

Improving Operational Flexibility of Integrated Energy Systems Through Operating Conditions Optimization of CHP Units

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Abstract—As a type of energy system with bright application prospects, the integrated energy system (IES) is environmentally friendly and can improve overall energy efficiency. Tight coupling between heat and electricity outputs of combined heat and power (CHP) units limits IES operational flexibility significantly. To resolve this problem, in this paper, we integrate operating mode optimization of the natural gas combined cycle CHP unit (NGCC-CHP) into dispatch of the IES to improve flexibility of the IES. First, we analyze operational modes of the CHP units from the perspectives of thermal processes and physical mechanisms, including the adjustable extraction mode, back-pressure mode, and switching mode. Next, we propose an explicit mathematical model for full-mode operation of the CHP units, in which the heat-electricity feasible region, switching constraints, and switching costs are all formulated in detail. Finally, a novel economic dispatch model is proposed for a heat and electricity IES, which uses the full-mode operation of CHP units to improve operational flexibility. The Fortuny-Amat transformation is used to convert the economic dispatch model into a mixed-integer quadratic programming model, which can then be solved using commercial solvers. Case studies demonstrate the proposed method can reduce operational costs and obviously promotes wind power utilization.

Index Terms—Adjustable extraction mode, back pressure mode, combined heat and power, economic dispatch, full-mode operations, integrated energy system, operational flexibility.

NOMENCLATURE

A. Abbreviations

DHN	District heating network.
NGCC	Natural gas combined cycle power.
CHP	Combined heat and power.
AE	Adjustable extraction mode of CHP.
BP	Back pressure mode of CHP.
HE-IES	Heat and electric integrated energy system.

ED	Economic dispatch.
HRSR	Heat recovery steam generators.
GT	Gas turbine.
HPC	High-pressure cylinder.
IPC	Intermediate-pressure cylinder.
LPC	Low-pressure cylinder.
SSS	Synchro-self-shifting.

B. Indices and Sets

Π^{CHP}	Index Set of CHP thermal units.
Π^{OT}	Index Set of non-CHP thermal units.
Π^{W}	Index Set of wind farms.
Π^{D}	Index Set of power loads.
Π_p	Index Set of pipelines.
T	Index Set of the simulation period.
Π_p^{k+}	Index Set of pipelines flowing into the node k .
Π_p^{k-}	Index Set of pipelines flowing out of the node k .
Φ_{in}	Index set of intersection nodes of pipelines.
Φ_{ln}	Index set of heat load nodes.
Φ_{sn}	Index set of heat source nodes.

C. Parameters and Functions

Ω_{ae}	The range region of CHP in AE mode.
Ω_{bp}	The range region of CHP in BP mode.
Ω_{chp}	The range region of CHP.
C_i^{CHP}	The operation cost of CHP units i .
C_i^{OT}	The operation cost of non-CHP units i .
C_i^{W}	The penalty cost of abandoned wind power i .
$\bar{P}_i^{\text{OT}}/\underline{P}_i^{\text{OT}}$	Maximum/minimum generation output of generation unit i .
$\tilde{P}_{i,t}^{\text{w}}$	Available power of wind farm i at period t .
Ru_i/Rd_i	Upward/downward ramping capability of generation unit i .
Su_t/Sd_t	Upward/downward spinning reserve requirement of the electric power system at the period t .
c_i^{ae}	Cost of unit i switching from mode BP to AE.
Δh	heat power consumed by flushing the IPC.
σ_i	Penalty factor of wind curtailment of wind farm i .
$t_{\text{ae}}^+/t_{\text{bp}}^+$	Minimum uptime for CHP in mode AE/BP.
t_{ba}	Operation time for switching from BP to AE.
N_m	Maximum mode switching times of CHP.

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τ_{abm}	The Ambient temperature at period t .
ρ_w, c_w	Density and specific heat capacity of water.
$\gamma_p, R_p, \delta_p, \xi_p$	Parameters of time delay and heat loss of pipeline p .
λ^j, A_p^c, l_p	Heat transfer coefficient, cross-sectional area and length of pipeline p .
$\dot{m}_p$	Mass flow in pipeline p .
$\bar{\tau}^s/\underline{\tau}^s$	Maximum/minimum node temperature in supply pipelines.
$\bar{\tau}^r/\underline{\tau}^r$	Maximum/minimum node temperature in return pipelines.
$\bar{\tau}_{in}/\underline{\tau}_{in}$	Maximum/minimum indoor temperature.
C_{eq}^k, R_{eq}^k	Equivalent heat capacity and heat resistance of heat load at load node k .
τ_{out}^t	Outdoor temperature at period t .
Δt	Time interval of dispatch period.

D. Variables

h_{I}^t/h_{II}^t	Heat production of CHP unit in mode AE/BP during period t .
h_{III}^t	Heat production of CHP unit in switching process from BP mode to AE mode during period t .
p_{I}^t/p_{II}^t	Power production of CHP unit in mode AE/BP during period t .
p_{III}^t	Power of CHP unit in switching process from BP mode to AE mode during period t .
h_{chp}^t	Heat production of CHP in full-mode operation.
p_{chp}^t	Power production of CHP in full-mode operation.
$\varepsilon_I^t/\varepsilon_{II}^t$	Binary variable, 1 if the CHP is running at mode AE/BP at period t and 0 otherwise.
ε_{III}^t	Binary variable, 1 if the CHP is switching from mode BP to mode AE at period t and 0 otherwise.
$P_{i,t}^{CHP}$	Power output of CHP unit i during period t .
$h_{i,t}^{CHP}$	Heat power output of CHP unit i during period t .
$\varepsilon_{i,t}^{OT}$	Binary variable, 1 if the generation i is on at period t and 0 otherwise.
$P_{i,t}^{OT}$	Power output of generation unit i during period t .
$P_{i,t}^W$	Power output of wind farm i during period t .
$P_{i,t}^D$	Power demand of load i during period t .
v_{ae}^t/ν_{bp}^t	Binary variable, 1 if the CHP is switched to mode AE/BP at period t and 0 otherwise.
w_a^t/w_{bp}^t	Binary variable, 1 if the CHP is switched from mode AE/BP to other modes at period t and 0 otherwise.
$\tau_{p,in}^{s,t}/\tau_{p,out}^{s,t}$	Inflow/outflow temperature of water in supply pipeline p .
$\tau_{p,in}^{r,t}/\tau_{p,out}^{r,t}$	Inflow/outflow temperature of water in return pipeline p .
$\tau_{j,n}^{s,t}/\tau_{j,n}^{r,t}$	Temperature of water at node j in supply/return pipeline.
$h_{load}^{k,t}$	Heat load at node k at period t (kW).
$\tau_{in}^{k,t}$	Indoor temperature of buildings at load node k at period t .

I. INTRODUCTION

THE increasing energy consumption and serious environmental issues humanity faces are driving development of low-carbon and sustainable energy systems [1]. Integrated energy system (IES), which applies multi-energy complementation and energy cascade utilization techniques to improve overall energy efficiency and renewable energy utilization, is regarded as a secure, efficient, clean, and flexible energy system with bright application prospects [2].

Heat and electric integrated energy systems (HE-IES), based on combined heat and power (CHP) units, is an important form of IES. Natural gas combined cycle (NGCC) CHP unit has been used as the primary heat resource among various types of CHP units in Beijing and other large cities in China because of its small size, high comprehensive efficiency, and small environmental impact [3], [4]. However, NGCC-CHP (denoted simply by CHP in this paper) is operated by following the thermal load, which affects economy and flexibility of the HE-IES [5]. Large amounts of wind power will then be abandoned when CHP power generation meets most electricity demand during off-peak hours [5], [6].

