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Optimal Operation Strategy for Combined Heat and Power System Based on Solid Electric Thermal Storage Boiler and Thermal Inertia

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ABSTRACT Aiming at the problem of source-load incoordination of combined heat and power (CHP) system caused by the high electro-thermal coupling strength, a optimal operation strategy of combined heat and power system based on electric thermal storage boiler and thermal inertia is proposed. Firstly, the internal heat transfer model of the solid electric thermal storage boiler was studied, and the three-dimensional numerical simulation of the temperature field of the thermal storage body was performed. Then, the thermal inertia model of the heating network and the building is established. On this basis, a coordinated optimization model of CHP system based on thermal storage boiler and thermal inertia is established with the goal of minimizing the operating cost of the system. The results show that the optimization strategy proposed in this paper can effectively reduce the electro-thermal coupling strength and improve the flexibility and economy of the CHP system.

INDEX TERMS Solid heat storage boiler, thermal inertia, electro-thermal coupling, wind power accommodation, CHP system.

I. INTRODUCTION

With the development of human society and gradual exhaustion fossil energy, various sectors of society have carried out many researches on the sustainable use of energy from the aspects of resources development and energy saving [1]–[3]. Integrated energy systems have emerged in such context, but the transmission characteristics and time scales of different energy sources are different, which brought new challenges to the coordinated operation of multiple energy sources [4], [5].

Due to the complementary features of electric energy and thermal energy, easy transfer and easy storage, electric heat storage unit was introduced in the regional CHP system for a better match with renewable energy output and peak-valley characteristics of load, and improving the overall controllability of energy system [6]–[8]. However, there are model differences in different thermal inertia of the heating pipe network and the building in the thermal system, which highlight the problem of source-load synchronization in CHP system. Therefore, the actual physical model characteristics of the solid electric heat storage boiler were studied, and its thermal inertia was matched with the thermal inertia of the heating pipe network and the building, which could effectively improve the adjustment flexibility of CHP system and reduce the economic cost, being significant for coordinated operation of multi-energy systems under the ubiquitous Internet of Things.

In order to reduce the electro-thermal coupling strength, the coordinated operation schemes of various combined heat and power systems had been proposed by scholars. In order to improve the flexibility of the power grid regulation, the literature [9] studied the heat and power output characteristics of the CHP unit with heat storage, and a coordinating dispatching model based on electric boilers for curtailed wind dissipation is established. In [10], the battery energy storage is added in the combined heat and power system, with the objective

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of maximizing wind power consumption and minimizing the number of electrode adjustments of the regenerative electric boiler, a multi-objective optimized operation method is proposed based on energy storage fusion electric boilers. In [11], a wind power plant, an electric boiler and a thermal power plant are combined power plants, and a two-stage optimal dispatching method for thermal load participation regulation is established. But the thermal dynamic characteristics of the electric heat storage boiler are not considered in current references.

Due to the different energy transfer characteristics of the thermo-electric medium in the CHP system, the inertia of the thermal system needs to be considered. In [12], the overall energy flow model of the cogeneration system including heat storage, heat transfer and heat leakage is established. In [13], Based on the thermal network delay and attenuation characteristics, an CHP system optimization scheduling model considering the characteristics of the heating network and the thermal load comfort elasticity is established. In [14], a new thermal energy flow model with transmission delay in mass regulation mode is proposed, and the thermal inertia of buildings under different heating modes is analyzed to improve the flexibility of CHP system.

The actual physical model of the heat storage body of the solid electric heat storage boiler was considered in this paper, and three-dimensional numerical simulation of the temperature field of the heat storage body was made based on the finite element, and the thermal inertia model of the solid electric heat storage boiler was established. According to the variation equation of heating network and the building temperature, the thermal inertia of the heating pipe network and the thermal inertia in the building were respectively modeled. Based on the thermal inertia model of electric heat storage boiler, thermal pipe network and building, the coordination optimization operation strategy considering interia of heating system was proposed. The simulation model was established for the CHP system in a certain area of Northeast China; the simulation and the result analysis showed that the coordination optimization operation model can effectively reduce the strength of electro-thermal coupling of the CHP system and improve adjustment capability of power grid.

II. THE ELECTRO-THERMAL COUPLING STRENGTH AND THE THERMAL INERTIA ANALYSIS OF THERMAL NETWORK

A. ANALYSIS OF THE ELECTRO-THERMAL COUPLING STRENGTH

For extraction units, the relationship between heating power and power generation is usually expressed by the operating interval, as shown in Figure 1. It can be seen that for a certain heating load, its electric power can be adjusted within a certain range [15]. However, during the period of wind abandonment in the power grid, the power grid requires thermal power units to reduce the generation power as much as possible to accommodate wind power on the premise of ensuring heat

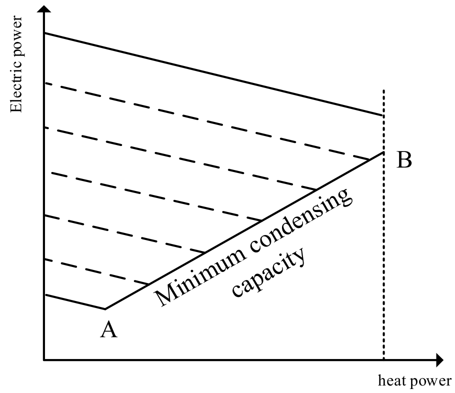


FIGURE 1. The relationship between heat and power output in CHP units.

supply. Therefore, it can be considered that the extraction unit is operating at the minimum condensing condition at this time, so that its electric power is also uniquely determined by a given heating load.

The electro-thermal coupling strength refers to the electro-thermal coupling characteristics of the CHP unit. That is, the electric power output adjustment range of the CHP unit is limited by the heat output. It can also be seen in the figure 1 that under the minimum condensing conditions, the heating power and the power generation are also approximately linearly coupled. During the heating period in winter, the wind power is large and the heat load is high at night. The CHP unit is limited by the heat load, which will increase the output of the electric output, and will severely squeeze the space for absorbing renewable energy and cause the curtailed wind. Therefore, if there is a way to reduce the electro-thermal coupling strength, the cost of the system can be reduced and the wind power consumption capacity can be improved.

