Two-stage stochastic optimal operation of integrated electricity and heat system considering reserve of flexible devices and spatial-temporal correlation of wind power

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Two-stage stochastic optimal operation of integrated electricity and heat system considering reserve of flexible devices and spatial-temporal correlation of wind power

Menglin Zhang, Qiuwei Wu*, Jinyu Wen, Bo Pan, Shiqiang Qi

* Center for Electric Power and Energy (CEE), Department of Electrical Engineering, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China

Jiaxing Guodiantong New Energy Technology Co., Ltd, Building 29, Zhifu center, No. 966, Xiuyuan Road, Jiaxing City, Zhejiang Province, 314000 China

* Corresponding author. E-mail address: qw@elektro.dtu.dk

Abstract

Using the improved flexibility from the district heating system with multiple flexible devices is an effective solution to ensure the cost-effective and secure operation of the integrated energy system with high penetration of renewables. This paper exploits the improved flexibility of the integrated electricity and heat systems by using reserves from multiple flexible devices to accommodate more wind power and reduce operational costs. A two-stage stochastic optimal dispatching scheme is proposed for the integrated electricity and heat system considering both power networks and heat pipelines, and reserves from the condensing combined heat and power units, heat pumps, electric boilers, and heat storage tanks. The proposed scheme balances the power and heat sectors both in the day-ahead and real-time stages with the synergy of different flexible devices and linkage for each device in the two stages. A scenario generation method considering spatial-temporal correlation is proposed to provide reasonable wind power profiles for the two-stage dispatch scheme. The Gaussian mixture model and exponential function are used to construct the spatial and temporal correlation, respectively, and the Gibbs sampling is utilized to reduce the sampling complexity. The case studies were conducted on a 6-bus integrated electricity and heat system and a practical integrated energy system in Northern China. The results show that utilizing the scenario set with spatial-temporal correlation and improved flexibility can effectively reduce the operational cost and wind power curtailment.

Keywords

Day-ahead stochastic scheduling of IEHS, unit commitment, reserve, Gaussian Mixture model, Gibbs sampling, spatial-temporal correlation of wind power

Nomenclature

Abbreviations

CHP Combined heat and power
EPS Electrical power system
DHS District heat system
IEHS Integrated electricity and heat system
HP Heat pump
EB Electric boiler
ST Storage tank
WP  Water pump
GMM  Gaussian mixture model

Indices and sets

\( \Lambda^T \)  Set of indices of time periods
\( \Psi_{TU} \)  Set of indices of thermal power units
\( \Psi_{CHP} \)  Set of indices of CHP units
\( \Psi_{WP} \)  Set of indices of water pumps
\( \Psi_W \)  Set of indices of wind farms
\( \Psi_{HP} \)  Set of indices of HPs
\( \Psi_{EB} \)  Set of indices of EBs
\( \Psi_{ST} \)  Set of indices of STs
\( \Psi_B \)  Set of indices of buses in the EPS
\( \Psi_L \)  Set of indices of transmission lines in the EPS
\( \Psi_S \)  Set of indices of wind power scenarios
\( \Psi_{pipe} \)  Set of indices of pipes in the DHS
\( \Psi_{node} \)  Set of indices of nodes in the DHS
\( \Psi_{HS} \)  Set of indices of nodes with heat sources
\( \Psi_{HES} \)  Set of indices of nodes with heat exchange stations
\( \Psi_{ID} \)  Set of indices of nodes with heat loads
\( \Theta_{TU/CHP/W/EB/HP,d} \)  Set of indices of thermal units/CHP units/wind farms/EB/HP located on bus \( d \)
\( \Phi_{TU} \)  Set of indices of segments of linearized fuel cost function of thermal units
\( \Omega_{b^+}/\Omega_{b^-} \)  Set of indices of start nodes and end nodes of pipe \( b \)
\( \Omega_{pipe}^{+}/\Omega_{pipe}^{-} \)  Set of indices of pipes to/from node \( n \)

Parameters

\( C_{i^{TU/CHP}} \)  Start-up cost of thermal/CHP unit \( i \)
\( C_W \)  Penalty price of wind power curtailment
\( C_L \)  Penalty price of load shedding
\( C_{i^{TU/UR/DR}} \)  Capacity price of upward/downward reserve of thermal unit \( i \)
\( C_{i^{TU/UR/DR,dep}} \)  Price of upward/downward reserve deployment for thermal unit \( i \)
\( C_{i^{CHP/UR/DR,dep}} \)  Price of upward/downward reserve deployment for CHP unit \( i \)
\( C_{i^{CHP/UR/DR}} \)  Capacity price of upward/downward reserve of CHP unit \( i \)
\( C_{wa} \)  Specific heat capacity of water
\( \text{cop}_{HP} \)  Coefficient of performance of HP
\( f_i^{min,TU} \)  Fuel cost corresponding to the minimum output level of thermal unit \( i \)
\( f_i^{CHP,A/B/C/D} \)  Fuel cost of vertices A/B/C/D for CHP unit \( i \)
\( f_i \)  Capacity of transmission line \( l \)
\( g_{i^{TU/CHP/W/EB/HP,B}} \)  Distribution factor of the thermal power unit/CHP unit/wind farm/HP/EB/load at bus \( d \) on line \( l \)
\( H_{ST}^{+}/H_{ST}^{-} \)  Maximum/minimum energy storage of STs
\( h_{ST}^{+} \)  Maximum charging and discharging rate of STs
\( h_{i^{CHP,A/B/C/D}} \)  Heat production of vertices A/B/C/D for CHP unit \( i \)
\( K_{i,k} \)  Slope of segment \( k \) of linearized fuel cost function of thermal unit \( i \)
\( L_{i,t} \)  Load at bus \( i \) in period \( t \)
\( L_{b} \)  Length of pipeline \( b \)
\( M \)  Number of GMM components
\( m_{i^{HS/HE}} \)  Mass flow rate in heat sources/heat exchange stations
Mass flow rate of pipeline $b$ in period $t$ in supply/return network

The $m$th Gaussian mixture component of the GMM

Number of wind farms

Maximum/minimum output of thermal unit $i$

Maximum/minimum output of CHP unit $i$

Maximum value of segment $k$ of thermal unit $i$

Power production of vertices A/B/C/D for CHP unit $i$

Maximum power consumption of HP/EB $i$

Maximum/minmum power consumption of WP $i$

Maximum/minimum temperature of supply/return pipes

Ambient temperature in period $t$

Minimum start-up time of thermal/CHP unit $i$

Minimum shut-down time of thermal/CHP unit $i$

Upward/downward ramping rate of thermal/CHP unit $i$

Forecast value of wind farm $i$ in period $t$

Wind power output for wind farm $i$ in period $t$

Heat transfer coefficient of pipes

Energy conversion efficiency of EB

Density of water

Weight of the $m$th component of the GMM

$2n$-dimensional mean vector of the $m$th component of the GMM

$2n \times 2n$ spatial covariance matrix of the $m$th component of the GMM

Variables

Total operational cost

The first-stage operational cost

The second-stage operational cost under scenario $s$

The total operational cost of all thermal/CHP units in the first stage

The regulation cost of all thermal/CHP units under scenario $s$ in the second stage

Penalty cost of wind power curtailment for all wind farms in the first stage

Penalty cost of wind power curtailment for all wind farms under scenario $s$ in the second stage

Penalty cost of load shedding under scenario $s$ in the second stage

Operational cost of CHP unit $i$ in period $t$

Heat energy level of ST $i$ in period $t$

Heat energy level of ST $i$ in period $t$ under scenario $s$

Heat production of CHP unit $i$ in period $t$

Heat production of HP/EB $i$ in period $t$

Power production of thermal/CHP unit $i$ in period $t$

The scheduled value of segment $k$ for thermal unit $i$ in period $t$

Electricity consumption of water pump $i$ in period $t$
1. Introduction

Wind power has been growing rapidly over the last decade. In Denmark, 47% of the power consumption was from the wind in 2019 [1]. The significant uncertainties and variations of wind power may result in the difficulty of scheduling in the power system [2]. Sufficient flexibility is needed to balance the wind power fluctuation and accommodate more wind power in a grid [3].