In order to increase wind power utilization and improve the energy system's economic efficiency, it will be necessary to implement measures that increase flexibility of the HE-IES with CHP units. A great deal of research has focused on enhancement of HE-IES flexibility, and the measures required can be divided into three categories: installation of extra devices [5], [7]–[9], use of thermal inertia of the heating system [10]–[13], and use of integrated demand response programs [14]–[16]. Some researchers focused on optimizing energy system structure by adding heat-electricity coupling devices, such as heat pumps, and electric boilers [7], [8] or energy storage devices such as batteries and heat storage tanks to the HE-IES [5], [8], [9]. The heating system's thermal inertia is reflected in the heat storage capacity and thermal delay of the heating network and buildings [10]. Using these heating system characteristics is an effective method to improve flexibility of the HE-IES, and researchers have performed valuable work from the perspectives of modeling methods [10], [11] and optimization strategies [12], [13].

Additionally, an integrated demand response also provides an effective way to improve system flexibility [14]–[17]. Reference [14] has used consumers' flexible thermal and power demands to provide additional flexibility for the resources and increase wind power utilization. In [15], both optimal load-output matching and optimal market participation were considered in a proposed control model. Reference [16] analyzed 34 engineering cases for electrothermal energy systems and proposed increasing flexibility of the power-to-heat demand response via careful adjustment of market rules. Reference [18] proposed an innovative framework for a multi-energy management system that incorporates a flexible energy complementarity strategy to improve operation of multiple energy prosumers.

Among methods to improve system flexibility proposed above, installing extra devices requires additional investment, which will bring additional operational and design burdens due

to changes in the physical and communication structures. Utilization of the system's thermal inertia is highly advantageous. However, flexibility provided by the thermal inertia of DHN is limited because supply/return temperature constraint cannot meet the need of IES. Finally, an integrated demand response requires applicable market rules and participation of multiple entities and users, which requires further research of relevant economic policy frameworks and coordination mechanisms.

On the other hand, as an essential component of the HE-IES, CHP plays an essential role in optimizing scheduling and improving system flexibility. References [19]–[21] improved operating efficiency and part-load performances of CHP units by optimizing their operating parameters, e.g., compressor pressure ratio and inlet gas turbine temperature. Reference [22], [23] improve the unit's operating efficiency under variable conditions and increase the load variation range of the CHP by adjusting the recovery mode of waste heat and improving design of the compressor, respectively. Research above focused on peak shaving characteristics and part-load operation performances of CHP units at the device level. Some other studies analyze flexibility of the CHP unit from the perspective of operation mode. Reference [24] summarized technical flexibility and characteristics of different operating modes of CHP units. Reference [25] simulates electrical and thermal load characteristics of adjustable extraction (AE) and back pressure (BP) modes of combined cycle heating units and optimizes the unit's operation mode in different heating periods.

In summary, the above research on improving operational flexibility of CHP units is mainly focused on equipment level. However, from the system level of the HE-IES, higher requirements can be proposed to improve flexibility of the CHP units. It will thus be necessary to make full use of the heat-electricity coupling characteristics of CHP units to expand their operational flexibility. The first research gap to be addressed is that flexibility of the CHP unit has rarely been investigated from a HE-IES perspective.

In the dispatch decision of HE-IES, the CHP unit is assumed to operate in either the AE mode or the BP mode. In fact, some CHP units (the NGCC-CHP) include both of these heating modes and can switch between modes without being shut down [25], [26]. Heat-electricity ratio of the AE mode can be adjusted within a specific range [27], which means it cannot achieve the "maximum heating power" because of minimum cooling flow requirements of the low-pressure cylinder (LPC) [28]. Heat-electricity ratio of the BP mode is fixed, meaning that it cannot meet different demands of the thermal and electrical loads [27]. It is foreseeable that mode switching ability of CHP will play an essential role in improving flexibility of the HE-IES.

Existing literature on the economic dispatch (ED) of CHP units rarely involves the CHP unit's detailed operating conditions [29], [30]. Characteristics of heat recovery steam generators (HRSGs) were considered in the ED model in [4], and results proved this model was better than the traditional polygonal model. Reference [31] established an ED model that was suitable for short-term NGCC-CHP load changes based on power and thermal load control logic during opera-

tion. Reference [32] first considered internal composition and physical processes of CHP plants in their dispatch model for IESs. These studies have considered equipment composition and the physical properties of CHP units in the ED, making the operating domain more accurate. However, CHP unit's specific heating mode and mode switching during operation are not involved. Therefore, the second research gap is the detailed CHP unit model that considers operating mode and mode switching process has not received sufficient attention.

To close these research gaps, we propose a novel ED model for the HE-IES that uses full-mode operation of the CHP units to improve operational flexibility. The main contributions of this study are summarized as follows.

1) Operating modes of NGCC-CHP are introduced in the optimization dispatch of HE-IES to expand flexibility resources of HE-IES. We comprehensively expound the operation modes of CHP units from the perspective of thermal process and physical mechanism and analyzes the source of flexibility of this operation mode in HE-IES.

2) We propose an explicit mathematical model of the full-mode operation of CHP units in which the heat-electricity feasible region, switching constraints, and switching costs are all formulated in detail.

3) A novel ED model that uses the full-mode operation of CHP units is proposed for the HE-IES. The Fortuny-Amat transformation is used to convert the ED model into a mixed-integer quadratic programming model.

4) In optimized dispatch of the HE-IES, we consider the synergy of the heating network, buildings, and proposed full mode operation mode of CHP to improve flexibility and economy of the IES.

The remainder of this paper is organized as follows: Section II discusses the NGCC-CHP operating mechanism. The model for full-mode CHP unit operations is given in Section III. Section IV establishes an optimal dispatch model that considers the proposed CHP model, including grid, heating network, and building constraints. In Section V, results of case studies demonstrate advantages of the proposed technology. Section VI summarizes the work.

II. OPERATING MODES OF CHP UNITS

A. Operating Mechanism of NGCC-CHP System

The NGCC-CHP structure mainly comprises the gas turbine (GT), HRSG, steam turbine, and a power plant heat exchanger [33], as shown in Fig. 1.

GT consumes natural gas to drive the generator to generate electricity and exhausts flue gas at high temperatures. HRSG then absorbs waste heat from flue gas to generate steam at a specific pressure and temperature, which is then used to drive the steam turbine to generate electricity or heat power.

The CHP's steam turbine system includes three cylinders: a high-pressure cylinder (HPC), an intermediate-pressure cylinder (IPC), and a low-pressure cylinder (LPC). Rotors of the HPC and IPC are connected to the LPC's rotor via the synchro-self-shifting (SSS) clutch. SSS clutch is a component that controls the connection state of the IPC and the LPC, which can cut off or connect to the LPC with IPC without shutdown.

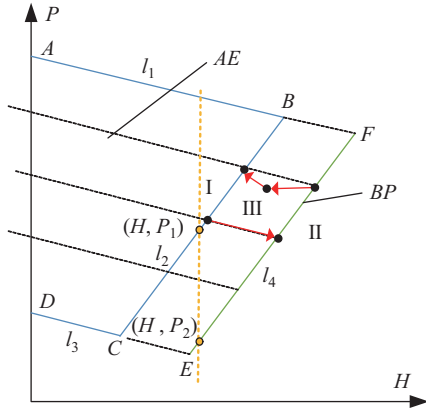


Fig. 2. Full safe operation range and mode switching of CHP unit.

III. MODEL FOR FULL-MODE OPERATIONS OF CHP UNITS

A. Full Model of the CHP System

Full-mode operation model of the CHP unit includes BP operation model, AE operation model, and switching process model. Output powers of these models are limited by operating conditions of GT and steam turbine, including GT maximum continuous power (GMCP), GT minimum continuous power (GNCP), and steam turbine maximum extraction (STME). Full safe operation domain is shown in Fig. 2.

1) Safe Operation Range of mode AE

In AE mode, the safe operation domain of the CHP is a two-dimensional area encompassing heating load and electrical power [34], which is shown in Fig. 2.

$$\begin{cases} h_I^t = \varepsilon_I^t h_I^{t'} \\ p_I^t = \varepsilon_I^t p_I^{t'} \end{cases} \quad \forall (h_I^t, p_I^t) \in \Omega_{ae} \cup \{(0, 0)\} \quad (1)$$

where Ω_{ae} is the range region of CHP in AE mode.