B. ANALYSIS OF THE THERMAL INERTIA

Unlike the grid, the heating system is affected by the specific heat capacity and mass of the medium, and the temperature change of the heated medium lags behind the heat transfer medium in time [16]. Power transfer can be done instantaneously, with state changes at the same time profile; while thermal energy transfer is slow, energy transfer and transformation span multiple time profiles [17]. This paper will study various inertia of thermal energy of the heating system.

The heating system consists of the heat source (CHP unit, electric heat storage boiler), heating pipe network and buildings. The thermal inertia in this paper focused on the thermal inertia of heating pipe networks and buildings. CHP system is shown in Figure 2:

The solid electric heat storage boiler in Figure 2 can be divided into four parts: heating, heat storage, heat insulation and heat exchange. The heat transfer process of solid electric heat storage boiler can be simplified as shown in Figure 3. The heating power of resistance wire to magnesium brick is Q_{TS+}; the frequency conversion fan enhances the convection of hot air in the insulation layer, the heat exchange air can

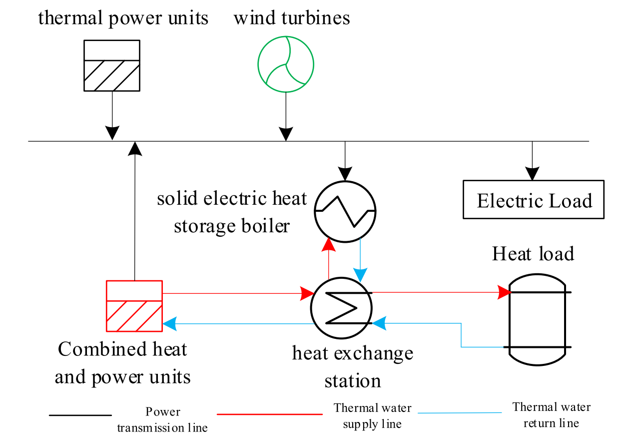


FIGURE 2. Combined heat and power system.

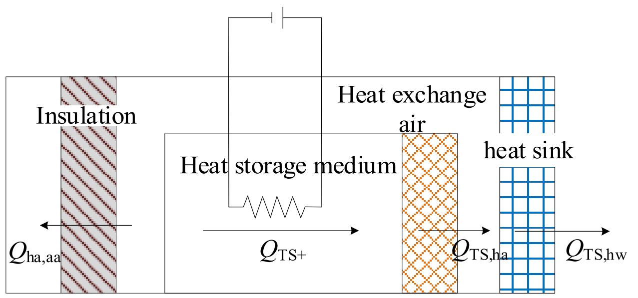


FIGURE 3. Electric heat storage boiler.

obtain heat from the magnesium brick, the power is $Q_{TS,ha}$; the hot air heats the back water of the heating, the heat release power in heat exchange part of heat pipe network is $Q_{ha,hw}$; in addition, the heat loss of the heat exchange air while passing through the heat insulation layer is $Q_{ha,aa}$.

The solid electric heat storage boiler is different from the traditional electric boiler, it has the advantages of low operating cost, high thermal efficiency and safety [18], [19]. The dynamic heat storage and discharge process of solid electric heat storage boiler can be regarded as a thermal inertia. In order to accurately describe the dynamic process of heat storage and heat release of electric heat storage boiler, the first-order model of heat storage and heat release of electric storage heat boiler considering heat loss is established in this paper.

The heating pipe contains a large amount of heat energy, which can be regarded as an energy storage. However, the heating network has the characteristics of big time lag and non-linearity. The time lag of the temperature change from the heat source to the user is regarded as the thermal inertia time of the heating pipe [20]. Unlike traditional energy storage devices, the heating network needs to consider heat loss and temperature drop of pipe.

As the terminal load of the heating network, the building obtains energy from the heating network through the radiator and reach the preset temperature after time delay and the changes of radiator's heating power [21]. The time delay of this temperature change can be considered as the thermal inertia of the building. The radiator heat dissipation can be used as an optimization control variable, and the indoor temperature constraint of the building was taken into account to adjust the heat load flexibly.

By making full use of the different thermal inertia between the heating pipe network and the building in the heating system, the electro-thermal coupling strength in the CHP system can be effectively reduced, and wind power flexible accommodation ability can be improved.

III. ELECTRIC HEAT STORAGE BOILER MODEL

According to the principle of heat storage and heat release of solid heat storage electric boiler, the regulation of heat storage and heat release inertia of electric boiler can be realized by changing the power consumption and air volume of heat exchanger [22]. Therefore, the electric heat storage boiler can realize the coordinated optimization of thermal inertia in the thermal system.

As a energy conversion link, solid electric heat storage boilers can change the thermal coupling strength of the electric heating combined system to a certain extent. Solid electric heat storage boilers store heat when the power grid has excess energy and release heat when thermal network is in need of thermal energy [23]. The solid electric heat storage boiler can bring a large room for improvement of the flexible adjustment capability of the combined heat and power system. Figure 15 shows the wind power accommodation of the electric heat storage boiler for the peak-load regulation.

A. THERMAL INERTIA MODEL OF ELECTRIC STORAGE HEAT BOILER

The heat storage body of the solid electric heat storage boiler is made up of a plurality of heat storage magnesia bricks, and the electric resistance wire is embedded as a heat source in the groove of the magnesia brick. The shape of the resistance wire was neglected in the simulation the model; the three-dimensional model of the heat storage body of the solid electric heat storage boiler was established by Solidwork and was imported into ANSYS for three-dimensional numerical simulation.

The solid electric heat storage boiler stores electric energy in the form of heat, such heat storage process is a three-dimensional unsteady heat conduction. The mathematical model for heat transfer of heat storage magnesia bricks in solid electric heat storage boiler is [24]:

$$\frac{\partial T_{HS}}{\partial t} = \frac{\lambda}{\rho_{Mg} c_{Mg}} \left(\frac{\partial^2 T_{HS}}{\partial x^2} + \frac{\partial^2 T_{HS}}{\partial y^2} + \frac{\partial^2 T_{HS}}{\partial z^2} \right) + \frac{P_{HS}}{V_{Mg} \rho_{Mg} c_{Mg}} \quad (1)$$

where, T is the temperature of the heat storage medium, °C; λ is the thermal conductivity, W/(m·K); P_{HS} is the electric power of the solid electric heat storage boiler; V_{Mg} is the volume of the heat storage medium; ρ is the heat storage medium density, kg/m^3; c_{Mg} is the specific heat capacity of the heat storage medium, J/(kg·°C).