The integrated electricity and heat system (IEHS), composed of the electrical power system (EPS) and district heat system (DHS), has been proposed to improve flexibility [4] and accommodate the increasing penetration of wind power [5]. A lot of work has been done on the optimal operation of the IEHS. The existing work mainly
focuses on the modeling of the thermal and hydraulic processes of the DHS [6]. On the basis of [6], other research advances the modeling and solution of the IEHS considering the time-delay in the DHS [7], heat regulation modes [8], the thermal inertia of buildings in the DHS [9], heat storage of the DHS network [10], market framework design of the IEHS [11], and distributed operation of the EPS and DHS [12].

In the IEHS, the EPS and DHS are mainly coupled by the combined heat and power (CHP) units. The CHP units usually have a higher fuel efficiency than conventional thermal units. However, their outputs are usually determined by heat load [13]. This limits the operational region of the CHP units and leads to a high wind power curtailment such as in the northeast region of China [14].

The coupling between heat and power production in CHP units can be relaxed by using the heat pumps (HPs), electric boilers (EBs), and heat storage tanks (STs) for higher integration of wind power. The HPs and EBs consume power to produce heat, while the STs store and release heat to compensate part of the heat production of the CHP units and thus increase the flexibility of the CHP units in the power sector. Ref. [15] considers both the STs and EBs to improve flexibility on the heat side in the economic dispatch and concludes that the EBs are more effective at reducing wind curtailment, while the STs save more energy. Based on [15], [16] considers the unit commitment of the CHP units to further improve operational flexibility. Ref. [17] employs the EBs to reduce wind curtailment and CO2 emission in the unit-commitment based power system chronological simulation. Ref. [18] considers the EBs, HPs, and STs to increase flexibility in the DHS.

In the above research, the flexibility from the HPs, EBs, STs, and CHP units is mainly investigated in the energy scheduling. Further studies are needed for flexibility improvement in two aspects. On the one hand, the potential and impact of the HPs, EBs, and STs providing reserve and heat regulation are not fully exploited; on the other hand, when a CHP unit has a larger feasible region due to the integration of the HPs, EBs, and STs, it also has the capability to provide reserve.

For the first aspect, research has been done on using flexible devices to provide reserve and heat regulation. In Ref. [19], the aggregator can participate in the regulation service by adjusting the consumption of domestic HPs. Ref. [20] aggregates small-scale HPs to provide spinning reserve without accounting for the DHS sector. Ref. [21] models the reserve capacity of the electric boiler with thermal storage. However, this model is not incorporated into the scheduling. Ref. [22] proposes a multi-scale model of STs, which is based on the partial differential equation. However, such a model is highly nonlinear, limiting its application in the scheduling of the IEHS. Ref. [23] considers the heat regulation by accumulator tanks in the two-stage unit commitment. However, flexible devices are not considered to provide reserve.

For the second aspect, reserve modeling of CHP units has been conducted. As the heat and power production are closely coupled in the CHP units, it is necessary to account for the heat regulation when implementing the reserve deployment. The CHP units are usually classified into two categories, i.e., the back-pressure unit and extraction condensing unit [13]. Ref. [24] considers the reserve modeling of back-pressure CHP units in the economic dispatch and utilizes the thermal inertia of a building to balance the changes of heat supply caused by reserve deployment. However, only relying on the thermal inertia of buildings is not sufficient to balance all the heat changes. The condensing CHP units usually have a larger capacity and higher proportion in the power system than the back-pressure units [17], but little work has been done on the reserve modeling of condensing CHP units. The operational region of a condensing CHP unit is usually represented by the linear combination of operational region vertices. Ref. [25] assumes the operational region of a CHP unit is convex and represents the operational cost and heat and power production as a convex combination of extreme characteristic points. In comparison, Ref. [26] considers the
non-convex operational region of condensing CHP units by combining the Benders decomposition algorithm. However, both [25] and [26] do not incorporate the reserve provision into the combination of vertices. In the meanwhile, the existing reserve modeling of back-pressure CHP units is not suitable for the condensing CHP units.

In addition, due to the uncertainty of wind power, the decision-making methods under uncertainty are also needed in the scheduling of the IEHS. Robust optimization and stochastic programming are the two popular techniques to cope with uncertainty in the IEHS. The former pursues the feasibility and minimum operational cost of the decision under the worst-case scenario but suffers from the conservativeness [27]. The latter focuses on the expected cost and can reduce the conservativeness [28].

In the stochastic programming, a scenario set reflecting the actual probability distribution of wind power outputs is necessary to guarantee a reliable and economic decision, because it is closely related to the reserve requirement. In the scheduling of the IEHS with multiple time periods and multiple wind farms, it is essential to account for the spatial and temporal correlations of wind power outputs to reduce the operational cost in the decision-making.

Several scenario generation methods accounting for the spatial and temporal correlations have been proposed. Ref. [29] utilizes an exponential function to construct the temporal correlation of wind power outputs. On the basis of [29], Ref. [30] considers the optimization of the control parameter in the exponential function to represent the correlation coefficient more accurately. Ref. [31] proposes evaluation indices for the scenario set based on the exponential function. However, the exponential function method in [29]-[31] is not suitable for modeling spatial correlation. Refs. [32]-[34] consider the spatial correlation of actual wind power production and forecast errors. Ref. [32] utilizes the Gaussian Copula to formulate the conditional distribution of forecast errors of multiple wind farms. Refs. [33] and [34] utilize the Gaussian mixture model (GMM) to represent the joint distribution of actual wind power production and forecast errors with respect to different forecast values of multiple wind farms, respectively. Although both the Copula and GMM methods can incorporate the spatial and temporal correlations simultaneously, they suffer from the curse of dimensionality. Ref. [35] constructs the temporal and spatial correlations simultaneously by combining the exponential function and Copula method. Besides, Gibbs sampling is utilized to reduce the complexity of sampling. However, the conditional distribution in the Gibbs sampling needs to select the Copula function and calculate the marginal distribution of each random variable. Ref. [35] selects the Gaussian copula and cumulative empirical distribution to calculate the conditional distribution but may influence the accuracy and computational efficiency of the scenario generation.

Compared to the existing work, this paper develops the detailed reserve modeling of condensing CHP units and other coordinated flexible devices, and scenario generation method considering spatial-temporal correlation, which can reduce the wind power curtailment and improve the operational economic efficiency of the IEHS. The main contributions of this paper are as follows:

- Propose a two-stage stochastic optimal dispatching scheme of the IEHS with detailed modeling of reserves from condensing CHP units, HPs, EBs, and STs;
- Develop the reserve model of condensing CHP units based on the convex-hull operational region in the unit commitment of the IEHS, which accounts for the coupling with heat regulation and coordination with HPs, EBs, and STs;
- Propose a spatial-temporal correlated scenario generation method to provide reasonable wind power profiles for the stochastic optimal dispatching, which combines the GMM, exponential function, and Gibbs sampling to improve the accuracy and computational efficiency of the scenario generation.
The remainder of the paper is organized as follows. A two-stage stochastic optimal dispatching scheme of the IEHS considering the reserve of condensing CHP units and other flexible devices is presented in Section 2. Section 3 describes the spatial-temporal correlated scenario generation method. The simulation results on a 6-bus and a practical energy system are presented and analyzed in Section 4, followed by the conclusions.

2. Two-stage stochastic optimal dispatching scheme of IEHS

2.1 Framework of dispatching scheme

The framework of the proposed two-stage stochastic optimal dispatching scheme for the IEHS is illustrated in Fig. 1. In the proposed scheme, the system operator aims to achieve the optimal operation of the IEHS and balance the uncertainty of renewables in an economic way by coordinating the reserve from conventional thermal units, CHP units, HPs, EBs, and STs, while keeping the balance between supply and demand for both power and heat sectors.