When GT is in GMCP condition, the CHP unit will have maximum electric power if no steam extraction (coordinate point A). In addition, if the CHP unit is simultaneously in STME condition, it will also have maximum heat supply (coordinate point B). Similarly, when GT is in GNCP condition, maximum electric power of the unit involves no steam extraction, and maximum thermal power is in STME condition (coordinate points C and D). By fitting points A–D in turn, we can obtain the boundary line for Ω_{ae} . In particular, boundary line BC represents the CHP unit's thermal power under STME condition at different GT loads.

2) Safe Operation Range of BP Mode

As shown in Fig. 2, the safe operating range of the BP mode is a curve encompassing electrical load and heating load [34]. CHP usually operates in the heating-load-following mode, and heating load is adjusted by varying GT load rate.

$$\begin{cases} h_{II}^t = \varepsilon_{II}^t h_{II}^{t'} \\ p_{II}^t = \varepsilon_{II}^t p_{II}^{t'} \end{cases} \quad \forall (h_{II}^t, p_{II}^t) \in \Omega_{bp} \cup \{(0, 0)\} \quad (2)$$

where Ω_{bp} is the BP mode range region, and working condition points E and F are determined by the GMCP and the GNCP, respectively.

3) Switching Model of CHP Unit

As indicated by the red arrow from points I to II in Fig. 2, we believe the AE mode can be switched directly to the BP mode because this process takes a short time and involves zero energy consumption. However, the switching process from BP mode to AE mode requires energy consumption. Therefore, we regard this process as an independent mode, called mode III, as indicated by the red arrows from II to III to I in Fig. 2. The model of mode III is given as follows:

$$\begin{cases} h_{III}^t = \varepsilon_{III}^t [(h_{II}^{t-1} - \Delta h) + h_{III}^{t-1}] \\ p_{III}^t = \varepsilon_{III}^t (p_{II}^{t-1} + p_{III}^{t-1}) \end{cases} \quad (3)$$

where Δh is heat power consumed to flush the IPC.

4) Full Model of the CHP System

In summary, the model for full-mode operation of the CHP unit is given by (4).

$$\begin{cases} h_{chp}^t = h_I^t + h_{II}^t + h_{III}^t \\ p_{chp}^t = p_I^t + p_{II}^t + p_{III}^t \end{cases} \quad (4)$$

Considering full-mode operation of the CHP unit, operating cost of CHP units is a function of thermal power, electrical power, and unit switching action, which is given as follows [11].

$$C_i^{CHP} = f(p_{chp}^t, h_{chp}^t) + c_i^{ae} v_{ae}^t \quad (5)$$

$$\begin{aligned} f(p_{chp}^t, h_{chp}^t) = & a_1 p_{chp}^{t^2} + a_2 p_{chp}^t + b_1 h_{chp}^{t^2} + b_2 h_{chp}^t \\ & + c p_{chp}^t h_{chp}^t + d \end{aligned} \quad (6)$$

where $f(p_{chp}^t, h_{chp}^t)$ is a quadratic function of electricity and heat productions [11]. The last item of (5) denotes costs of switching from BP to AE. As illustrated above, the switching process from BP mode to AE mode is complex and requires energy consumption.

B. CHP Constraints

CHP constraints include safe operation domain constraints, switching time constraints between different modes, minimum uptime/downtime constraints for AE and BP modes, and mode switching time constraints.

The operational domain of the CHP unit is as follows.

$$\Omega_{chp} = \Omega_{ae} \cup \Omega_{bp} \cup \{(0, 0)\} \quad (7)$$

The operating mode of the CHP unit must satisfy the following logical constraints.

$$\varepsilon_I^t + \varepsilon_{II}^t + \varepsilon_{III}^t \leq 1 \quad (8)$$

During actual operation, after completion of a switching process, the operator must monitor operation status to ensure stability and safety of the CHP unit. Subsequent switching can only be carried out when the unit runs stably for a specified period. Therefore, the AE mode and the BP mode of the CHP unit must satisfy uptime and downtime constraints.

$$\begin{cases} \sum_{\tau=t-t_{ae}^+ + 1}^t v_{ae}^t \leq \varepsilon_I^t \\ \varepsilon_I^t - \varepsilon_I^{t-1} = v_{ae}^t - w_{ae}^t \end{cases} \quad (9)$$

$$\begin{cases} \sum_{\tau=t-t_{bp}^+ + 1}^t v_{bp}^t \leq \varepsilon_{II}^t \\ \varepsilon_{II}^t - \varepsilon_{II}^{t-1} = v_{bp}^t - w_{bp}^t \end{cases} \quad (10)$$

As mentioned above, it takes some time to switch from BP mode to AE mode (that is, mode III). The engineering operation process of Mode III is fixed, and so is time spent in the operation process.

$$\varepsilon_{\text{III}}^t = \sum_{\tau=1}^{t_{\text{ba}}} \varepsilon_{\text{II}}^{t-\tau} \varepsilon_1^{t+t_{\text{ba}}-\tau+1} \quad (11)$$

Frequent switching of the operation mode is not friendly to the system crew, so frequency of switching operations must be limited.

$$\sum_{t=1}^T (v_{\text{ae}}^t + v_{\text{bp}}^t) \leq N_m \quad (12)$$

IV. ECONOMIC DISPATCH MODEL WITH FULL-MODE OPERATIONS OF CHP UNITS

A. Objective Function

The objective of the proposed economic dispatch problem is to minimize total operating cost.

$$\sum_{t \in \mathbf{T}} \sum_{i \in \mathbf{\Pi}^{\text{CHP}}} C_i^{\text{CHP}} + \sum_{t \in \mathbf{T}} \sum_{i \in \mathbf{\Pi}^{\text{OT}}} C_i^{\text{OT}} + \sum_{t \in \mathbf{T}} \sum_{i \in \mathbf{\Pi}^{\text{W}}} C_i^{\text{W}} \quad (13)$$

In (13), the three terms are operation cost of CHP units, operation of non-CHP operation thermal units, and penalty cost of abandoned wind power, respectively. The operation cost of CHP units is given by (5) and (6).

The penalty cost of the abandoned wind power is defined as follows:

$$C_i^{\text{W}} = \sigma_i (\tilde{P}_{i,t}^{\text{W}} - p_{i,t}^{\text{W}}) \quad (14)$$

B. Constraints

The constraints of the model proposed in this paper include power system constraints, CHP units' constraints, district heating network constraints, and building thermal constraints.

1) Electrical Power System

The power system constraints are given by (15)–(18). Equation (15) gives the balance for total electric generation and total load; (16) represents the operation constraint of the non-CHP units, and renewable energy; (17) represents the ramping constraints of the generator; and (18) gives spinning reserve constraints. Other electrical power system constraints, e.g., transmission flow limits, voltage limits, and any other optimal power flow inequality constraints, can be found in [35], [36] and are omitted here.