B. DISCRETE MODEL OF HEAT STORAGE AND RELEASE VALUE

The electric heat conversion model of the electric boiler is as follows

$$Q_{HS+} = P_{HS} \cdot \lambda \tag{2}$$

where, Q_{HS+} is the heat stored in the heat storage medium; λ is electric heat conversion efficiency of electric boiler.

The multi-dimensional heat conduction model described above is suitable for analyzing the dynamic process inside the electric heat storage boiler. The heat storage capacity of a solid electric heat storage boiler includes two parts: the volume of the heat storage medium and the volume of the heat exchange air. From t_1 to t_2, according to the conservation law of heat, the energy changes of the heat storage medium and the heat exchange air are expressed as:

$$\begin{cases} \Delta E_{HS} = Q_{HS+} - Q_{HS,ha} \\ \Delta E_{ha} = Q_{HS,ha} - Q_{ha,aa} - Q_{ha,hw} \end{cases} \tag{3}$$

where, ΔE_{HS} is the energy change of the heat storage medium; ΔE_{ha} is the change amount of the heat exchange air energy; $Q_{HS,ha}$ is the heat exchange heat of the heat storage medium and the heat exchange air; $Q_{ha,aa}$ is the exchange of heat between the hot air and the environment; $Q_{ha,hw}$ is the exchange heat between the heat exchange air and the hot water.

It is complicated to describe the heat storage and release process of electric heat storage boilers by first-order linear differential equations. Therefore, the first-order heat storage and heat release model of electric heat storage boilers needs to be differentiated to obtain a simplified numerical discrete model. The differential numerical model of the electric heat storage boiler can be expressed by the following formula:

$$E_{HS}(t+1) = E_{HS}(t) + \Delta t[Q_{HS+}(t) - Q_{HS-}(t)] - Q_{ha,aa}(t) \tag{4}$$

where, Δt is the time step.

$$Q_{ha,aa}(t) = \int_{t}^{t+\Delta t} (T_{HS} - T_{aa})/R_{HS} \mathrm{d}t \tag{5}$$

The above formula can be used as a discrete model of heat storage and heat release of an electric heat storage boiler, which can be calculated on the basis of the internal temperature of the heat storage system, and is suitable for power system optimization scheduling.

IV. HEATING NETWORK AND BUILDING THERMAL INERTIA MODEL

A. HEATING NETWORK THERMAL INERTIA MODEL

The thermal inertia time of the temperature change at the head end and end of the heating network can be expressed as [25]

$$t_{PIPE} = K_{delay} \cdot \frac{L}{v} \tag{6}$$

where, t_{pipe} is the thermal inertia time constant of the heating network; L is the transmission distance of the pipeline; K_{delay} is the thermal delay coefficient, which is related to the laying depth of the pipeline; v is the velocity of the heat medium.

B. THERMAL INERTIA MODEL OF THE BUILDING

The thermal inertia of a building can be described as following [21]:

$$C\frac{\mathrm{d}T_{in}}{\mathrm{d}t} = Q_R - Q_L \tag{7}$$

where, C is the total heat capacity of the building; Q_R is the heat supply from the heating network; Q_L is the heat loss of the building;

In this paper, the heat supply to the building is regarded as the total heat load, and the indoor temperature can be changed by adjusting flow rate of the water supply and temperature of the radiator.

$$\begin{cases} Q_r = \varepsilon_r W_{rs}(t_g - t_n) \\ Q_L = S\mu(T_{in} - T_{out}) \end{cases} \tag{8}$$

where, Q_r is the heat dissipation amount of the radiator; ε_r is the effective coefficient of the radiator; W_{rs} is the heat equivalent of the heat medium flow on the thermal user side, $W_{rs} = G_c$, G is the heat medium circulation flow rate; t_g is the water supply temperature of the radiator inlet; t_n is the average indoor temperature of the building.

In order to apply the thermal inertia of the building to the power system optimization operation with time interval, it is necessary to discretize the continuous function which describes the thermal inertia of the building. So, the formula (10) is differentiated to obtain the differential numerical model of the thermal inertia of the building:

$$\begin{cases} k_1 T_{in}(t) - T_{in}(t-1) = k_2 Q_R + k_3 T_{out}(t) \\ k_1 = \dfrac{\Delta t}{C'S}, \quad k_2 = \dfrac{\mu \cdot \Delta t}{C'}, \ k_3 = 1 + k_2 \end{cases} \tag{9}$$

where, Δt is a scheduling period; $T_{in}(t)$ and $T_{out}(t)$ are the indoor and an outdoor temperature at time t; C' is the heat capacity per unit heating area; k_1, k_2, k_3 are the corresponding coefficients.

The electro-thermal coupling strength in the CHP system can be effectively reduced and the electro-thermal coordination capability can be improved by utilizing the thermal inertia of the heating network and the building.

V. ELECTRO-THERMAL COORDINATION OPTIMIZATION MODEL

A. OBJECTIVE FUNCTION OF COORDINATED RUNNING

The electro-thermal coordination optimization under multiple thermal inertia proposed in this paper is to make full use of the various inertia of the thermal system, which can realize the economic operation of the CHP system. The optimization objective can be expressed as follows:

$$C = \min C_{CON} + C_{CHP} + C_{curt} \tag{10}$$

where, C is the total cost of coordinated operation of the system; C_{CON} and C_{CHP} are the operating cost of the thermal power unit and the CHP unit respectively;

1) Thermal power unit operating costs

$$C_{CON}(t) = \mu_{coal}(aP_{CON}(t)^2 + bP_{CON}(t) + c) \quad (11)$$

where, $C_{CON}(t)$ is the operating cost of the thermal power unit in the t period, μ_{coal} is the coal price; $P_{CON}(t)$ represents the electric output of the thermal power unit during the period t; a, b and c are the fitting coefficients of the operating cost of the thermal power unit.

2) Operating costs of cogeneration unit

$$C_{CHP}(t) = \mu_{coal}(e_0D^2 + e_1P_{CHP}D + e_2P_{CHP}^2 + e_3D + e_4P_{CHP} + e_5) \quad (12)$$

where $C_{CHP}(t)$ is the operating cost of the CHP unit in the t period; e_0 and e_5 are the fitting coefficients of the CHP unit; D is the air drawing amount of the CHP unit.