Fig. 1 Framework of two-stage stochastic optimal dispatching scheme of the IEHS.

In Fig. 1, the optimal operation of the IEHS involves two stages. The first stage corresponds to the day-ahead scheduling and the second stage relates to the real-time regulation. By coordinating these two stages, the day-ahead decisions are made with the impact of real-time uncertainties incorporated.

In the dispatching scheme, all the units and devices can be divided into three categories according to their functions. The first category, i.e., the conventional thermal units, can participate in both the energy and reserve scheduling in the power sector. The second category, including the CHP units, HPs, and EBs, can not only participate in the energy and reserve scheduling in the power sector but also produce heat in the heat sector. The third category, i.e., the STs, store or release heat energy to balance the heat supply and heat demand.
The proposed dispatching scheme focuses on exploiting flexibility from the coordination of the CHP units, EBs, HPs, and STs. For the condensing CHP units, their reserve is used to increase flexibility. A detailed reserve model of the condensing CHP units is presented in Section 2.3. In addition, the virtual reserve from the HPs and EBs and the heat regulation capacity from the STs are coordinated with the CHP units in the optimal operation of the IEHS. The synergy constraints of all the units and devices and linkage constraints between two stages are also incorporated in the dispatching scheme.

2.2 Schematic diagram of stochastic optimal operation of IEHS

Fig. 2 is the schematic diagram of the two-stage stochastic optimal operation of the IEHS, which further illustrates the objective and operational constraints of the dispatching scheme, and interactions between the day-ahead and real-time operation, and the EPS and DHS.

As shown in Fig. 2, the optimal operation of the IEHS minimizes the operational cost including the day-ahead energy cost and real-time regulation cost. The operational constraints of the IEHS can be divided into four parts according to the energy carriers and operational stages, i.e., 1) day-ahead operational constraints of the EPS, 2) day-ahead operational constraints of the DHS, 3) real-time operational constraints of the EPS in each uncertainty scenario, and 4) real-time operational constraints of the DHS in each uncertainty scenario.

The constraints of four parts are coupled. In the day-ahead stage, the EPS and DHS are coupled by the operational region of the CHP units, HPs, and EBs. In the real-time stage, when the reserve deployment and heat regulation are implemented, the two energy sectors are still linked by the operational region of the CHP units, HPs, and EBs. In the EPS, the day-ahead stage and real-time stage are coupled by the reserve capacity and reserve deployment in each uncertainty scenario of wind power. In the DHS, the two stages are linked by the heat regulation.

**Optimal Operation of the IEHS**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Minimize the operational cost including the day-ahead energy cost and real-time regulation cost</th>
</tr>
</thead>
</table>
| **Day-ahead operational constraints of the EPS** | • Power balance  
• Transmission limits  
• Power output limits of conventional and CHP units  
• Power consumption limits of HPs and EBs  
• Reserve capacity allocation of conventional and CHP units  
• Wind curtailment |
| **Real-time operational constraints of the EPS in each uncertainty scenario** | • Power rebalance after reserve deployment  
• Transmission limits after reserve deployment  
• Power output limits of conventional and CHP units after reserve deployment  
• Wind curtailment and load shedding after reserve deployment  
• Reserve deployment of conventional and CHP units, HPs, and EBs |
| **Operational region of CHP units, HPs, and EBs** |  |
| **Day-ahead operational constraints of the DHS** | • Heat balance  
• Heat network limits  
• Heat production limits of CHP units  
• Energy conversion of HPs and EBs  
• Heat storage and release of STs |
| **Real-time operational constraints of the DHS in each uncertainty scenario** | • Heat rebalance after heat regulation  
• Heat network limits after heat regulation  
• Heat regulation of CHP units, HPs, EBs, and STs  
• Heat storage and release of STs after heat regulation |
| **Heat regulation** |  |

Fig. 2 Conceptual representation of two-stage stochastic optimal operation of the IEHS.
2.3 Mathematical formulation of stochastic optimal operation of IEHS

According to the conceptual representation for the optimal operation of IEHS, a mathematical model for the two-stage stochastic optimal operation of the IEHS is formulated in this section. Firstly, a reserve model of the condensing CHP units is formulated in Section 2.3.1. The proposed reserve model considers the on-off status of CHP units and the feasible operational region of a CHP unit after reserve deployment and heat regulation. On the basis of that, the objective function and operational constraints for the two-stage stochastic optimal operation of the IEHS are modeled in Section 2.3.2 and Section 2.3.3, respectively.

2.3.1 Reserve model of condensing CHP units

The operational region of a condensing CHP unit is restricted by multiple boundaries, as shown in Fig. 3. The boundaries AB, BC, CD, and DA reflect the maximum limit of power output, maximum limit of fuel injection, maximum heat rate, and minimum limit of steam injection, respectively [15].

![Fig. 3 Operational region of condensing CHP unit for heat and power production.](image)

The heat and power production with on/off status of unit commitment is firstly formulated in (1)-(5) due to their close relationship with the reserve capacity in a CHP unit. Any heat and power production levels in the operational region can be represented by the linear combination of the convex-hull vertices [16], as shown in Fig. 3.

\[
P_{ij}^{\text{CHP}} = \alpha_{i,j,a} P_{ij}^{\text{CHP},a} + \alpha_{i,j,b} P_{ij}^{\text{CHP},b} + \alpha_{i,j,c} P_{ij}^{\text{CHP},c} + \alpha_{i,j,d} P_{ij}^{\text{CHP},d}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(1)

\[
h_{ij}^{\text{CHP}} = \alpha_{i,j,a} h_{ij}^{\text{CHP},a} + \alpha_{i,j,b} h_{ij}^{\text{CHP},b} + \alpha_{i,j,c} h_{ij}^{\text{CHP},c} + \alpha_{i,j,d} h_{ij}^{\text{CHP},d}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(2)

\[
f_{ij}^{\text{CHP}} = \alpha_{i,j,a} f_{ij}^{\text{CHP},a} + \alpha_{i,j,b} f_{ij}^{\text{CHP},b} + \alpha_{i,j,c} f_{ij}^{\text{CHP},c} + \alpha_{i,j,d} f_{ij}^{\text{CHP},d}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(3)

\[
\alpha_{i,j,a} + \alpha_{i,j,b} + \alpha_{i,j,c} + \alpha_{i,j,d} = x_{ij}^{\text{CHP}}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(4)

\[
0 \leq \alpha_{i,j,a}, \alpha_{i,j,b}, \alpha_{i,j,c}, \alpha_{i,j,d} \leq 1, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(5)

where (1)-(2) represent the power production and heat production, respectively; (3) is the simplified linearized fuel cost function; (4) combines the coefficients of vertices with the on/off status of unit commitment; and (5) limits the range of coefficients.