$$\sum_{i \in \mathbf{\Pi}^{\text{CHP}}} P_{i,t}^{\text{CHP}} + \sum_{i \in \mathbf{\Pi}^{\text{OT}}} P_{i,t}^{\text{OT}} + \sum_{i \in \mathbf{\Pi}^{\text{W}}} P_{i,t}^{\text{W}} = \sum_{i \in \mathbf{\Pi}^{\text{D}}} P_{i,t}^{\text{D}}, \quad \forall t \in \mathbf{T} \quad (15)$$

$$\begin{cases} \varepsilon_{i,t}^{\text{OT}} \underline{P}_i^{\text{OT}} \leq P_{i,t}^{\text{OT}} \leq \varepsilon_{i,t}^{\text{OT}} \bar{P}_i^{\text{OT}}, & \forall i \in \mathbf{\Pi}^{\text{OT}}, t \in \mathbf{T} \\ 0 \leq P_{i,t}^{\text{W}} \leq \bar{P}_{i,t}^{\text{W}}, & \forall i \in \mathbf{\Pi}^{\text{W}}, t \in \mathbf{T} \end{cases} \quad (16)$$

$$-Rd_i \leq p_{i,t}^j - p_{i,t-1}^j \leq Ru_i, \quad \forall i \in \mathbf{\Pi}^{\text{OT}} \cup \mathbf{\Pi}^{\text{CHP}}, t \in \mathbf{T} \quad (17)$$

$$\begin{cases} \sum_{i \in \mathbf{\Pi}^{\text{OT}}} \min \{ Ru_i, \bar{P}_{i,t}^{\text{OT}} - p_{i,t}^{\text{OT}} \} \geq Su_t, & \forall t \in \mathbf{T} \\ \sum_{i \in \mathbf{\Pi}^{\text{OT}}} \min \{ Rd_i, p_{i,t}^{\text{OT}} - \underline{P}_i^{\text{OT}} \} \geq Sd_t, & \forall t \in \mathbf{T} \end{cases} \quad (18)$$

2) District Heating Network Constraints

The node method is used in this paper. Because of its excellent performance, the node method is used widely to model the heat dynamics of district heating networks (DHNs) during operation optimization [36], [37].

$$\begin{cases} \tau_{p,\text{out}}^{i,t} = \tau_{p,\text{in}}^{i,t-\gamma_p-1} + \delta_p \tau_{p,\text{in}}^{i,t-\gamma_p+1} - \tau_{p,\text{in}}^{j,t-\gamma_p} \\ \tau_{p,\text{out}}^{i,t} = \tau_{\text{amb}}^t + \xi_p (\tau_{p,\text{out}}^{i,t} - \tau_{\text{amb}}^t) \end{cases} \quad p \in \mathbf{\Pi}_p, i \in \{s, r\} \quad (19)$$

Equation (19) describes the pipe temperature distribution, which is obtained through the node method [37], where parameters δ_p , γ_p , and ξ_p used in (19) are defined as:

$$\begin{cases} \gamma_p = \lfloor \rho_w A_p^c l_p / (\dot{m}_p \Delta t) \rfloor \\ R_p = (\gamma_p + 1) \dot{m}_p \Delta t \\ \delta_p = (R_p - \rho_w A_p^c l_p) / (\dot{m}_p \Delta t) \\ \xi_p = \exp \left[-\frac{\lambda^j \Delta t}{\rho_w A_p^c l_p} (\gamma_p + 3/2 - \delta_p) \right] \end{cases} \quad (20)$$

Other constraints for DHN include the node temperature mixing equation, heat power balance equations, and network topology equation.

$$\tau_{j,n}^{i,t} \sum_{p \in \mathbf{\Pi}_p^{k-}} \dot{m}_p = \sum_{p \in \mathbf{\Pi}_p^{k+}} (\dot{m}_p \tau_{p,\text{out}}^{i,t}) \quad j \in \Phi_{\text{in}}, i \in \{s, r\} \quad (21)$$

$$\begin{cases} c_w \dot{m}_p (\tau_{s,n}^{k,t} - \tau_{r,n}^{k,t}) = Q_s^{k,t} & p \in \mathbf{\Pi}_p^{k+}, k \in \Phi_{\text{sn}} \\ c_w \dot{m}_p (\tau_{s,n}^{k,t} - \tau_{r,n}^{k,t}) = Q_r^{k,t} & p \in \mathbf{\Pi}_p^{k-}, k \in \Phi_{\text{ln}} \end{cases} \quad (22)$$

$$\tau_{p,\text{in}}^{i,t} = \tau_{j,n}^{i,t} \quad p \in \mathbf{\Pi}_p^{k+}, j \in \Phi_{\text{in}}, i \in \{s, r\} \quad (23)$$

Equation (21) describes node temperature mixing limits. Equation (22) represents heat power balance at supply pipelines and return pipelines. Topological constraint of the heating network is shown in Equation (23). Specifically, pipe inlet temperature is the temperature of the corresponding node. Additionally, node temperature is limited to ensure required heating quality and is shown as follows:

$$\underline{\tau}^i \leq \tau_{p,n}^{i,t} \leq \bar{\tau}^i \quad p \in \mathbf{\Pi}_p, i \in \{s, r\} \quad (24)$$

3) Buildings Constraints

The first-order equivalent thermal parameter model of the building is used in this paper [10], [38], which is given as follows:

$$h_{\text{load}}^{k,t} = a^k \tau_{\text{in}}^{k,t} - b^k \tau_{\text{in}}^{k,t-1} - c^k \tau_{\text{out}}^t \quad (25)$$

where the parameters used in (25) are illustrated in (26):

$$\begin{aligned} a^k &= \frac{1}{R_{\text{eq}}^k \left(1 - e^{-\Delta t / (R_{\text{eq}}^k C_{\text{eq}}^k)} \right)} \\ b^k &= a^k e^{-\frac{\Delta t}{R_{\text{eq}}^k C_{\text{eq}}^k}}, \quad c^k = \frac{1}{R_{\text{eq}}^k} \end{aligned} \quad (26)$$

In addition, indoor temperature $\tau_{\text{in}}^{k,t}$ is limited to ensure a comfortable temperature range for consumers.

$$\underline{\tau}_{\text{in}} \leq \tau_{\text{in}}^{k,t} \leq \bar{\tau}_{\text{in}} \quad (27)$$

4) CHP Constraints

Operational constraints of the CHP unit are given in Section II, where (1)–(4) are operating range constraints, and (7)–(10) are operational logic constraints.

C. Problem Transformation

The compact form of the proposed dispatch model can be represented as follows:

$$\begin{aligned} \min \quad & \mathbf{x}^T \mathbf{Q} \mathbf{x} + \mathbf{b} \mathbf{x} + \mathbf{c} \\ \text{s.t.} \quad & \mathbf{A} \mathbf{x} + \mathbf{B} \boldsymbol{\varepsilon} + \mathbf{C} \mathbf{y} \leq \mathbf{d} \quad (\text{a}) \\ & \mathbf{y} = \boldsymbol{\varepsilon} \mathbf{x} \quad (\text{b}) \\ & \boldsymbol{\varepsilon} \in \{0, 1\} \end{aligned} \quad (28)$$

where $\mathbf{Q}$ is a semi-definite matrix; $\mathbf{b}$, $\mathbf{c}$ and $\mathbf{d}$ are constant vectors; $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ are constant matrices.

Among the constraints of the proposed model, constraints (1)–(4) of CHP unit belongs to constraint of (28b), and other CHP constraints, power system constraints, heating network constraints, and building constraints including (5)–(12) and (15)–(27) belong to constraint of (28a). Constraint of (28b) is nonlinear due to introduction of boundary variables. The Fortuny-Amat transformation is used in this paper to solve the problem [27], [36].

According to the Fortuny-Amat transformation, constraint (28b) can be similarly transformed to (29).

$$\begin{cases} -\varepsilon M \leq y \leq \varepsilon M \\ x - (1 - \varepsilon)M \leq y \leq x + (1 - \varepsilon)M \end{cases} \quad (29)$$

where M represents a maximum value, after Fortuny-Amat transformation, the economic dispatch model becomes a mixed-integer quadratic programming model.

V. CASE STUDIES

In this section, two systems on different scales are used to perform case studies. Case I is a six-node heating network and a six-node grid system. Case II is based on an actual 118-node network in northern China. Time intervals for the heating network and power grid are 0.5 h and 1 h, respectively, and dispatch period is 24 h. The reason for using these time intervals to model the heating system and power system is that it can meet the requirement of heat power balance between heat power supply and demand in system operation. Arguments and explanations for selecting time intervals in thermal and electrical simulation are presented in [37]. Simulation is performed in MATLAB 2020a, and the solver used is CPLEX.