3) The cost of the curtailed wind

$$C_{curt}(t) = \left[P_{WT,y}(t) - P_{WT,s}(t)\right] \cdot \varepsilon_{curt} \quad (13)$$

where $P_{WT,y}(t)$ is the predicted wind power value of the period t which is predicted by the system scheduling or predicted by the wind farm and reported to the dispatch plan; $P_{WTs}(t)$ is the actual power of the wind power during the period t; ε_{curt} is the penalty coefficient of curtailed wind

B. EQUALITY CONSTRAINTS

(1) Balance constraint of power supply:

$$P_{CHP}(t) + P_{CON}(t) + P_{WT,s}(t) - P_{HS}(t) = P_{load}(t) \quad (14)$$

(2) Heat exchange constraint at heat source

$$Q_{CHP}(t) + Q_{HS}(t) = w[T_{pipe,sup}(t) - T_{pipe,back}(t)] \quad (15)$$

where, Q_{CHP} and Q_{HS} are the heat output power of the CHP unit and the electric heat storage boiler at time t; w is the equivalence heat value of the flow in the heat network; $T_{pipe,sup(t)}$ and $T_{pipe,back(t)}$ are the temperatures of supplied water and return water at heat source respectively.

(3) Heat exchange constraint at heat exchange station

$$Q_{station}(t) = \varepsilon_{station} w[T_{station,sup}(t) - T_{station,back}(t)] \quad (16)$$

where, $Q_{station}(t)$ is the heat power input of the heat exchange station; $T_{station,sup}(t)$ and $T_{station,back}(t)$ are respectively the temperatures of supplied water and return water at time t of the source side of the heat exchange station. $\varepsilon_{station}$ is the energy consumption coefficient of the heat exchange station.

(4) The constraints of heat dissipation and building temperature

$$k_1T_{in}(t) - T_{in}(t-1) = k_2Q_R + k_3T_{out}(t) \quad (17)$$

where, Q_R is the heat dissipation amount of the building radiator; $T_{in}(t)$ is the indoor temperature; $T_{out}(t)$ is the outdoor temperature.

(5)Constraints of pipeline thermal delay and temperature drop

$$\begin{cases} T_m(t) = T_s(t)(t - t_{pipe})\text{-}\Delta T_l(t) \\ \Delta T_l(t) = k_{loss} \cdot (T_s(t) - T_m(t)) \end{cases} \quad (18)$$

where $T_s(t)$ and $T_m(t)$ are the temperature at the head end and end of the heating pipe at time t; ΔT_l is the temperature drop of the pipe; k_{loss} is the temperature loss coefficient.

C. INEQUALITY CONSTRAINTS

(1)Unit output constraints

$$\begin{cases} P_{CHP,i,min} \le P_{CHP,i}(t) \le P_{CHP,i,max} \\ P_{CON,i,min} \le P_{CON,i}(t) \le P_{CON,i,max} \\ P_{WT,i,min} \le P_{WT,i}(t) \le P_{WT,i,max} \end{cases} \quad (19)$$

where, $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum values of the i-th power output respectively.

(2)Unit ramp constraints

$$\begin{cases} -R_{con,e}^{down}\Delta t \le P_{con,e}(t) - P_{con,e}(t-1) \le R_{con,e}^{up}\Delta t \\ -R_{CHP,e}^{down}\Delta t \le P_{CHP,e}(t) - P_{CHP,e}(t-1) \le R_{CHP,e}^{up}\Delta t \\ -R_{CHP,h}^{down}\Delta t \le Q_{CHP,h}(t) - Q_{CHP,h}(t-1) \le R_{CHP,h}^{up}\Delta t \end{cases} \quad (20)$$

where, R_{CON}^{down} and R_{CHP}^{down} are the landslide powers of the thermal power unit and the CHP unit respectively; R_{CON}^{up} and R_{CHP}^{up} are the ramp power of the thermal power unit and the CHP unit respectively;

(3) Constraints of solid electric heat storage

$$\begin{cases} 0 \le P_{HS}(t) \le P_{HS,max}(t) \\ \Delta P_{HS,min} \le \Delta P_{HS}(t) \le \Delta P_{HS,max} \\ T_{HS,min} \le T_{HS}(t) \le T_{HS,max} \\ 0 \le Q_{HS}(t) \le Q_{HS,max} \end{cases} \quad (21)$$

where, $P_{HS}(t)$ and $Q_{HS}(t)$ are the electric power and heat release power of the solid electric heat storage boiler in the period t; $P_{HS,max}(t)$ and $Q_{HS,max}(t)$ are the upper limit of the electric power and heat release power of the solid electric storage boiler; $\Delta P_{HS}(t)$ is the input power change of solid electric heat storage boiler in period t; $\Delta P_{HS,max}$ are $\Delta P_{HS,min}$ are the maximum and minimum values of ramp rate of solid electric heat storage boiler respectively; $T_{HS}(t)$ is temperature of the heat storage body of the heat boiler; $T_{HS,min}$ and $T_{HS,max}$ are the minimum and maximum temperatures of the heat storage part of the solid electric heat storage boiler respectively.

(4)Constraints of heating pipe temperature

In this paper, the heating pipe network is regarded as a special energy storage, so the temperature range of the water supply pipe is the adjustable capacity of the heating network, which can be matched with the thermal inertia of the heating network.

$$\begin{cases} T_{pipe,sup}(t) \le T_{pipe,sup,max} \\ T_{pipe,back}(t) \ge T_{pipe,back,min} \end{cases} \quad (22)$$

where, $T_{pipe,sup,max}$ is the upper temperature limit of the water supply pipe ; $T_{pipe,back,min}$ is the lower temperature limit of the return water pipe.

(5)Indoor temperature constrains in heating area

The thermal inertia of the building can be fully utilized by optimizing the heat dissipation of the radiator to maintain the indoor temperature of the building within the expected range:

$$T_{\text{in}}^{\min} \leq T_{\text{in}} \leq T_{\text{in}}^{\max} \tag{23}$$

where, $T_{\text{in}}^{\max}$ and $T_{\text{in}}^{\min}$ are the upper and lower limits of the indoor temperature user allowed.