On the basis of (1)-(5), a detailed reserve model of the condensing CHP units is proposed, which includes the reserve capacity in the first stage and reserve deployment and heat regulation in the second stage. Define variables $\Delta r_{i,j,a}^{\text{UR,DR}}$, $\Delta r_{i,j,b}^{\text{UR,DR}}$, $\Delta r_{i,j,c}^{\text{UR,DR}}$, and $\Delta r_{i,j,d}^{\text{UR,DR}}$, and the linkage between reserve deployment and heat regulation in real time can be established as,

\[
r_{ij}^{\text{UR,DR}} \leq \min \{U_{ij}^{\text{CHP},a} x_{ij}^{\text{CHP}}, U_{ij}^{\text{CHP},b} x_{ij}^{\text{CHP}}, U_{ij}^{\text{CHP},c} x_{ij}^{\text{CHP}}, U_{ij}^{\text{CHP},d} x_{ij}^{\text{CHP}}\}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(6)

\[
r_{ij}^{\text{DR,UR}} \leq \min \{D_{ij}^{\text{CHP},a} x_{ij}^{\text{CHP}}, D_{ij}^{\text{CHP},b} x_{ij}^{\text{CHP}}, D_{ij}^{\text{CHP},c} x_{ij}^{\text{CHP}}, D_{ij}^{\text{CHP},d} x_{ij}^{\text{CHP}}\}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(7)

\[
0 \leq \Delta r_{i,j,a}^{\text{UR,DR}}, \Delta r_{i,j,b}^{\text{UR,DR}}, \Delta r_{i,j,c}^{\text{UR,DR}}, \Delta r_{i,j,d}^{\text{UR,DR}} \leq r_{ij}^{\text{UR,DR}}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(8)

\[
0 \leq \Delta r_{i,j,a}^{\text{DR,UR}}, \Delta r_{i,j,b}^{\text{DR,UR}}, \Delta r_{i,j,c}^{\text{DR,UR}}, \Delta r_{i,j,d}^{\text{DR,UR}} \leq r_{ij}^{\text{DR,UR}}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(9)

\[
\Delta r_{ij}^{\text{UR,DR}} = \sum_{j} \Delta r_{ij,a}^{\text{UR,DR},j}, \quad j \in \{A, B, C, D\}, \quad \forall i, \forall i \in \Psi^\text{CHP}
\]

(10)
where (6)-(7) represent the upward and downward reserve capacity in the first stage, and (8)-(17) represent the reserve deployment and heat regulation in each scenario of the second stage. Among (8)-(17), (8)-(9) ensure the upward and downward reserve deployments in each scenario no more than the reserve capacity; (10)-(11) utilize the linear combination of convex-hull vertices to represent the reserve deployment in each scenario; (12)-(13) represent the relationship of the regulation coefficient of four vertices, which can be deduced from (4) and \((\alpha_{i,t,a} + \Delta \alpha_{i,t,a,DR}) + (\alpha_{i,t,b} + \Delta \alpha_{i,t,b,DR}) + (\alpha_{i,t,c} + \Delta \alpha_{i,t,c,DR}) + (\alpha_{i,t,d} + \Delta \alpha_{i,t,d,DR}) = x_{i,t}^{CHP}\); (14)-(16) limit the range of regulation coefficient; and (17)-(18) represent the heat regulation caused by reserve deployment.

2.3.2 Objective function of IEHS

The objective function of the proposed dispatching scheme can be expressed as (19). It minimizes the total operational cost in two stages, i.e., the day-ahead operational cost and real-time expected cost.

\[
\begin{align*}
\min f & = f_1 + \sum_{i=1}^{s} p_i f_{s,i} \\
f_1 = & f_{1,TU}^{CHP} + f_{1,TU}^{W} + f_{2,TU}^{CHP} + f_{2,TU}^{W} + f_{2,LD}^{CHP} \\
f_{1,TU}^{CHP} = & \sum_{i=1}^{s} \left( C_{i,j} H_j + \sum_{i=1}^{s} K_{i,j} P_{i,j} + \sum_{i=1}^{s} C_{i,j} X_{i,j} \right) \\
f_{1,TU}^{W} = & \sum_{i=1}^{s} \left( C_{w,j} W_j \right) \\
f_{2,TU}^{CHP} = & \sum_{i=1}^{s} \sum_{i=1}^{s} \left( \Delta C_{i,j} W_j \right) \\
f_{2,TU}^{W} = & \sum_{i=1}^{s} \sum_{i=1}^{s} \left( \Delta W_j \right) \\
f_{2,LD}^{CHP} = & \sum_{i=1}^{s} \sum_{i=1}^{s} \left( \Delta L_{i,j} \right) \\
\end{align*}
\]

2.3.3 Operational constraints of IEHS

As can be seen from Fig. 1, the optimal operation problem of the IEHS includes the day-ahead operational constraints and real-time regulation constraints. They are described in the following subsections.

**Day-ahead operational constraints of EPS**

- Power balance constraint
  \[
  \sum_{i=1}^{s} p_{i,j} + \sum_{i=1}^{s} \left( p_{i,j}^{CHP} - p_{i,j}^{W} \right) - \sum_{i=1}^{s} p_{i,j}^{EB} - \sum_{i=1}^{s} p_{i,j}^{EP} + \sum_{i=1}^{s} \left( W_{i,j} - \Delta W_{i,j} \right) = \sum_{i=1}^{s} L_{i,j}, t \in \Lambda^T
  \]
- Constraints of thermal units and CHP units
where (22)-(24) represent the output limits of thermal units with piece-wise linearization; (25)-(26) describe the upward and downward ramping rate limits of the thermal units and CHP units; (27)-(30) model the changes of the on/off status of the thermal units and CHP units and their minimum up and downtime requirements [36]; and (31)-(32) limit the reserve capacity of thermal units.

- **Constraints of HPs/EBs/WPs**

\[
P_{i}^\text{HP}, x_{i}^\text{HP} \leq P_{i}^\text{XP}, x_{i}^\text{XP}, \forall t \in \Lambda^T, \forall i \in \Psi^\text{HP} \quad (33)
\]

\[
0 \leq p_{i}^\text{EB} \leq P_{i}^\text{EB}, \forall t \in \Lambda^T, \forall i \in \Psi^\text{EB} \quad (34)
\]

\[
P_{i}^\text{WP} \leq p_{i}^\text{XP} \leq P_{i}^\text{WP}, \forall t \in \Lambda^T, \forall i \in \Psi^\text{WP} \quad (35)
\]

where (33) represents the power consumption constraint of HPs with the on/off status; (34) is the power consumption constraint of the EBs [18]; (35) represents the power consumption limit of water pumps (WPs) to sustain a certain level of pressure for the water cycle.

- **Constraints of wind power curtailment**

\[
0 \leq \Delta W_{i,j} \leq W_{i,j}, \forall t \in \Lambda^T, \forall i \in \Psi^W \quad (36)
\]

- **Constraints of transmission lines** [37]

\[
\sum_{i \in \text{in}} g_{i,j}^\text{TU} p_{i,j}^\text{TU} + \sum_{i \in \text{in}} g_{i,j}^\text{CHP} (p_{i,j}^\text{CHP} - p_{i,j}^\text{XP}) + \sum_{i \in \text{in}} g_{i,j}^\text{WP} \left(W_{i,j} - \Delta W_{i,j}\right) \leq f_{i,j}^\text{T}, \forall t \in \Lambda^T, \forall d \in \Psi^D, \forall i \in \Psi^H \quad (37)
\]

Apart from the above constraints, the constraints of the condensing CHP units in (1) and (4)-(7) should also be included in this part.

**Day-ahead operational constraints of DHS**

- **Heat output and heat exchange**

\[
\sum_{i \in \text{in}} h_{i,j}^\text{CHP} + \sum_{i \in \text{in}} h_{i,j}^\text{EB} + \sum_{i \in \text{in}} h_{i,j}^\text{WP} - \sum_{i \in \text{in}} \Delta h_{i,j}^\text{HT} = C_{\text{ins}} m_{i,j}^\text{HS} (T_{n,j}^S - T_{n,j}^S), \forall t \in \Lambda^T, n \in \Psi^\text{HS}, \quad (37)
\]

\[
C_{\text{ins}} m_{i,j}^\text{RES} (T_{n,j}^S - T_{n,j}^S) = H_{i,j}^\text{RES}, \forall t \in \Lambda^T, n \in \Psi^\text{RES}, e \in \Psi^\text{RES} \quad (38)
\]

where (38) reflects that the heat balance of the heat network, and (39) describes that the heat exchange in the heat station is equal to the heat demand.