A. Case I

The structure of case I is shown in Fig. 3. The system includes a 6-node power grid and a 6-node heating network. The power system includes two non-CHP units, a wind farm, and an NGCC-CHP thermal unit. The CHP is a 9FB combined-cycle unit with an M701F4 GT, a three-pressure reheated HRSG, and a steam turbine (TC2F-40.5). Main parameters of the CHP are given in Table I. Peak electric load value is 940 MW, the comfortable indoor temperature is set at 21°C, and upper and lower temperature limits are set at 19°C and 23°C, respectively.

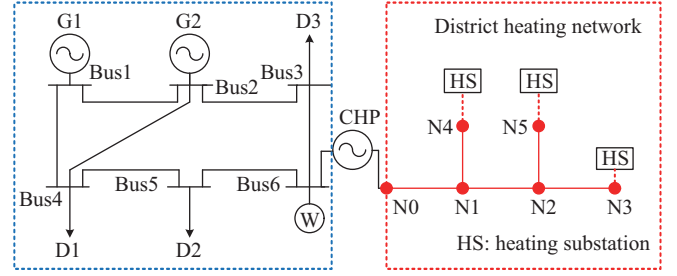


Fig. 3. Structure of the HE-IES 6-bus system in Case I.

TABLE I
PARAMETERS OF CHP IN DESIGN HEATING CONDITIONS

Parameters	AE mode	BP mode
Gas turbine power (MW)	335.5	335.5
Main steam flow (t/h)	292.5	292.5
Main steam temperature (°C)	523.9	524.1
Main steam pressure (MPa)	12.59	12.60
Reheated steam flow (t/h)	342.4	342.4
Reheated steam temperature (°C)	549.2	548.8
Reheated steam pressure (MPa)	3.36	3.37
Exhaust pressure (kPa)	3.4	–
Steam power (MW)	157.5	77
Heating extraction steam flow (t/h)	309.8	–
Heat power (MW)	256.5	322.7
Combined cycle power (MW)	493	412.65

1) Comparison of Economic Efficiency

Operating mode status of the CHP unit is shown in Table II. It can be concluded from Table II that in one dispatch period, the CHP unit operating mode has been switched twice. At 09:00, the CHP unit switched from BP mode to AE mode, and it ran in AE mode until 16:00 and switched to BP mode. The switchable mode does not affect the next dispatch period because exactly two switching operations were performed during the dispatch period.

TABLE II
OPERATING MODE STATUS OF CHP

Hour	1	2	3	4	5	6	7	8	9	10	11	12
BP	0	0	0	0	0	0	0	0	0	0	1	1
AE	1	1	1	1	1	1	1	1	1	0	0	0
switch	0	0	0	0	0	0	0	0	0	1	0	0
Hour	13	14	15	16	17	18	19	20	21	22	23	24
BP	1	1	1	1	0	0	0	0	0	0	0	0
AE	0	0	0	0	1	1	1	1	1	1	1	1
switch	0	0	0	0	0	0	0	0	0	0	0	0

To verify the effect on improving economic efficiency and flexibility of the HE-IES by considering the CHP unit operating conditions, we compare results of the three CHP unit operating conditions, i.e., the AE mode (M1), the BP mode (M2), and switchable mode (M3) over the entire dispatch period.

Table III shows total operating costs and cost of each unit when the CHP is running in AE mode (M1), BP mode (M2), and switchable mode (M3). Compared with M1 and M2, operating cost of M3 is reduced by 16.84% and 7.66%, respectively. With regard to operating expenditures of specific units, the cost of G1&G2 at M1 is lower than at M3. In contrast, cost of the CHP and especially of wind curtailment

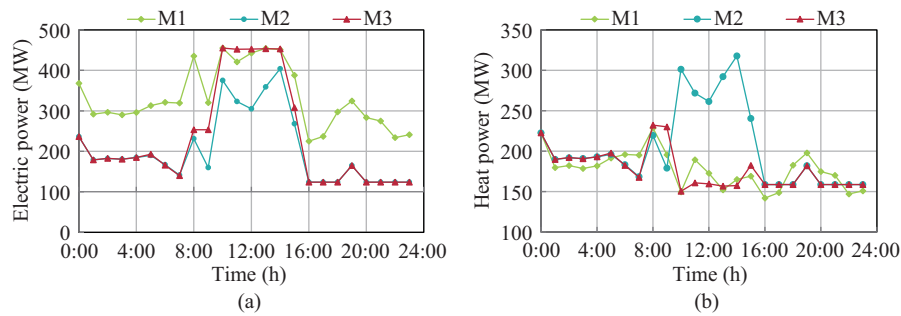


Fig. 4. Outputs of CHP units. (a) Electrical power. (b) Heat power.

TABLE III
COSTS UNDER DIFFERENT CHP MODES

Subcase No.	M1	M2	M3
G1&G2	110.314	168.054	141.539
Cost	41.258	4.863	4.853
($\times 10^3$ \$)	CHP	244.937	184.170
Total	396.509	357.088	329.713

is higher than in M3. Higher operating expenditure for M2, when compared with M3, is reflected in the cost of G1&G2. Therefore, results show that the overall economic efficiency of the HE-IES system can be improved significantly by considering the CHP unit's operating conditions.

2) Comparison of Dispatch Results

Electrical power and thermal power outputs of CHP units are illustrated in Fig. 4. We can see electrical power in M1 is higher than in M2 and M3 during the periods from 00:00–08:00 and 17:00–24:00, as shown in Fig. 4(a). In contrast, thermal power of M2 is significantly higher than of M1 and M3 from 10:00–16:00, as shown in Fig. 4(b). Electrical and thermal power curves of M3 are roughly a combination of partial electric and thermal curves of M1 and M2. From 0:00–09:00 and 16:00–24:00, M3's power curve is similar to M2. From 9:00–16:00, M3's power curve is similar to M1.

Wind power utilizations of the three modes are shown in Fig. 5. During periods from 00:00–08:00 and 16:00–24:00, M1 has a relatively large amount of wind curtailment. In connection with higher electrical power output of M1 during the same period (shown in Fig. 4(a)), we find the increased electrical power of the CHP limited the system's capacity to absorb wind power.

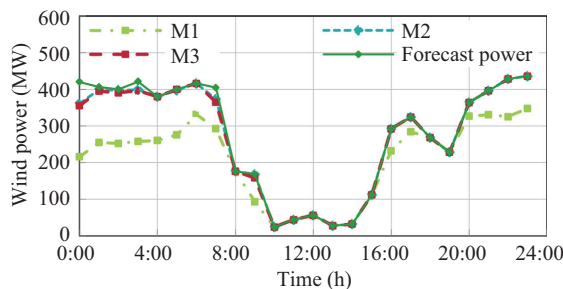


Fig. 5. Wind power utilization comparison of the different CHP modes.

Figure 6 shows heat load at the source node and heat curtailment of the three subcases. The overall heat load trend in

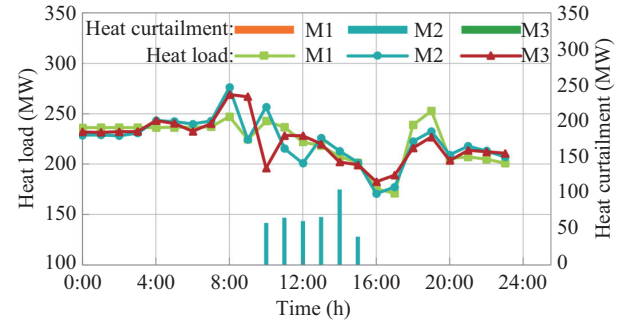


Fig. 6. Comparison of heat loads and curtailments of three operating modes.

the three subcases is roughly the same, and slight differences appear from 08:00–20:00. The reason for fluctuations is that both the thermal inertia model of the buildings and heating network model are considered in this paper. Building temperature can fluctuate within a small comfortable temperature range. In addition, as shown by the bar chart in Fig. 6, only M2 has significant heat rejection among the three subcases.