D. MODEL SOLVING

The CHP system operation optimization model can be described as

$$\begin{cases} \min f(x) & j = 1 \\ \text{s.t.} \begin{cases} h_k(x) = 0, & k = 1, 2, \cdots, p \\ g_l(x) \leq 0, & l = 1, 2, \cdots, q \end{cases} \end{cases} \tag{24}$$

where, f is the objective function, $x = [x_1, x_2, x_3, x_4, x_5, x_6]$ is a 6-dimensional decision vector consisting of optimization variables, which are the electrical powers of the thermal power unit, CHP unit, and electric heat storage boiler; powers of CHP unit, electric heat storage boiler and radiator heat release. $h_k(x) = 0$ is an equality constraint, and $g_l(x) \leq 0$ is an inequality constraint.

The electro-thermal coordinated optimization strategy is to improve the adjustment capability of the power system based on the net electric load in the system by making full use of the three thermal inertia characteristics of the thermal system. The heat dissipation of the electric heat storage boiler is optimized according to the internal energy of the heat storage medium considering the thermal inertia of the electric heat storage boiler. For the thermal inertia of the heat network, the temperature of the hot network pipe is used as a constraint, the storage and heat release of the heating network can be optimized before power grid requiring increasing power consumption. As for the thermal inertia of the building, the heat dissipation of the radiator is optimized by taking the indoor temperature range of the building as the constrain.

The optimization model is a mixed integer linear programming problem containing multiple equality and inequality constraints. This model is solved with CPLEX 12.6.

VI. EXAMPLE SIMULATION

A certain area in the northeast China was taken as a simulation example and the unit parameters are shown in Table 1. The load and outdoor temperature data were measured during January 2019 in this area. The heating area in the heating area is 5.0 km^2, the indoor temperature is 18-26 °C; the upper and lower limits of the hot water of the heat network are 100°C and 80°C respectively, and the working mode of the heat network is the sizing flow mode; the scheduling period is 15 minutes. The parameters of each unit are shown in Table 1, the operating parameters of the electric heat storage boiler are shown in Appendix , and the electric load and wind power prediction curves are shown Figure 15. The grid's demand for accommodating curtained wind was taken as an example to verify the adjusting ability of electric heating coordination to the grid.

TABLE 1. Output parameters range of each unit.

Unit type	Installed capacity/MW	Electric output range/MW	Heating output range/MW
CHP1	50	[50, 100]	[100, 200]
CHP2	150	[100, 150]	[100, 300]
CON1	100	[50, 100]	[0, 0]
CON2	100	[50, 100]	[0, 0]
WT	110	[0,110]	[0, 0]
HS	20	[0, 20]	[0, 20]

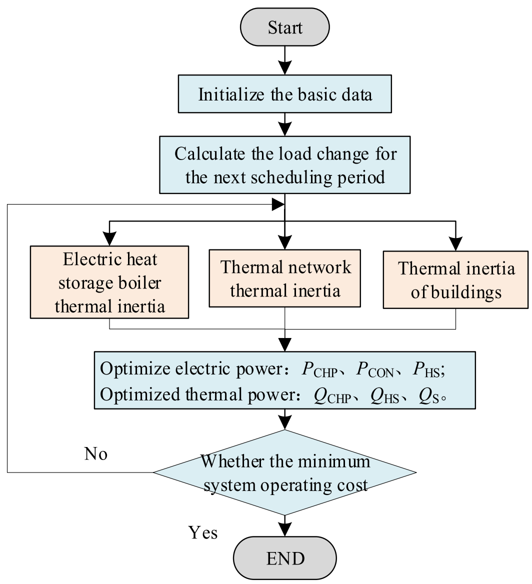


FIGURE 4. The electro-thermal coordination optimization strategy.

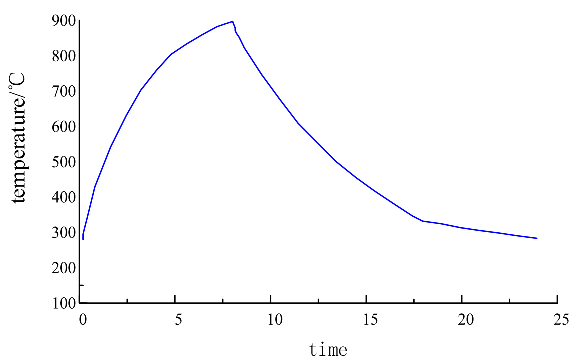


FIGURE 5. Fitting curve of average temperature of heat storage body of solid heat storage electric boiler.

A. SIMULATION OF HEAT STORAGE BODY OF SOLID ELECTRIC HEAT STORAGE BOILER

The DZ-20000kW model electric heat storage boiler was used in this paper for simulation and the basic parameters of the equipment are shown in Appendix. Based on ANSYS simulation, the temperature distribution of the 20MW solid electric heat storage boiler 3h and 9h after heating is shown in Figure 6. The temperature distribution results of the solid electric heat storage boiler 4h and 12h after heat release are

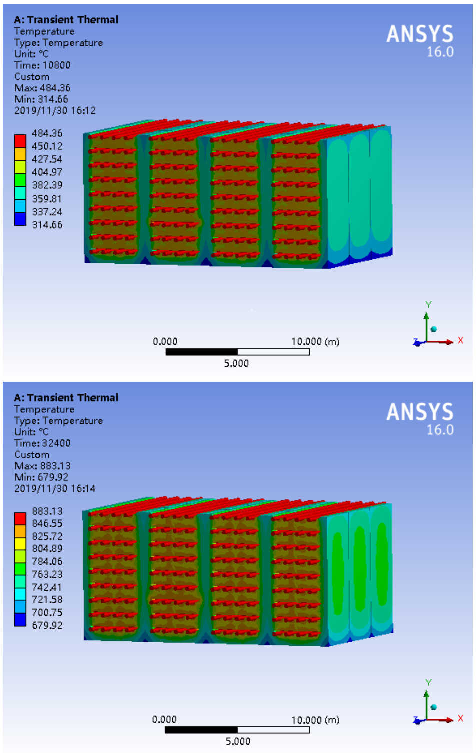


FIGURE 6. Temperature distribution of electric storage heat storage boiler 3h and 9h after heating.

