilation heat loss at period \(t\); \(T^{in}_{t}\) is the average temperature of heat users at period \(t\); \(C_{M}\) is the specific heat capacity of thermal mass; \(M_{L}\) is the mass of thermal mass of buildings.

There is also heat loss when hot water flows in the heat transmission network, resulting in heat attenuation during heat transfer [27], [28]. The heat attenuation characteristic is mainly related to the insulation material of the pipeline and the temperature difference between the inside and outside of
the pipeline. The heat loss can be written as

$$\Delta Q_p = \frac{(T_p - T_0)}{\sum_{i=1}^{n} 1/\lambda_i \ln \frac{d_i}{d_{i-1}}} \cdot L_p$$  \hspace{1cm} (23)

where $\Delta Q_p$ is the heat loss of heat transmission network; $T_p$ is the temperature of hot water in the pipeline; $T_0$ is the surface temperature of the pipeline; $\lambda_i$ is the heat conductivity of the insulation material $i$; $d_i$ is the outer average diameter of the insulation material $i$.

Hot water transmission is much different from electric power, which always requires a certain time to transport hot water from heat sources to heat-exchange stations. The time-delay characteristic in the heat transmission process is mainly related to pipeline parameters and water flow [29]. The delayed time is given as

$$\tau = \frac{L_p \pi r_p^2 \cdot \rho}{G_t}$$  \hspace{1cm} (24)

where $\tau$ is the delayed time of heat transmission network; $L_p$ is the length of transmission pipeline; $r_p$ is the inside radius of transmission pipeline; $\rho$ is the density of hot water; $G_t$ is the hot water flow in the transmission pipeline.

When considering the time-delay and heat attenuation of the heating network, the thermal balancing constraint of the system will change [30]. The new thermal balance equation becomes

$$\sum_{i=1}^{N_{chp}} Q_{chp}^{i,t-\tau} + \sum_{i=1}^{N_{HS}} Q_{HS}^{i,t-\tau} + \sum_{j=1}^{N_{EB}} Q_{EB}^{j,t-\tau} = \Delta Q_p + H_t$$  \hspace{1cm} (25)

where $Q_{chp}^{i,t-\tau}$ is the heat power output of coal-fired thermal power unit $i$ at time $t - \tau$; $Q_{HS}^{i,t-\tau}$ is the thermal power of the thermal storage tank $i$ at time $t - \tau$; $Q_{EB}^{j,t-\tau}$ is the thermal power of electric boiler $i$ at time $t - \tau$.

In Fig. 5, three 15MW electric boilers and one 360MW thermal storage tank are configured. There is a 200 MW thermal power plant on node 1, and a 220 MW thermal power plant on node 3. There is a CHP unit and a wind farm on node 6, wind farm is composed of 100 1.2 MW wind turbines. In this case, the day-ahead scheduling method is adopted and one time period is set 15 minutes, so one day is divided into 96 time periods. The wind power prediction curve and the electric load prediction curve are shown in Fig. 6, and the heat load prediction curve is shown in Fig. 5.

VI. CASE STUDIES
A. THE CASE SCENARIOS
The case uses a changed 6-node system consisting of two thermal power plants, one CHP unit, three electric boilers, and one wind farm. The structural diagram of the case is shown in Fig. 4.

In order to observe clearly the optimization performance of heat storage tanks and electric boilers, the following four Scenarios are used in the case studies.

Scenario 1: In this Scenario, the heating networks supply heat to the heat load by the CHP unit only, and power networks supplied by the wind farm, conventional thermal power plants, and CHP units. The traditional combined-heat-power model for heating is used.

Scenario 2: In this Scenario, the heating networks supply heat to the heat load by the CHP and the thermal storage tank, and power sources are the same as Scenario 1.

Scenario 3: In this scenario, the heat load is simultaneously supplied by the CHP, thermal storage tank and the electric boiler, which is the added load based on the power networks in Scenario 1. The proposed economic dispatching model for combined heat and power energy system is used.

Scenario 4: In this Scenario, combined heat and power energy system is as same as Scenario 3. The heat and power economic dispatching model considering heat time-delay and heat attenuation in heating networks is used.
B. HEAT AND POWER ANALYSIS IN DIFFERENT SCENARIOS

Thermal powers of CHP in Scenarios 1-3 are shown in Fig. 6. The wind power accommodation and prediction curves based on the proposed method in Section 4 under three Scenarios are shown in Fig. 7. In the four Scenarios, wind power is relatively redundant at the time 0-16 and 80-96 (20:00-4:00), the electric load is low, and the heat load is large. If the electric-thermal coordination is not performed, the wind turbine generates a large amount of power curtailment during the low-power load period at night.

In Fig. 7, the wind power curtailment of Scenario 1 to Scenario 3 is respectively 496.72MWh, 455.26MWh, 291.31MWh. In Scenario 1, the conventional CHP unit operates under the model of combined-heat-power, and the wind power curtailment is the largest in this Scenario. Because the electric-thermal regulation flexibility of the conventional CHP unit is limited, CHP limits the capability of wind power accommodation. In Scenario 2, the CHP unit is equipped with a thermal storage tank. Compared with Scenario 1, wind power curtailment is alleviated to a certain extent. When the wind power output is large at night, the thermal storage tank absorbs wind power partly, which makes the electric-thermal integrated system have partial flexibility and reduces the heat power of the thermal power plant. In Scenario 3, the accommodation effect of wind curtailment is optimal, the deviation from wind power prediction value is the smallest, and most of the wind curtailment is absorbed.