3) Explanation and Discussion of Dispatch Results

The above dispatch results provide simulation verification for flexible source analysis of operation modes of CHP units in Section II. We can provide a reasonable explanation for the dispatch results based on operating characteristics of AE mode and BP mode.

During the periods from 00:00–08:00 and 16:00–24:00, system heat load is relatively high, and the CHP supplies heat power to the heating network, following the principle of “heat-to-electricity.” As explained in Section II, the AE mode's minimum electrical power generation is higher than in the BP mode at the same heating power. If the CHP unit is running in AE mode at this time, electrical power should be more significant to ensure required heating power, which corresponds to the M1 curve characteristics in Fig. 4(a). In general, during this period, wind power is generally relatively large. In connection with the high level of wind curtailment for M1 during the same period (as shown in Fig. 5), we find the increase of CHP unit's electrical output has limited the system's capacity to absorb wind power.

The heat-electricity ratio of BP mode is constant, which means that it cannot meet the differential demand between heat and power supplies. During daytime, electrical load is high, and forecast wind power at this time is generally low. Therefore, increasing the CHP unit's electrical power to meet

the electrical load demand is necessary. Thermal load is relatively small during the middle of the day, and if the CHP unit is running in BP mode at this time, it will inevitably result in heat losses due to redundancy of heat power. As shown in Fig. 6, there is high heat curtailment for M2 from 10:00–15:00.

4) Economic Efficiency under Different Wind Power Ratios

To analyze the advantages of the method proposed in this paper under different application scenarios, we compared system economics under various wind power forecast conditions. Forecast wind power is 50%–120% of the basic calculation case.

Wind curtailment and heat curtailment under different forecast power conditions are presented in Fig. 7. The figure shows that M1 and M2 have opposite phenomena in terms of curtailment of wind and heat. Specifically, M1 does not have heat curtailment. The amount of wind curtailment required increases significantly with high forecast wind powers, but M2 always has a more significant amount of heat curtailment and requires a small amount of wind curtailment when forecast wind power is higher.

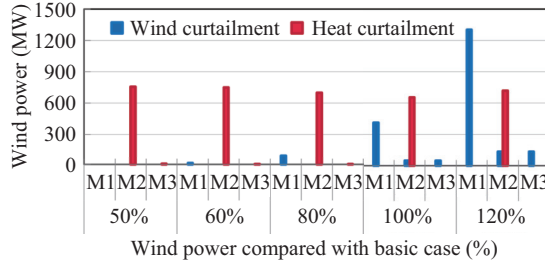


Fig. 7. Wind curtailment and heat curtailment for various forecast wind power.

There is almost no energy curtailment in M3, except for a small amount of wind curtailment when forecast wind power is immense. It shows M3 is better placed to meet differential heating and power supply demands, which is essential for realization of thermo-electrolytic coupling and improving the HE-IES's flexibility, particularly when the proportion of wind power is significant.

The operating expenditure of M1 initially decreases slightly and then increases sharply as the proportion of wind power increases, while costs of M2 and M3 both show downward trends, as shown in Fig. 8.

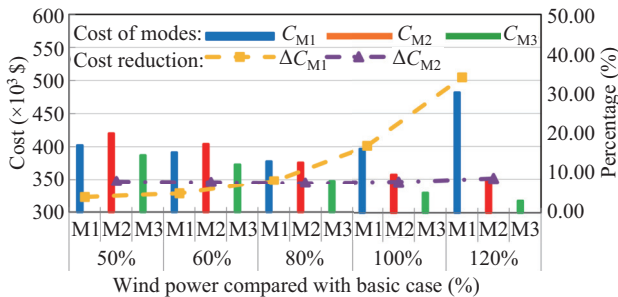


Fig. 8. Total costs and improvements in economic efficiency under various wind power ratios.

Line charts in Fig. 8 show the economic benefits of M3 when compared with M1 and M2. Here, ΔC_{M1} and ΔC_{M2}

are calculated as follows:

$$\Delta C_{Mi} = \frac{(C_{Mi} - C_{M3})}{C_{Mi}}, \quad i = 1, 2 \quad (30)$$

Note here that ΔC_{M1} increases obviously, when wind power is high, but ΔC_{M2} does not change significantly. Overall, results indicate that IES can absorb more wind power and improve its economy and flexibility by considering the CHP operating conditions.

B. Case II

The structure in case II includes a 118-bus electric power system and 10 independent DHNs. Generators contain 34 non-CHP thermal units, 10 wind farms, and 10 CHPs. A detailed system diagram is shown in Fig. 9 [39]. In order to assess the effect of improving IES's economy and flexibility by considering full-mode operation of the CHP units, five scenarios with different load profiles, wind powers, and outdoor temperatures are simulated.

1) Comparison of Economic Efficiency

Total cost of the IES under different operational conditions is listed in Table IV. Value of ΔC_{M1} and ΔC_{M2} fluctuate from 5.04%–5.94% and 8.91%–9.41%, respectively. ΔC_{M1} is larger than ΔC_{M2} in both Cases I and II. We considered the energy waste in M1 to be wind power, and there is a penalty for wind curtailment; however, energy waste in M2 is heat power, and additional heat curtailment cost is only the operating cost of CHP units.

TABLE IV
COST VALUES UNDER DIFFERENT CHP OPERATION CONDITIONS

Subcase No.	Case1	Case 2	Case 3	Case 4	Case 5
C_{M1}	7115.0	7117.9	7106.2	7111.0	7119.7
C_{M2}	6819.9	6808.9	6881.7	6858.3	6792.1
C_{M3}	6452.9	6453.4	6473.1	6473.5	6450.0
$\Delta \text{Cost} (\%)$					
ΔC_{M1}	9.31%	9.34%	8.91%	8.96%	9.41%
ΔC_{M2}	5.38%	5.22%	5.94%	5.61%	5.04%

2) Comparison of Energy Curtailment and Flexibility

Energy curtailment characteristics of the IES are presented in Fig. 10 and Table V. ΔE_a is the D-value of abandoned energy. $\bar{W}_a$ and $\bar{H}_a$ are average values of heat and electric power abandoned in the five subcases. Values of $\Delta \bar{W}_a$ and $\Delta \bar{H}_a$ for M1 and M2 are calculated as follows:

$$\begin{cases} \Delta \bar{W}_{a,i} = \frac{(\bar{W}_{a,i} - \bar{W}_{a,M3})}{\bar{W}_{a,i}} \\ \Delta \bar{H}_{a,i} = \frac{(\bar{H}_{a,i} - \bar{H}_{a,M3})}{\bar{H}_{a,i}} \end{cases}, \quad i \in \{M1, M2\} \quad (31)$$

In the five cases, M3 shows an average of 87.6% less wind curtailment than M1 and 99.42% less heat curtailment than M2. It is important to note M1 and M2 have high amounts of heat and wind curtailment, respectively, and M3 has much less energy curtailment, which shows M3 offers good heating and power supply flexibility.

3) Computational Cost Analysis

Table VI lists average computation time of three modes of Case I and Case II. Compared with M2, M1 significantly increases computational time by 15 times in case I and 120 times in case II. Improvement of computational times becomes significant with system scale increases.