- **Constraints of thermal process**

\[
T_{n,j}^\text{SR} \leq T_{n,j}^\text{SR} \leq T_{n,j}^\text{SR}, \forall t \in \Lambda^T, \forall n \in \Psi^\text{code} \quad (39)
\]
\[ \begin{align*} 
T_{Q_{s,r}}^b - T_{h_{s,r}}^b = (T_{Q_{s,r}}^b - T_{h_{s,r}}^b) e^{-\frac{\lambda_{C_M}}{m_{b,s,r}}}, \quad \forall t \in \Lambda^T, \forall b \in \Psi^{pipe} 
\end{align*} \] 

(40)

\[ \begin{align*} 
\left( \sum_{b \in \Omega^{C_M}} m_{s,r}^{s,R} \right) p_{R,s,r}^{s,R} = \sum_{b \in \Omega^{C_M}} m_{s,r}^{s,R} T_{Q_{s,r}}^{s,R}, \quad \forall t \in \Lambda^T, \forall b \in \Psi^{pipe} 
\end{align*} \] 

(41)

where (40) limits the temperature range of supply and return pipes; (41) represents the temperature drop along the pipe; and (42) presents the water mixture process [38].

- **Constraints of hydraulic process**

\[ \begin{align*} 
pr_{s,r}^S - pr_{s,r}^R \geq \eta_{HES}^{HES}, \quad \forall t \in \Lambda^T, \forall n \in \Psi^{node} 
\end{align*} \] 

(42)

\[ \begin{align*} 
p_W^{WSE} = \frac{m_h^{WSE} (pr_{s,r}^S - pr_{s,r}^R)}{\eta_{WSE}^{WSE}}, \quad \forall t \in \Lambda^T, \forall n \in \Psi^{WS} 
\end{align*} \] 

(43)

\[ \begin{align*} 
pr_{s,r}^{s,R} - pr_{s,r}^{s,R} = \mu_b (m_{s,r}^{s,R})^2, \quad \forall t \in \Lambda^T, \forall b \in \Psi^{pipe}, n_1 \in \Omega^{hs}, n_2 \in \Omega^{hs} 
\end{align*} \] 

(44)

where (43) represents that the pressure between supply and return water in a heat exchange station is required to be larger than a specified level to sustain the mass flow; (44) describes that the power consumption of WPs is proportional to the pressure difference; (45) represents that the pressure difference between the two ends of a pipe is proportional to the square of mass flow rate [39].

- **Heat production constraints of HPs/EBs**

\[ \begin{align*} 
h_{HP}^{i} = \text{cop}^{HP} p_{HP}^{i}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{HP} 
\end{align*} \] 

(45)

\[ \begin{align*} 
h_{EB}^{i} = \eta_{EB}^{EB} p_{EB}^{i}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{EB} 
\end{align*} \] 

(46)

- **Constraints of STs**

\[ \begin{align*} 
-\Delta_{HST} \leq \Delta_{HST} \leq \Delta_{HST}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{ST} 
\end{align*} \] 

(47)

\[ \begin{align*} 
H_{i,s,t}^{ST} - H_{i,s,t}^{ST} \leq \Delta_{HST}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{ST} 
\end{align*} \] 

(48)

\[ \begin{align*} 
H_{i,s,t}^{ST} \leq H_{i,s,t}^{ST} \leq H_{i,s,t}^{ST}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{ST} 
\end{align*} \] 

(49)

where (48) limits the maximum charging/discharging rate; (49) reflects the changes in energy level; and (50) constrains the capacity of heat storage.

Apart from the above constraints, constraint (2) for the heat production of CHP units should also be included in this part.

**Real-time operational constraints of EPS**

In this section, the reserve from the thermal units, CHP units, HPs, and EBs is deployed to balance the wind power deviations in scenarios. As the deployed reserve from those devices is tightly coupled with the base plan in the first stage, the linkage constraints between the two stages are modeled for each device.

- **Power re-balance constraints**

\[ \begin{align*} 
\sum_{i \in \Psi^{TU}} \left( \Delta_{i,s,t}^{TU} - \Delta_{i,s,t}^{DR} \right) + \sum_{i \in \Psi^{CHP}} \left( \Delta_{i,s,t}^{CHP} - \Delta_{i,s,t}^{DR} \right) - \sum_{i \in \Psi^{WP}} \Delta_{i,s,t}^{WSE} - \sum_{i \in \Psi^{EB}} \Delta_{i,s,t}^{EB} + \sum_{i \in \Psi^{HU}} \left( W_{i,s,t} - W_{i,s,t} - \Delta W_{i,s,t} + \Delta W_{i,s,t} \right) = \sum_{i \in \Psi^{SU}} \left( L_{i,s,t} - \Delta L_{i,s,t} \right), \quad \forall t \in \Lambda^T, \forall s \in \Psi^S 
\end{align*} \] 

(50)

- **The linkage constraints of thermal units/HPs/EBs between two stages**

\[ \begin{align*} 
0 \leq \Delta_{i,s,t}^{TU} - \Delta_{i,s,t}^{DR} \leq \delta_{i,s,t}^{TU}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{SU}, \forall s \in \Psi^S 
\end{align*} \] 

(51)

\[ \begin{align*} 
p_{SP}^{HP} - p_{SP}^{HP} \leq \Delta_{i,s,t}^{HP}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{HP}, \forall s \in \Psi^S 
\end{align*} \] 

(52)

\[ \begin{align*} 
p_{SP}^{EB} - p_{SP}^{EB} \leq \Delta_{i,s,t}^{EB}, \quad \forall t \in \Lambda^T, \forall i \in \Psi^{EB}, \forall s \in \Psi^S 
\end{align*} \] 

(53)

where (52) represents the deployed upward/downward reserve of thermal units in each scenario is no more than the scheduled capacity in the first stage; (53) and (54) describe that the reserve deployment of the HPs and EBs is...
mainly by changing the power consumption.

- Wind power curtailment and load shedding under each scenario
  \[ 0 \leq \Delta W_{i,t,s} \leq W_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^W \]  
  \[ 0 \leq \Delta L_{i,t,s} \leq L_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^B \]  

- Constraints of transmission lines under each scenario
  \[ \sum_{i \in \Psi^E} g^T_{d,i} \left( p^T_{i,t,s} + \Delta p^T_{i,t,s} \right) - \Delta p^T_{i,t,s} + \sum_{i \in \Psi^H} g^B_{d,i} \left( p^B_{i,t,s} + \Delta p^B_{i,t,s} \right) - \Delta p^B_{i,t,s} + \sum_{i \in \Psi^H} g^B_{d,i} \left( p^B_{i,t,s} - \Delta p^B_{i,t,s} \right) - \Delta p^B_{i,t,s} (54) \]

- Ramping constraints after reserve deployment under each scenario
  \[ \left( \Delta p^T_{i,t,s} - \Delta p^T_{i,t,s} \right) \right) - \left( \Delta p^T_{i,t,s} + \Delta p^T_{i,t,s} - \Delta p^T_{i,t,s} \right) \leq U_{i,t,s} (1 - u^T_{i,t,s}) + P^T_{i,t,s} \]  
  \[ \left( \Delta p^T_{i,t,s} + \Delta p^T_{i,t,s} - \Delta p^T_{i,t,s} \right) \right) - \left( \Delta p^T_{i,t,s} + \Delta p^T_{i,t,s} - \Delta p^T_{i,t,s} \right) \leq D_{i,t,s} (1 - V^T_{i,t,s}) + P^T_{i,t,s} \]  

Besides, constraints (8)-(15) for the reserve deployment of the condensing CHP units should be included in this part.

**Real-time operational constraints of DHS**

- Heat re-balance constraints under each scenario
  \[ \sum_{i \in \Psi^H} \left( \Delta h^W_{i,t,s} - \Delta h^W_{i,t,s} \right) + \sum_{i \in \Psi^E} \left( \Delta h^W_{i,t,s} - \Delta h^W_{i,t,s} \right) - \sum_{i \in \Psi^H} \left( \Delta h^W_{i,t,s} - \Delta h^W_{i,t,s} \right) = \]  
  \[ C^H m^H_{i,s} - T^R_{i,t,s} - T^B_{i,t,s} + T^D_{i,t,s}, \forall t \in \Lambda^T, \forall s \in \Psi^H \]  
  \[ C^W m^W_{i,s} - T^S_{i,t,s} - T^S_{i,t,s} = H_{i,t,s}, \forall t \in \Lambda^T, \forall s \in \Psi^H, e \in \Psi^E \]  

- Thermal process under each scenario
  \[ T^S_{i,t,s} \leq T^S_{i,t,s} \leq T^S_{i,t,s}, \forall t \in \Lambda^T, \forall s \in \Psi^S \]  
  \[ T^S_{i,t,s} - T^S_{i,t,s} = \left( T^S_{i,t,s} - T^S_{i,t,s} \right) e^{\frac{T^S_{i,t,s}}{C^W m^H_{i,s}}}, \forall t \in \Lambda^T, \forall s \in \Psi^S \]  

where (62)-(64) are similar to (40)-(42), which represent the thermal process in each scenario.