It can be seen from Fig. 7 that when the electric boiler helps wind power accommodation in Scenario 3, wind power consumption is significantly improved compared with Scenario 1. The electric boiler and the CHP unit with thermal storage tank work together. During the day, the electric load is high and the output of the CHP unit is large, the thermal storage tank can flexibly regulate the output of the CHP unit, provide a certain wind power accommodating space, and save operating costs. After the electric boiler is added to the system, the excess electric power is converted into thermal energy by the electric boiler, achieving the maximum economic and environmental protection for the heat and power combined energy system.

It can be seen from Fig. 8 that during the period 0-23 and 88-96 (22:00-6:00), the thermal storage tank is in the exothermic working state, and reaches the complete exothermic state at 24 (8:00). During this period, the CHP unit uses the thermal storage tank to supply heat to users, so that the CHP unit has a downward peak-shaving capacity, which increases the ability of wind power accommodation. During the period 24-79 (6:00-20:00), the wind power is low and the electric load is large, the thermal storage tank is in the heat endothermic state, and the CHP unit increases the electric and heat output, the excess heat is stored in the thermal storage tank for heating at night. By comparing Scenario 2 and Scenario 3, the CHP unit introduces the thermal storage tank and electric boiler absorb 163.95 MWh of wind energy more than the unit which only contains the thermal storage tank. The unit that adds the electric boiler provided 217.09 MWh of heat energy more than the unit that does not add the electric boiler. As the stored thermal energy increases, the wind power curtailment continues to decline. In Scenario 3, the optimal thermal storage capacity of the electric-thermal integrated system is obtained, which minimizes the defect of the forced electric output of the CHP unit when the heat load is large.

Fig. 9 depicts the output of the electric boiler in 24h, which starts working at time 86 (21:30). During the wind curtailment period 0-15 and 92-96 (23:00-4:00), in order to improve wind power accommodation and reduce the electric power of the CHP, the electric boiler is full capacity operation. During the daytime 28-79 (7:00-20:00), there is no wind power curtailment at this period, so the electric boiler does not work.

Table 1 shows the operational costs of the combined heat and power energy system in three Scenarios. It can be concluded that compared with Scenarios 1 and 2, the total power operational cost of the Scenario 3 decreased by ¥34,100.
and ¥29,300, respectively, and the wind curtailment energy decreased by 205.41 MWh and 163.95 MWh, respectively. This is because the thermal storage tank highly couples electric power and thermal power. The electric boiler improves the adjustment capability between electric power and thermal power, reduces the output of the CHP unit, accommodates the wind power curtailment, and saves the total power generation cost.

**C. TIME-DELAY OF HEAT LOAD IN INTEGRATED ENERGY SYSTEM**

In order to analyze the time-delay and heat attenuation effect of the building mass, Scenario 4 is studied in this section. The CHP unit, heat storage tank and electric boiler jointly supply heat energy, at the same time, where the time-delay and heat attenuation are considered in the heat network. Fig. 10 shows the results of the thermal power output in Scenario 3 and Scenario 4.

**TABLE 1. The economy of three scenarios.**

| Operation mode | Total operating costs, ¥ | Wind power curtailment, MWh |
|----------------|--------------------------|----------------------------|
| Scenarios 1    | 4.11×10⁶                 | 496.72                     |
| Scenarios 2    | 4.06×10⁶                 | 455.26                     |
| Scenarios 3    | 3.77×10⁶                 | 291.31                     |

We can set users’ comfort temperature limit from 18°C to 22°C according to the Heat Supply Standard of China (DB22/T5014-2018). In Scenario3, we find in some periods, the indoor temperature is larger than the upper limit, and the maximum temperature is 22.9°C. Heat users may feel too hot to open their windows to decrease the indoor temperature which causes a great waste of resources. The indoor temperature is lower than the minimum limit sometimes in Scenario 3, which can affect the user’s comfort. In Scenario4, the indoor temperature of heat users at all times are controlled in required limits. Besides, the temperature fluctuation range is also much smaller than that in Scenario3.

**VII. CONCLUSION**

In this research work, a novel economic dispatching framework of combined heat and power energy systems is presented, which uses an electric boiler to optimize heat and power output. The goal of the optimization problem is to minimize wind power curtailment and the total operational cost of the system. For this purpose, the punishment function of wind power curtailment is formulated in the objection function of the prosed framework. The convex polygons in solving the optimization problems in heat and power integration systems are linearly represented by vertices. Especially, dynamic time-delay equations from the thermal mass of end consumers’ buildings and pipelines are replaced with algebraic equations considering the slow response between heat power and temperature.

The simulation results shows that the power generation cost is reduced and the flexibility for dispatching heat and power energy is improved by adding an electric boiler in the conventional CHP unit, which will provide a novel framework for the construction of electric-thermal integrated energy systems, compared with the effects of wind power curtailment and coal consumption under CHP,
C H P + H S T , and C H P + H S T + E B scenarios. In the economic dispatch of electric-thermal integrated energy systems, the time-delay characteristic makes the heat output lead profile of the power combined energy system appear. Especially, temperature-based predictive economic dispatch for integrated energy systems without heat loss can improve heat consumers’ comfort and reinforce the coupling between heat and power considering slow-response performance for heat supply. This may help the system operator to increase the efficiency and improve the dispatch performance in combined heat and power energy systems.

Future work will investigate the smoothing methods for uncertain events in combined heat and power energy systems in economic dispatch in order to accommodate more wind power and decrease computational cost. Strategic behavior of heat user requirements and intermittent wind power will also be investigated in the context of Scenario-based or time-series economic dispatch framework.

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