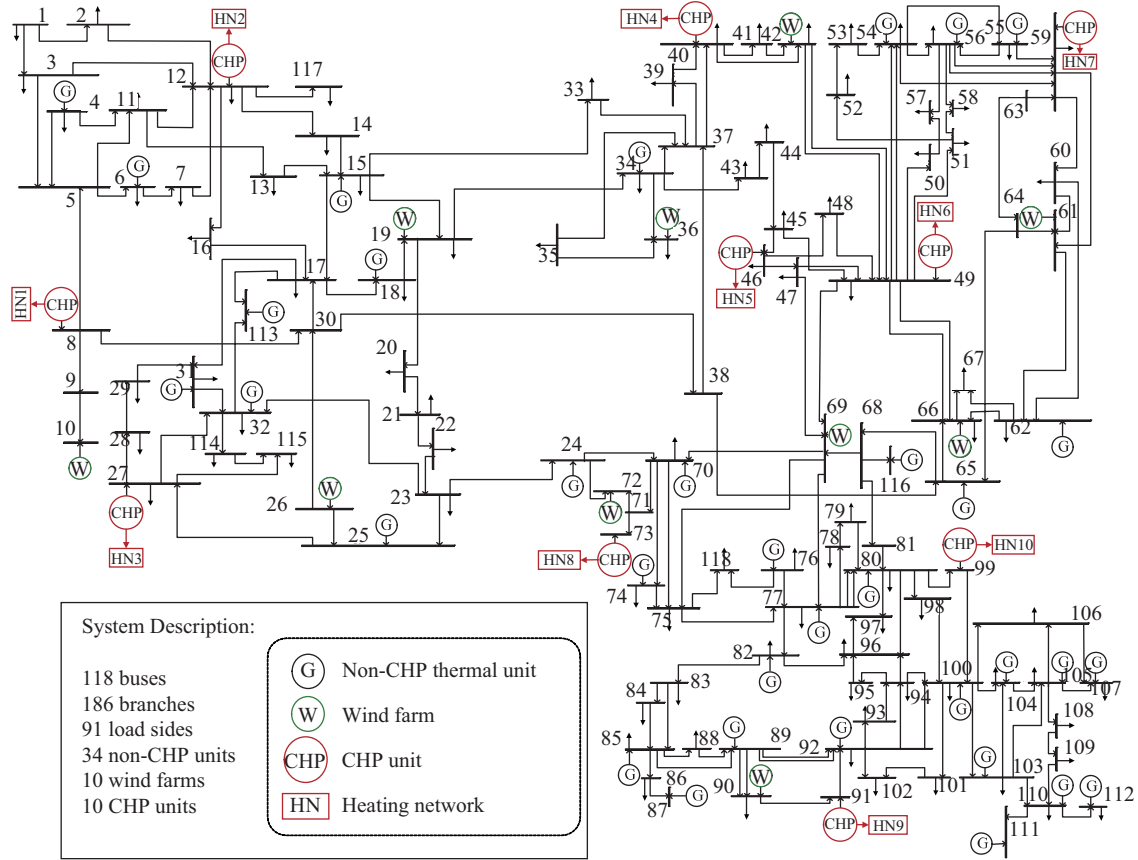


Fig. 9. Detailed system diagram.

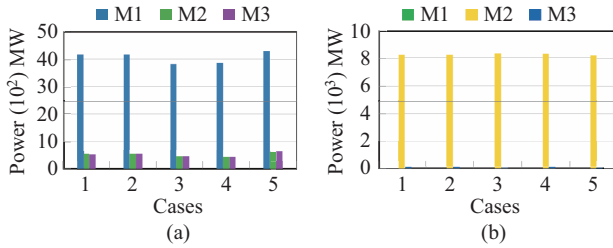


Fig. 10. Energy curtailment of IES. (a) Wind curtailment. (b) Heat curtailment.

TABLE V
COST VALUES UNDER DIFFERENT CHP OPERATING CONDITIONS

Subcase No.		M1	M2	M3
Energy abandon	$\bar{W}_a$	4045.1	499.1	501.7
($\times 10^3$ \$)	$\bar{H}_a$	0	8243.9	48.1
ΔE_a	$\Delta \bar{W}_a$	87.60%	-0.53	-
(%)	$\Delta \bar{H}_a$	-	99.42%	-

TABLE VI
COMPUTATION TIME BY DIFFERENT CHP MODES

Subcase No.	M1	M2	M3
Case I	0.122 s	0.132 s	2.095 s
Case II	1.562 s	1.613 s	202.167 s

VI. CONCLUSIONS AND PROSPECTS

A. Conclusions

We propose a comprehensive dispatch method that considers

operating mode optimization of natural gas combined cycle CHP unit to improve flexibility of the IES. A comprehensive dispatch model of IES involves the CHP full working condition model, the DHN heat dynamic model, and thermal inertia model of buildings. The proposed CHP full working condition model considers AE mode, BP mode, and switching process mode of the CHP units. Based on theoretical analysis and case studies, we can obtain the following conclusions:

1) Full mode operation of CHP units can significantly improve economy of the IES and reduce wind power curtailment, especially when the proportion of wind power in the IES is significant.

2) By optimizing operating conditions of the CHP unit, flexibility of IES is significantly improved. The reason is that full mode operation of CHP units can be better placed to meet differential heating and power supply demands and realize further decoupling of electricity and heat.

3) When heat load is large, and the proportion of wind power is significant in the IES, the CHP unit is suitable to operate in BP mode. When heat load is small, and power load is significant in the IES, the CHP is suitable to operate in AE mode.

B. Prospects

The current work mainly focuses on integrating operating mode optimization of a natural gas combined-cycle CHP unit (NGCC-CHP) into the IES dispatch to improve IES's

flexibility. Some unresolved challenges are summarized as follows for further study:

1) As described in Section II, the CHP consists of several components. This paper does not consider detailed physical models of each component and CHP performance during the switching process. It would be interesting to assess these aspects in future studies.

2) The current work does not consider renewable uncertainties in the IES. How to extend the CHP full mode operation and the optimal dispatch model proposed in this paper to deal with the renewable uncertainties will be significant work.