- Heat regulation of HPs/EBs
  \[ \Delta h^W_{i,t,s} = \eta^W \Delta h^W_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^W \]  
  \[ \Delta h^B_{i,t,s} = \eta^B \Delta h^B_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^B \]  

where (65) and (66) reflect that the heat regulation of HPs and EBs is linearly related to their power regulation in each scenario.

- Heat regulation of STs under each scenario
  \[ -\Delta h^W_{i,t,s} \leq -\Delta h^W_{i,t,s} \leq -\Delta h^W_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^W \]  
  \[ H^S_{i,t,s} = H^S_{i,t,s} + \Delta h^S_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^S \]  
  \[ H^S_{i,t,s} = H^S_{i,t,s} + \Delta h^S_{i,t,s}, \forall t \in \Lambda^T, \forall i \in \Psi^S \]  

where (67)-(69) are similar to (48)-(50), representing the charging/discharging rate, changes of heat energy level, and heat storage capacity under each scenario.
Besides, constraints (17)-(18) for the heat regulation of the condensing CHP units should be included in this part.

2.4 Compact form of two-stage stochastic optimal operation

In summary, the compact form of the mathematical formulation for the two-stage stochastic optimal operation of the IEHS can be described as follows,

\[
\begin{align*}
\min_{x, y} & \quad f_1(x) + \mathbb{E}(f_2(y)) \\
n.s. & \quad A_1x \leq b_1, A_2x + B_2y \leq b_2, \forall s
\end{align*}
\]

The decision variables include the day-ahead scheduling variable \(x\) and real-time regulation variable \(y\), where

\[
x = \{ \text{TU/CHP}, \text{itu}, \text{TU/UR/DR}, \text{itr}, \text{TU/UR/DR}, \text{ith}, \text{TU/CHP}, \text{itp}, \ldots \},
\]

and

\[
y = \{ \text{TU,UR/DR}, \text{itsr}, \text{CHP,UR/DR}, \text{itsr}, \text{CHP,UR/DR}, \text{itsh}, \text{CHP}, \text{itp}, \ldots \},
\]

3. Spatial-temporal correlated scenario generation

In order to implement the two-stage optimization model, a reasonable scenario set of the wind power profiles needs to be generated. In this section, a scenario generation method considering both spatial and temporal correlation is proposed.

The temporal correlation and spatial correlation are formulated separately using different methods and they are linked by inverse sampling. The temporal correlation is constructed by the exponential covariance function. By the spatial correlation, the GMM method is adopted to model the conditional joint distribution of actual wind power outputs with respect to forecast values. Based on the conditional joint distribution modeled by the GMM, the Gibbs sampling is used to improve the computational efficiency.

3.1 Conditional joint distribution based on Gaussian mixture model

The distribution of actual wind power outputs varies significantly with respect to different forecast values. Therefore, the spatial correlation of actual wind power outputs is constructed based on the conditional distribution with respect to forecast values.

Let \(w^a = [w_1^a, w_2^a, \ldots, w_n^a]\) denotes the actual realized wind power outputs of \(n\) wind farms, and \(w^f = [w_1^f, w_2^f, \ldots, w_n^f]\) denotes the corresponding forecast values. The conditional joint probability density functions (PDF) can be computed as,

\[
f\left(w^a | w^f\right) = \frac{f_1\left(w^a, w^f\right)}{f_2\left(w^f\right)} = \frac{f_1\left(w_1^a, w_2^a, \ldots, w_n^a, w_1^f, w_2^f, \ldots, w_n^f\right)}{f_2\left(w_1^f, w_2^f, \ldots, w_n^f\right)}
\]

In (71), computing the joint distribution function \(f_1\) and \(f_2\) is required to determine the conditional joint distribution \(f\). This paper adopts the GMM to build the joint distribution \(f_1\) and \(f_2\) due to its capability in fitting the non-Gaussian correlated random variables.

Mathematically, a GMM for the PDF of a random vector \([w^a, w^f]^T\) is a convex combination of multivariate Gaussian distribution functions with an adjustable parameter set \(\gamma = \{\mu_m, \Sigma_m, \omega_m\}_{m=1}^M\). Take \(f_1\) as an example, the GMM model can be expressed as,

14
The parameter set of the GMM can be determined by the parameter estimation function `gmdistribution` in Matlab. Similarly, the parameter set of the GMM for \( f_2 \) and other joint distribution can be determined by this method.

### 3.2 Gibbs sampling

Sampling from the conditional joint distribution in (71) is necessary to obtain the spatial-correlated scenarios. However, the direct sampling from high-dimensional continuous probability distributions is intractable due to the calculation of multiple integrals.

Gibbs sampling is an efficient way of reducing a multi-dimensional sampling problem to a one-dimensional sampling problem. In the Gibbs sampling, the one-dimensional conditional distribution of each random variable is necessary. By sampling from the conditional distribution of each variable, the joint distribution in (71) can be approximately simulated. Take the sampling in (71) as an example. Fig. 4 details the process of using the Gibbs sampling to generate a spatial-correlated scenario set with \( N_s \) scenarios [35], [40]. As the Gibbs sampling in each period \( t \) is independent of the other periods, Fig. 4 only shows the sampling in a single period.

**Initialization:** Assign initial values to random variables in period \( t 

**Let** \( \mathbf{w}^*, \mathbf{w}' \) = \begin{bmatrix} \mathbf{w}_{1}^*, \mathbf{w}_{2}^*, \ldots, \mathbf{w}_{n}^*, \mathbf{w}_{1}'^*, \mathbf{w}_{2}'^*, \ldots, \mathbf{w}_{n}'^* \end{bmatrix} = \begin{bmatrix} \mathbf{W}_{1}^*, \mathbf{W}_{2}^*, \ldots, \mathbf{W}_{n}^*, \mathbf{W}_{1}'^*, \mathbf{W}_{2}'^*, \ldots, \mathbf{W}_{n}'^* \end{bmatrix}

**s=0**

**Calculate conditional PDF** \( f_j \left( \mathbf{w}_{j}^*, \mathbf{w}_{j}' \right) \)

**Calculate conditional CDF** \( F_j \left( \mathbf{w}_{j}^*, \mathbf{w}_{j}' \right) \)

**Utilize the inverse transform sampling** \( \mathbf{W}_{j,s}^* = F_j^{-1} \left( U_{j,s} \right) \) to obtain the actual wind power scenario, and update \( \mathbf{w}_{j,s}' = \mathbf{W}_{j,s}' \)

**If** \( j < n \) **then** **Y**

**S=1**

**j=1**

**Y**

**If** \( s < s_{max} \) **then** **N**

**Output the spatial-correlated scenario set in period \( t \).**
In Fig. 4, in the initialization, the random variables \( \{w_{i,t}^f, w_{j,t}^f, \ldots, w_{n,t}^f\} \) are paired to the forecast values \( \{W_{i,t}^f, W_{j,t}^f, \ldots, W_{n,t}^f\} \); the initial values \( \{W_{i,t,0}^a, W_{j,t,0}^a, \ldots, W_{n,t,0}^a\} \) of random variables \( \{w_{i,t}^a, w_{j,t}^a, \ldots, w_{n,t}^a\} \) are also set as the forecast values. The calculation of conditional PDF \( f_{j,t} \) for the \( j \)th wind farm in scenario \( s \) is similar to (71)-(74), where the conditional variables \( \ldots, w_{j,i,t,s}^a, w_{j,i,s}^e, \ldots, w_{j,n,t,s}^a, w_{j,n,s}^e \) of random output \( w_{j,t,s}^a \) are the values \( \ldots, W_{i,t,s}^a, W_{j,i,t,s}^a, \ldots, W_{j,i,s}^e, W_{j,n,s}^a, W_{j,n,t,s}^f \). The calculation of conditional CDF \( F_{j,t} \) for the \( j \)th wind farm in scenario \( s \) is based on the accumulation of sample points on \( f_{j,t} \). Given the probability value \( U_{j,t,s} \) of sampling points, a scenario value \( w_{j,t,s}^a \) for variable \( w_{j,t,s}^a \) can be obtained through the inverse transformation \( F_{j,t}^{-1} \).