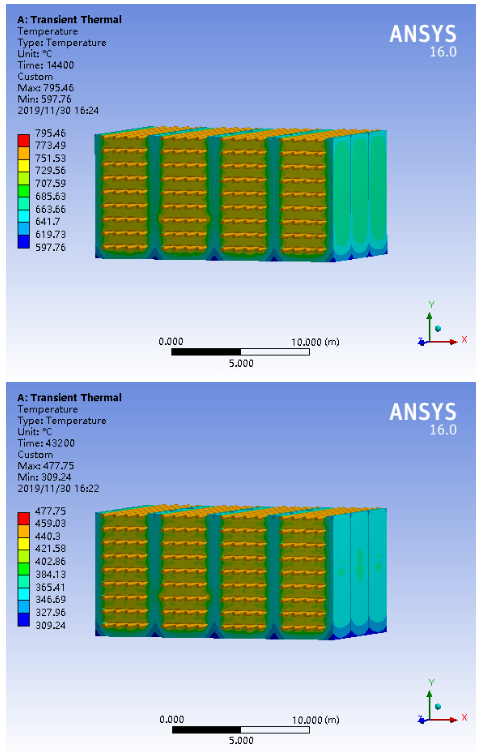


FIGURE 7. Temperature distribution of solid electric heat storage boiler 4h and 12h after heat release.

shown in Figure 6. It can be seen from Figure 6 and Figure 7 that the temperature distribution in the heat storage body is not uniform, and the energy state of the solid heat storage and its participation in the joint coordinated optimization can be obtained by the simulation result of ANSYS. According to the simulation results, the average temperature of the heat storage body is fitted as shown in Figure 5 and the thermal inertia of the electric heat storage boiler is quantified.

B. ELECTRO-THERMAL JOINT COORDINATION OPTIMIZATION RESULTS

The electro-thermal coordinated optimal operation model considering the interia of the heating system proposed in this paper can be divided into four operating modes according to whether the thermal inertia of the electric storage heat boiler and the thermal inertia of the thermal pipe network are considered.

Strategy A doesn't consider the thermal inertia of the electric heat storage boiler, so the electric heat storage unit in the strategy A of this paper can be set as a traditional direct heat type electric boiler and heat storage device. Figures 8 and 9 respectively show the electricity and heat release curves of the electric heat storage boiler, which can analyze the operation results of the two strategies. In strategy A, since there is no need for direct-heating electric boiler to consider the heat storage inertia, the electric boiler's heat output can be supplied to the heat network directly or to the heat storage device partly. Thermal inertia of the electric heat storage boiler was

TABLE 2. Four types of operational strategies.

Operational strategy	Whether considering the thermal inertia of electric storage heat boiler	Whether considering the thermal inertia of the building	Whether considering thermal inertia of the heating network
A	No	No	No
B	Yes	No	No
C	Yes	Yes	No
D	Yes	Yes	Yes

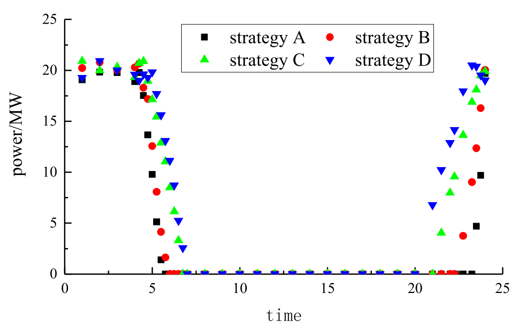


FIGURE 8. Power utilization curve of electric heat storage boiler.

considered in strategy B, and the medium temperature of the electric heat storage device rises slowly in the initial stage of opening, so the strategy B electric heat storage boiler will be opened earlier than A.

Moreover, the strategy B electric heat storage boiler needs to meet the temperature constraint of the electric heat storage

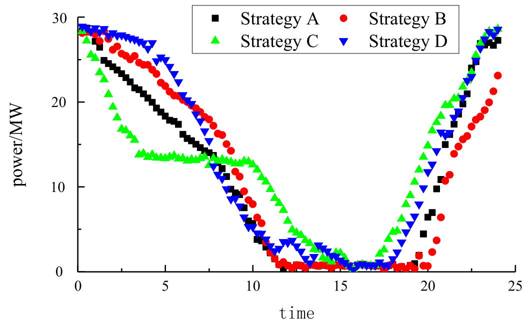


FIGURE 9. Thermal output of electric heat storage boiler.

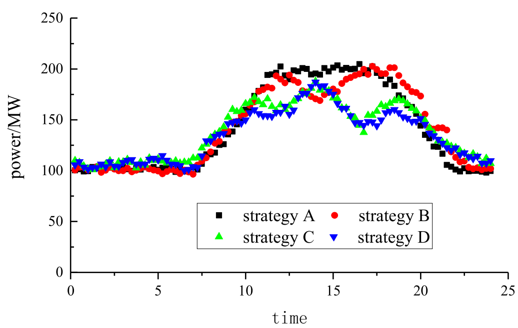


FIGURE 10. Output curve of thermal power unit.

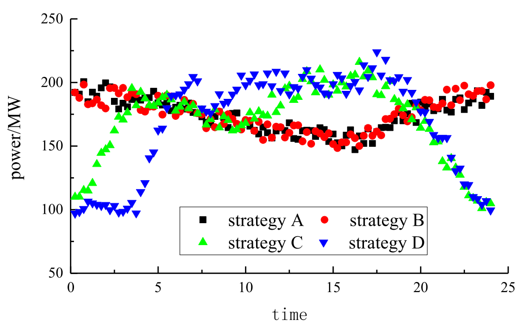


FIGURE 11. Output curve of CHP unit.

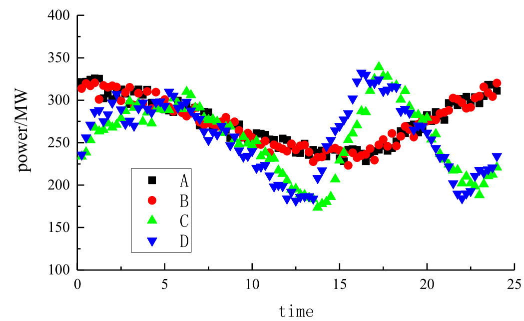


FIGURE 12. Heat dissipation curve of radiator.