REFERENCES

- [1] X. Zhou, Q. Zhao, Y. Zhang and L. Sun, "Integrated energy production unit: An innovative concept and design for energy transition toward low-carbon development," *Proceedings of the CSEE*, vol. 7, no. 6, pp. 1133–1139, Nov. 2021.
- [2] S. Yao, W. Gu, S. Lu, S. Y. Zhou, Z. Wu, G. S. Pan, and D. He, "Dynamic optimal energy flow in the heat and electricity integrated energy system," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 1, pp. 179–190, Jan. 2021.
- [3] Z. Aminov, N. Nakagoshi, T. D. Xuan, O. Higashi, and K. Alikulov, "Evaluation of the energy efficiency of combined cycle gas turbine. Case study of Tashkent thermal power plant, Uzbekistan," *Applied Thermal Engineering*, vol. 103, pp. 501–509, Jun. 2016.
- [4] B. B. Chen, Q. L. Guo, Y. W. Chen, and H. B. Sun, "An economic dispatch model for combined heat and power systems considering the characteristics of heat recovery steam generators," *International Journal of Electrical Power & Energy Systems*, vol. 118, pp. 105775, Jun. 2020.
- [5] X. Y. Chen, C. Q. Kang, M. O'Malley, Q. Xia, J. H. Bai, C. Liu, R. F. Sun, W. Z. Wang, and H. Li, "Increasing the flexibility of combined heat and power for wind power integration in China: modeling and implications," *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 1848–1857, Jul. 2015.
- [6] X. Lu, M. B. McElroy, W. Peng, S. Y. Liu, C. P. Nielsen, and H. K. Wang, "Challenges faced by China compared with the US in developing wind power," *Nature Energy*, vol. 1, no. 6, pp. 16061, May 2016.
- [7] M. G. Nielsen, J. M. Morales, M. Zugno, T. E. Pedersen, and H. Madsen, "Economic valuation of heat pumps and electric boilers in the Danish energy system," *Applied Energy*, vol. 167, pp. 189–200, Apr. 2016.
- [8] X. R. Liu, F. J. Zhang, Q. Y. Sun, and W. Y. Zhong, "Multi-objective optimization strategy of integrated electric-heat system based on energy storage situation division," *IEEE Access*, vol. 9, pp. 19004–19024, Jan. 2021.
- [9] H. C. Wang, W. S. Yin, E. Abdollahi, R. Lahdelma, and W. L. Jiao, "Modelling and optimization of CHP based district heating system with renewable energy production and energy storage," *Applied Energy*, vol. 159, pp. 401–421, Dec. 2015.
- [10] S. Lu, W. Gu, K. Meng, S. Yao, B. Liu, and Z. Y. Dong, "Thermal inertial aggregation model for integrated energy systems," *IEEE Transactions on Power Systems*, vol. 35, no. 3, pp. 2374–2387, May 2020.
- [11] Z. G. Li, W. C. Wu, M. Shahidepour, J. H. Wang, and B. M. Zhang, "Combined heat and power dispatch considering pipeline energy storage of district heating network," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 12–22, Jan. 2016.
- [12] Y. Li, C. L. Wang, G. Q. Li, J. L. Wang, D. B. Zhao, and C. Chen, "Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings," *Energy Conversion and Management*, vol. 207, pp. 112526, Mar. 2020.
- [13] X. Li, W. M. Li, R. F. Zhang, T. Jiang, H. H. Chen, and G. Q. Li, "Collaborative scheduling and flexibility assessment of integrated electricity and district heating systems utilizing thermal inertia of district heating network and aggregated buildings," *Applied Energy*, vol. 258, pp. 114021, Jan. 2020.
- [14] C. Z. Shao, Y. Ding, J. H. Wang, and Y. H. Song, "Modeling and integration of flexible demand in heat and electricity integrated energy system," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 1, pp. 361–370, Jan. 2018.
- [15] J. Salpakari, J. Mikkola, and P. D. Lund, "Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion," *Energy Conversion and Management*, vol. 126, pp. 649–661, Oct. 2016.
- [16] V. Z. Gjorgievski, N. Markovska, A. Abazi, and N. Duić, "The potential of power-to-heat demand response to improve the flexibility of the energy system: an empirical review," *Renewable and Sustainable Energy Reviews*, vol. 138, pp. 110489, Mar. 2021.
- [17] Y. Chen, W. Wei, F. Liu, E. E. Sauma, and S. W. Mei, "Energy trading and market equilibrium in integrated heat-power distribution systems," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 4080–4094, Jul. 2019.
- [18] F. Y. Si, J. K. Wang, Y. H. Han, Q. Zhao, P. Han, and Y. Li, "Cost-efficient multi-energy management with flexible complementarity strategy for energy internet," *Applied Energy*, vol. 231, pp. 803–815, Dec. 2018.
- [19] A. M. Bassily, "Numerical cost optimization and irreversibility analysis of the triple-pressure reheat steam-air cooled GT commercial combined cycle power plants," *Applied Thermal Engineering*, vol. 40, pp. 145–160, Jul. 2012.
- [20] A. G. Kaviri, M. N. M. Jaafar, and T. M. Lazim, "Modeling and multi-objective exergy based optimization of a combined cycle power plant using a genetic algorithm," *Energy Conversion and Management*, vol. 58, pp. 94–103, Jun. 2012.
- [21] T. K. Ibrahim, M. K. Mohammed, O. I. Awad, M. M. Rahman, G. Najafi, F. Basrawi, A. N. Abd Alla, and R. Mamat, "The optimum performance of the combined cycle power plant: a comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 459–474, Nov. 2017.
- [22] Z. M. Liu and I. A. Karimi, "New operating strategy for a combined cycle gas turbine power plant," *Energy Conversion and Management*, vol. 171, pp. 1675–1684, Sep. 2018.
- [23] L. Barelli and A. Ottaviano, "Supercharged gas turbine combined cycle: an improvement in plant flexibility and efficiency," *Energy*, vol. 81, pp. 615–626, Mar. 2015.
- [24] J. W. Wang, S. You, Y. Zong, C. Træholt, Z. Y. Dong, and Y. Zhou, "Flexibility of combined heat and power plants: a review of technologies and operation strategies," *Applied Energy*, vol. 252, pp. 113445, Oct. 2019.
- [25] Z. H. Ge, L. Q. Ma, J. He, and S. F. Zhao, "Study on load characteristics of multiple operation modes of gas-steam combined cycle cogeneration unit," *Proceedings of the CSEE*, vol. 40, no. 8, pp. 2587–2596, Apr. 2020.
- [26] N. C. Lu, L. Pan, Z. X. Liu, K. Y. Lee, Y. J. Song, and P. Y. Si, "Dynamic modeling of thermal-supply system for two-by-one combined-cycle gas and steam turbine unit," *Fuel Processing Technology*, vol. 209, pp. 106549, Dec. 2020.
- [27] M. L. Zhang, Q. W. Wu, J. Y. Wen, Z. W. Lin, F. Fang, and Q. Chen, "Optimal operation of integrated electricity and heat system: a review of modeling and solution methods," *Renewable and Sustainable Energy Reviews*, vol. 135, pp. 110098, Jan. 2021.
- [28] Y. H. Dai, L. Chen, Y. Min, Q. Chen, K. Hu, J. H. Hao, Y. W. Zhang, and F. Xu, "Dispatch model of combined heat and power plant considering heat transfer process," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1225–1236, Jul. 2017.
- [29] M. I. Santos and W. Uturbey, "A practical model for energy dispatch in cogeneration plants," *Energy*, vol. 151, pp. 144–159, May 2018.
- [30] J. F. Rist, M. F. Dias, M. Palman, D. Zelazo, and B. Cukurel, "Economic dispatch of a single micro-gas turbine under CHP operation," *Applied Energy*, vol. 200, pp. 1–18, Aug. 2017.
- [31] H. Q. Yu, L. O. Nord, C. Yu, J. X. Zhou, and F. Q. Si, "An improved combined heat and power economic dispatch model for natural gas combined cycle power plants," *Applied Thermal Engineering*, vol. 181, pp. 115939, Nov. 2020.
- [32] T. Jiang, Y. Min, G. P. Zhou, L. Chen, Q. Chen, and F. Xu, "Dispatch model for integrated heat and power systems considering internal composition of CHP plants," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 2, pp. 396–407, Mar. 2021.
- [33] M. Jarre, M. Noussan, and A. Poggio, "Operational analysis of natural gas combined cycle CHP plants: energy performance and pollutant emissions," *Applied Thermal Engineering*, vol. 100, pp. 304–314, May 2016.
- [34] P. D. Ge, Q. R. Hu, Q. W. Wu, X. B. Dou, Z. J. Wu, and Y. Y. Ding, "Increasing operational flexibility of integrated energy systems by introducing power to hydrogen," *IET Renewable Power Generation*, vol. 14, no. 3, pp. 372–380, Feb. 2020.
- [35] G. S. Pan, Q. R. Hu, W. Gu, S. X. Ding, H. F. Qiu, and Y. P. Lu, "Assessment of plum rain's impact on power system emissions in

- Yangtze-Huaihe River basin of China,” *Nature Communications*, vol. 12, no. 1, pp. 6156, Oct. 2021.
- [36] Z. G. Li, W. C. Wu, J. H. Wang, B. M. Zhang, and T. Y. Zheng, “Transmission-constrained unit commitment considering combined electricity and district heating networks,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 480–492, Apr. 2016.
- [37] S. Lu, W. Gu, S. Y. Zhou, W. W. Yu, S. Yao, and G. S. Pan, “High-resolution modeling and decentralized dispatch of heat and electricity integrated energy system,” *IEEE Transactions on Sustainable Energy*, vol. 11, no. 3, pp. 1451–1463, Jul. 2020.
- [38] X. Y. Chen, J. X. Wang, J. Xie, S. Y. Xu, K. Yu, and L. Gan, “Demand response potential evaluation for residential air conditioning loads,” *IET Generation, Transmission & Distribution*, vol. 12, no. 19, pp. 4260–4268, Oct. 2018.
- [39] W. Gu, J. Wang, S. Lu, Z. Luo, and C. Y. Wu, “Optimal operation for integrated energy system considering thermal inertia of district heating network and buildings,” *Applied Energy*, vol. 199, pp. 234–246, Aug. 2017.



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