Implementing the process for all periods, a scenario set with spatial correlation can be derived.

It should be noted that samples from early iterations may not represent the actual joint distribution, i.e., the Gibbs sampling needs a burn-in period to converge to the true distribution [41]. Therefore, it is common to discard samples in early iterations.

### 3.3 Scenario generation procedure

The detailed procedure of the spatial-temporal correlated scenario generation method is detailed as follows. Step 1 is used for the construction of temporal correlation. Step 2 is used to construct the spatial correlation and generate spatial-temporal correlated scenarios.

**Step 1:** Construct the temporal correlation.

**Step 1.1:** For the \( j \)th \((j=1, 2, \ldots, n)\) wind farm, construct the temporal covariance matrix \( \Sigma_{jt}^{tem} \) of actual wind power outputs in different time periods, and each element in \( \Sigma_{jt}^{tem} \) can be calculated by (75). The parameter \( \varepsilon_j \) is used to control the strength of correlation [30, 31].

\[
\rho_{t_i,t_j} = \exp \left( -\frac{|t_i - t_j|}{\varepsilon_j} \right) \tag{75}
\]

**Step 1.2:** Use the `mvnrnd` function in Matlab to generate \( N_s \) scenarios of Gaussian random series \( \{X_j,t,s, X_{j,2,s}, \ldots, X_{j,t,s}\}, j = 1, 2, \ldots, n; s = 1, 2, \ldots, N_s \) for each wind farm, which follows the joint distribution \( N_j\left(\mu_j^{tem}, \Sigma_j^{tem}\right) \). \( \mu_j^{tem} \) is an \( n \)-dimensional zero vector; \( \Sigma_j^{tem} \) is an \( n \times n \) covariance matrix, and each element in \( \Sigma_j^{tem} \) can be calculated by the following exponential function.

**Step 1.3:** Calculate the cumulative distribution function (CDF) value of the Gaussian random variable \( U_{j,t,s} = \Phi \left(X_{j,t,s}\right) \). \( \Phi \left(\cdot\right) \) is a Gaussian CDF; \( U_{j,t,s} \) is the random data that follow the uniform distribution in \([0, 1]\).

**Step 2:** Construct spatial correlation and generate spatial-temporal correlated scenarios.

**Step 2.1:** Calculate the conditional CDF \( F_{j,t} \) \((j = 1, 2, \ldots, n)\) of actual wind power output for the \( j \)th wind farm based on the corresponding conditional PDF \( f_{j,t} \) \((j = 1, 2, \ldots, n)\).

**Step 2.2:** Utilize the inverse transform sampling \( W_{j,t,s}^a = F_{j,t}^{-1} \left(U_{j,t,s}\right) \) to obtain the actual wind power scenario.

**Step 2.3:** Implement Step 2.1 and Step 2.2 for each time period \( t \) and each scenario \( s \).

**Step 2.4:** Discard the first \( N_b \) scenarios in the burn-in period and take the remaining scenarios as the final spatial-temporal correlated scenario set of actual wind power outputs.
4. Case study

Four wind farms with spatial and temporal correlations were used to validate the performance of the proposed scenario generation method. Two integrated energy systems with wind power were used to demonstrate the efficacy of the proposed two-stage stochastic optimal dispatch scheme of the IEHS. The simulation was conducted using Yalmip and solved by GUROBI 8.0. The tolerance gap was set at 0.01%.

4.1 Performance of spatial-temporal correlated scenario set

The data of the four wind farms is from the Western Denmark data set [42], [43]. The historical wind power measurements have an hourly resolution and each wind farm has 4,300 historical observations. Each wind farm has a capacity of 50 MW and the wind power data has been scaled to match the wind farm capacity. As the data set does not give the corresponding forecast values, the forecast values were generated by using the moving average method.

Before generating the spatial-temporal correlated scenario set, the correlation features of actual wind power outputs are firstly analyzed. Fig. 5 shows the scattered data between each pair of wind farms.

![Fig. 5 Spatial correlation of each pair of wind farms.](image)

One of the obvious features in Fig. 5 is that the actual wind power outputs for each pair of wind farms are positively correlated. The bottom-left and top-right area has a larger data density, which means the PDF of actual wind power outputs for each wind farm is a multimodal function and it is hard for the traditional Gaussian distribution to fit this feature.

The key to conditional joint PDF in (70) lies in the calculation of the joint distribution function \( f_1 \) and \( f_2 \). Since the dimensions of \( f_1 \) and \( f_2 \) are 8 and 7, it is difficult to visualize the fitting performance. Here, the aggregate actual wind power production and aggregate forecast values are selected to test the fitting performance. The PDF of \( f_1 \left( \sum_{j=1}^{n} w_j \right) \) and \( f_2 \left( \sum_{j=1}^{n} w_j \right) \) fitted by the GMM are given in Fig. 6, which shows that the GMM model with five Gaussian mixture components can fit the multimodal feature of the PDF accurately.
(a) The fitted PDF of aggregate forecast values by GMM
(b) The fitted joint PDF of aggregate forecast values and aggregate actual wind power outputs by GMM

Fig. 6 Fitted PDF of $f_1$ and $f_2$ by GMM.

For comparison, the scenario generation method in [35] was also conducted to generate scenarios. The method in [35] combines the Gaussian Copula and exponential function to construct spatial and temporal correlation. For simplicity, the method in [35] is abbreviated as Copula-exponential, while the method proposed in this paper is called the GMM-exponential method. The scenario set for each wind farm and aggregate outputs of all wind farms are given in Fig. 7. During the process of scenario generation, the total number of scenarios $N_t$ is set as 2000, and $N_b$ is set as 1500 for the burn-in period. Therefore, 500 scenarios are remained in Fig. 7.

(a1) W1 by GMM-exponential
(b1) W2 by GMM-exponential
(c1) W3 by GMM-exponential
(d1) W4 by GMM-exponential
(e1) Aggregate outputs by GMM-exponential

(a2) W1 by Copula-exponential
(b2) W2 by Copula-exponential
(c2) W3 by Copula-exponential
(d2) W4 by Copula-exponential
(e2) Aggregate outputs by Copula-exponential

Fig. 7 Scenario sets generated by GMM-exponential and Copula-exponential methods.

To qualify the performance of these two methods, two indices are used to evaluate the quality of the scenario set. One is the coverage rate [31], which aims to evaluate whether the actual wind power outputs can be covered by the scenario set at each period. The other is the envelope area of the scenario set, which is used to test whether the scenario set can cover the actual wind power outputs with as small as areas. These two indices are selected from the view of the dispatching center to guarantee a reasonable reserve. They are expressed as follows

\[
\begin{align*}
\text{index 1} & = \frac{1}{T} \sum_{t=1}^{T} B_t, \quad B_t = \begin{cases} 1 & \text{if } W_{\text{act}}^t \in \left[ \min_{x \in \left[ x_2, x_1 \right]} (W_{\text{f},t}^x), \max_{x \in \left[ x_2, x_1 \right]} (W_{\text{f},t}^x) \right] \\
0 & \text{otherwise} \end{cases} \\
\text{index 2} & = \frac{1}{T} \sum_{t=1}^{T} \left( \max_{x \in \left[ x_2, x_1 \right]} (W_{\text{f},t}^x) - \min_{x \in \left[ x_2, x_1 \right]} (W_{\text{f},t}^x) \right)
\end{align*}
\]
Table 1 compares the two scenario generation methods in scenario quality and calculation time. To guarantee the robustness of test results, the data of 30 days are selected to generate scenarios. Table 1 gives the average value of the 30 days. The results show that the GMM-exponential method not only saves calculation time by 95% but also guarantees a larger coverage rate and a smaller envelope area than the Copula-exponential method.