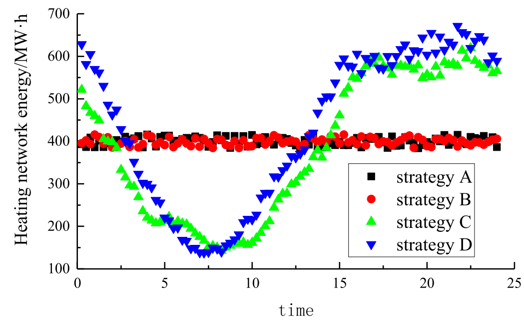


FIGURE 13. Energy curve of heat network.

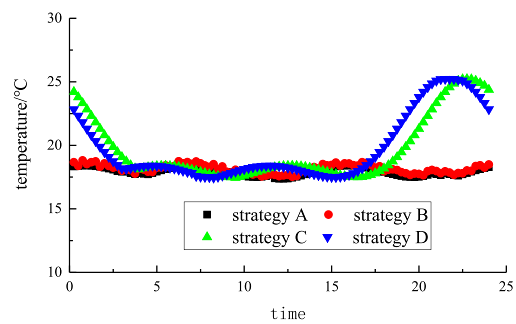


FIGURE 14. Indoor temperature curve of the building.

boiler at the initial stage of opening, so the heat release is less than that of the A strategy. However, the electric heat storage boiler has higher thermal efficiency than the direct heat type electric boiler, so strategy B electric heat storage boiler has more heat release than A throughout the day. Figures 10 and 11 show the electric output curve of the thermal power unit and the CHP unit.

Figure 12 shows the heat dissipation curve of the radiator. It is the traditional power real-time balance in the strategy A and B, so the thermal network energy and the indoor temperature curve of A and B are almost unchanged, and the heat dissipation of the radiators of A and B is the real-time thermal output of the CHP unit and the electric boiler. The function of the heat network as energy storage can be clearly seen from strategy C figure considering the thermal inertia of the building; the heat storage of the heat network is the heat output of the CHP unit and the electric boiler, and the heat release is the heat dissipation of the radiator. Figure 13 shows the heat release curve and heat grid energy change of the solid electric heat storage boiler, and Figure 14 shows the indoor temperature change of the heating area.

According to simulation results before the time when the power grid needs to increase power consumption, CHP unit will increase the heat supply to the heat network, so that the heat network stores more energy In the meanwhile, the heat network also increases the heat dissipation of the building and increases the overall temperature of the heating area. When the power grid needs to increase power consumption, the solid electric heat storage boiler is turned on, and the heat release of the heat network is reduced. The power output of the CHP unit can be minimized to improve the electric heating coordination capability considering the thermal inertia of the building.

It has thermal inertia of the heating network in strategy D comparing with strategy C, which is the coordination

TABLE 3. Operating costs and curtailed wind under four strategy.

Operating strategy	Operating cost /10^4 ¥	Curtailed wind amount/MW·h
A	1 003.3	623.1
B	901.2	311.7
C	897.7	347.6
D	759.5	38.4

TABLE 4. Power consumption and heat release of electric storage heat boilers under four operating strategies.

Operating strategy	Power consumption amount/MW·h	Heat release amount/MW·h
A	184.3	181.2
B	190.0	186.3
C	194.9	192.4
D	206.5	204.7

optimization strategy proposed in this paper. As shown in Figures 8 and 11-13, before the time when the power grid needs to increase power consumption, the strategy D increases the radiator heat dissipation amount in advance of the strategy C and enables a longer period with the lowest output of CHP unit And it can be seen that the adjustment range of the electric heat storage boiler is expanded.

C. COORDINATION OPTIMIZATION RESULTS ANALYSIS

The electro-thermal coordination optimization operation model considering thermal inertia was proposed in this paper; the optimization results can be seen from Table 3 through comparing the operating cost and the curtailed wind power amount under four operating modes. The electricity consumption and heat release of the electric storage heat boiler under four operating strategies was compared in Table 4, and it can be concluded that the solid electric heat storage boiler can bring a large space for the flexible adjustment of the CHP system, and considering more thermal inertia is equivalent to increasing the capacity of the electric heat storage boiler and improving the coordination ability of the CHP system.

VII. CONCLUSION

1) To reduce the electro-thermal coupling strength, the mathematical model of thermal inertia model of electric heat storage boiler, thermal network and building were established, and the optimal operation strategy for combined heat and power system based on solid electric thermal storage boiler and thermal inertia was proposed.

2) According to the three-dimensional numerical simulation of the heat storage body, the energy state of the heat storage body is obtained, and thus participates in the optimal scheduling of the combined heat and power system.

3) Take advantage of inertia of the heating system is in favor of improving system flexibility and economy, reducing electro-thermal coupling, and effectively enhancing the system's wind power consumption capability.

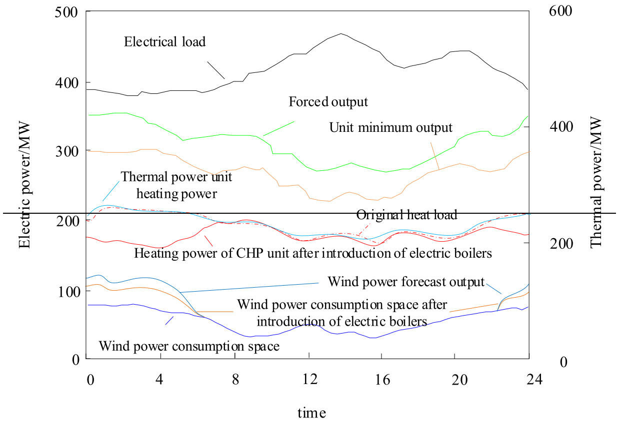


FIGURE 15. Mechanism of wind power accommodation of electric heat storage boiler.

TABLE 5. Basic parameters of heat storage electric boiler.

Parameter	value
Model	DRXG-20 000kW
Rated voltage	10kV
Dimensions	14800mm×15400mm×4800mm
Thermal conductivity	3.5 W/(m·K)
Thermal efficiency	99%

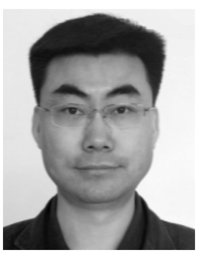
APPENDIX

See Figure 15 and Table 5.

REFERENCES

[1] E. Baccarelli, P. G. V. Naranjo, M. Scarpiniti, M. Shojafar, and J. H. Abawajy, "Fog of everything: Energy-efficient networked computing architectures, research challenges, and a case study," *IEEE Access*, vol. 5, pp. 9882–9910, 2017.
[2] J. Chen and Q. Zhu, "Interdependent strategic security risk management with bounded rationality in the Internet of Things," *IEEE Trans. Inf. Forensics Security.*, vol. 14, no. 11, pp. 2958–2971, Nov. 2019.
[3] M. Mohammadi, Y. Noorollahi, B. Mohammadi-Ivatloo, M. Hosseinzadeh, H. Yousefi, and S. T. Khorasani, "Optimal management of energy hubs and smart energy hubs—A review," *Renew. Sustain. Energy Rev.*, vol. 589, pp. 33–50, Jun. 2018.
[4] Z. Li, W. Wu, M. Shahidehpour, J. Wang, and B. Zhang, "Combined heat and power dispatch considering pipeline energy storage of district heating network," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 12–22, Jan. 2016.
[5] Y. Teng *et al.*, "Autonomous optimization operation model for multi-source microgrid considering electrothermal hybrid energy storage," *Proc. CSEE*, vol. 39, no. 18, pp. 5316–5324, 2019.
[6] J. F. Zheng, Z. G. Zhou, J. N. Zhao, and J. D. Wang, "Integrated heat and power dispatch truly utilizing thermal inertia of district heating network for wind power integration," *Appl. Energy*, vol. 211, pp. 865–874, Feb. 2018.
[7] J. L. Diaz C, C. Ocampo-Martinez, N. Panten, T. Weber, and E. Abele, "Optimal operation of combined heat and power systems: An optimization-based control strategy," *Energy Convers. Manage.*, vol. 199, Nov. 2019, Art. no. 111957.
[8] D. Wang, Y.-Q. Zhi, H.-J. Jia, K. Hou, S.-X. Zhang, W. Du, X.-D. Wang, and M.-H. Fan, "Optimal scheduling strategy of district integrated heat and power system with wind power and multiple energy stations considering thermal inertia of buildings under different heating regulation modes," *Appl. Energy*, vol. 240, pp. 341–358, Apr. 2019.
[9] W. Li, L. Yang, Y. Ji, and P. Xu, "Estimating demand response potential under coupled thermal inertia of building and air-conditioning system," *Energy Buildings*, vol. 182, pp. 19–29, Jan. 2019.

[10] Y. Teng, Z. Wang, Y. Li, Q. Ma, Q. Hui, and S. Li, "Multi-energy storage system model based on electricity heat and hydrogen coordinated optimization for power grid flexibility," *CSEE J. Power Energy Syst.*, vol. 5, no. 2, pp. 266–274, Jun. 2019.
[11] Z. Jinfu, Z. Zhigang, and Z. Jianing, "Effects of the operation regulation modes of district heating system on an integrated heat and power dispatch system for wind power integration," *Appl. Energy*, vol. 230, pp. 126–1139, 2018.
[12] M. Cheng, S. S. Sami, and J. Wu, "Benefits of using virtual energy storage system for power system frequency response," *Appl. Energy*, vol. 194, pp. 376–385, 2017.
[13] W. Ge *et al.*, "Robust estimation model of wind power prediction availability in the period of power system peak load," *High Voltage Eng.*, vol. 45, no. 4, pp. 281–1288 2019.
[14] X. Chen, C. Kang, M. O'Malley, Q. Xia, J. Bai, C. Liu, R. Sun, W. Wang, and H. Li, "Increasing the flexibility of combined heat and power for wind power integration in China: Modeling and implications," *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 1848–1857, Jul. 2015.
[15] S. Kuboth, F. Heberle, A. Konig-Haagen, and D. Bruggemann, "Economic model predictive control of combined thermal and electric residential building energy systems," *Appl. Energy*, vol. 240, pp. 372–385, 2019.
[16] L. Wang, Z. X. Jing, J. H. Zheng, Q.-H. Wu, and F. Wei, "Decentralized optimization of coordinated electrical and thermal generations in hierarchical integrated energy systems considering competitive individuals," *Energy*, vol. 158, pp. 607–622, Sep. 2018.
[17] Y. Li, Y. Zou, Y. Tan, Y. Cao, X. Liu, M. Shahidehpour, S. Tian, and F. Bu, "Optimal stochastic operation of integrated low-carbon electric power, natural gas, and heat delivery system," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 273–283, Jan. 2018.
[18] P. Li, H. Wang, Q. Lv, and W. Li, "Combined heat and power dispatch considering heat storage of both buildings and pipelines in district heating system for wind power integration," *Energies*, vol. 10, pp. 89–93, 2017.
[19] Y. Yang, K. Wu, H. Long, J. Gao, X. Yan, T. Kato, and Y. Suzuoki, "Integrated electricity and heating demand-side management for wind power integration in China," *Energy*, vol. 78, pp. 235–246, Dec. 2014.
[20] G. Fenghui, H. Linxian, and Z. Shengyu, "Dispatching model of wind power accommodation based on heat storage electric boiler for peak-load regulation in secondary heat supply network," *Autom. Electr. Power Syst.*, vol. 42, no. 19, pp. 50–59, 2018.
[21] Y. Zhongkai and L. Zhimin, "Combined heat and power dispatching strategy considering heat storage characteristics of heating network and thermal inertia in heating area," *Power Syst. Technol.*, vol. 42, no. 5, pp. 378–1384, 2018.
[22] J. Li, J. Fang, Q. Zeng, and Z. Chen, "Optimal operation of the integrated electrical and heating systems to accommodate the intermittent renewable sources," *Appl. Energy*, vol. 167, pp. 244–254, Apr. 2016.
[23] Z. Pan, Q. Guo, and H. Sun, "Interactions of district electricity and heating systems considering time-scale characteristics based on quasi-steady multi-energy flow," *Appl. Energy*, vol. 167, pp. 230–243, 2016.
[24] Y. Teng, T. Zhang, and Z. Chen, "Review of operation optimization and control of multi-energy interconnection system based on micro-grid," *Renew. Energy Resour.*, vol. 36, no. 3, pp. 467–474 2018.
[25] Y. Dai, L. Chen, Y. Min, Q. Chen, J. Hao, K. Hu, and F. Xu, "Dispatch model for CHP with pipeline and building thermal energy storage considering heat transfer process," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 192–203, Jan. 2019.



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