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<thead>
<tr>
<th>Scenario generation methods</th>
<th>Copula-exponential</th>
<th>GMM-exponential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage rate</td>
<td>0.9653</td>
<td>0.9875</td>
</tr>
<tr>
<td>Envelope area</td>
<td>0.5213</td>
<td>0.4422</td>
</tr>
<tr>
<td>Calculation time (s)</td>
<td>988</td>
<td>49</td>
</tr>
</tbody>
</table>

4.2 Case Study with integrated six-bus EPS and six-node DHS

**System 1**: The first test system is a small-scale system, which consists of a six-bus EPS and a six-node DHS. The four wind farms with spatial and temporal correlations in Section 4.1 is integrated into this system. Fig. 8 shows the single-line diagram. Fig. 9 shows the hourly power demand, heat demand, and wind power aggregate forecast values of System 1.

In System 1, the EPS sector includes 2 thermal units (G1 and G2), 1 condensing CHP unit (CHP1), 4 wind farms (W1, W2, W3, and W4), 1 EB (EB1), 1 HP (HP1), 1 WP (WP1), and 7 transmission lines. The data of transmission lines is from [44]. EB1 has a capacity of 10 MW and its conversion efficiency is 0.9. HP1 has a capacity of 10 MW and its conversion efficiency is set as 3. The DHS sector includes 5 pipelines, 3 heat exchange stations, and 1 ST (ST1) with a capacity of 20 MW. The EPS and DHS are coupled by CHP1, EB1, and HP1.

In the simulation, the cost parameters are set as follows. The compensation for wind curtailment and load shedding is 80 $/MWh and 1500 $/MWh, respectively. The reserve capacity price of conventional units is 40% of their highest incremental cost of producing energy [45]. The reserve capacity price of CHP1 is 25 $/MWh. The reserve deployment prices of conventional units and CHP1 unit are 40 $/MWh.

Fig. 8 Configuration of the six-bus and six-node integration system.
Fig. 9  Power demand, heat demand, wind power forecast values in System 1.

Five cases are selected for analyzing the impact and effect of different flexibility reserve on reducing the wind curtailment rate and operational cost, which relates to the energy and economic efficiency of the IEHS. The aim of the comparison is to identify which measure is more beneficial to achieve a high share renewable-based energy system while guaranteeing a cost-effective solution. The cases are described below.

Case 1.1: The conventional thermal units are the only reserve resource to balance wind power uncertainty. This case is the base case for comparison.

Case 1.2: The condensing CHP units and STs are included as additional power reserve and heat regulation sources.

Case 1.3: The CHP units, EBs, and STs are integrated to provide power reserve and heat regulation.

Case 1.4: The CHP units, HPs, and STs are integrated to provide power reserve and heat regulation.

Case 1.5: The CHP units, HPs, EBs, and STs are all accounted to provide power reserve and heat regulation.

4.2.1 Impact of spatial-temporal correlation on economic efficiency

To balance the computation burden, the generated scenarios are reduced to 30 and incorporated into the two-stage optimization model. Take Case 1.5 as an example. The scheduling results taking different scenario sets as input for Case 1.5 are compared in Table 2 to validate the advance of the proposed scenario generation method in improving economic efficiency.

As can be seen from Table 2, the two scenario generation methods have similar wind curtailment, but the proposed GMM-exponential method outperforms the Copula-exponential method in total operational cost due to the smaller envelope area of the scenario set, improving the economic efficiency by 12.40%.

Table 2  Operational cost based on the different scenario set

<table>
<thead>
<tr>
<th>Scenario generation</th>
<th>Copula-exponential</th>
<th>GMM-exponential</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-stage cost/$</td>
<td>1.6146×10^5</td>
<td>1.4858×10^5</td>
</tr>
<tr>
<td>Second-stage cost/$</td>
<td>4.4369×10^4</td>
<td>3.1718×10^4</td>
</tr>
<tr>
<td>Total cost/$</td>
<td>2.0583×10^5</td>
<td>1.8030×10^5</td>
</tr>
<tr>
<td>Wind curtailment</td>
<td>3.77%</td>
<td>3.90%</td>
</tr>
</tbody>
</table>

As the input of the optimal operation of the IEHS, not only the profile patterns of the scenario set but also the number of remained scenarios has a great and direct influence on the decision results. Usually, the number of scenarios affects both the calculation time and the robustness of the decision. Table 3 compares the operational cost and calculation time of Case 1.5 under different numbers of scenarios. All the scenarios are generated by the proposed GMM-exponential method.

As can be seen from Table 3, the calculation time increases with the number of scenarios, while the operational cost fluctuates with the number of scenarios. A larger number of scenarios usually means a more robust decision, but it is at the expense of consuming more calculation time, especially for large-scale system. For practical
application, the number of scenarios should be a compromise between the calculation time and robustness of the decision.

Table 3  Operational cost and calculation time of Case 1.5 with different numbers of scenarios

<table>
<thead>
<tr>
<th>Number of scenarios</th>
<th>Operational cost/$</th>
<th>Calculation time/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.5082×10^5</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>1.6758×10^5</td>
<td>18</td>
</tr>
<tr>
<td>30</td>
<td>1.8030×10^5</td>
<td>24</td>
</tr>
<tr>
<td>100</td>
<td>1.6901×10^5</td>
<td>72</td>
</tr>
<tr>
<td>200</td>
<td>1.5839×10^5</td>
<td>156</td>
</tr>
<tr>
<td>500</td>
<td>1.5407×10^5</td>
<td>622</td>
</tr>
</tbody>
</table>

4.2.2 Improved flexibility from condensing CHP units and flexible devices

In this section, System 1 is used to simulate the stochastic joint dispatch of all devices. The impact and effect of utilizing different flexible devices are analyzed based on comparisons of operational cost and wind power utilization. The operational cost and wind power curtailment for five cases are compared in Table 4. In Table 4, the improvement of economic efficiency of Cases 1.2, 1.3, 1.4 and 1.5 are calculated with Case 1.1 as the base case.

Table 4  Operational cost and wind curtailment of System 1

<table>
<thead>
<tr>
<th>Cases</th>
<th>Case 1.1</th>
<th>Case 1.2</th>
<th>Case 1.3</th>
<th>Case 1.4</th>
<th>Case 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-stage cost/$</td>
<td>1.8112×10^4</td>
<td>1.7484×10^4</td>
<td>1.6135×10^5</td>
<td>1.5506×10^5</td>
<td>1.4858×10^5</td>
</tr>
<tr>
<td>Second-stage cost/$</td>
<td>6.5291×10^4</td>
<td>5.5688×10^4</td>
<td>4.4144×10^4</td>
<td>4.5750×10^4</td>
<td>3.1718×10^4</td>
</tr>
<tr>
<td>Total cost/$</td>
<td>2.4641×10^4</td>
<td>2.3054×10^4</td>
<td>2.0549×10^4</td>
<td>2.0081×10^4</td>
<td>1.8030×10^4</td>
</tr>
<tr>
<td>Improvement of economic efficiency</td>
<td>--</td>
<td>6.44%</td>
<td>10.87%</td>
<td>12.90%</td>
<td>26.83%</td>
</tr>
<tr>
<td>Wind curtailment rate</td>
<td>10.23%</td>
<td>8.21%</td>
<td>5.95%</td>
<td>6.10%</td>
<td>3.90%</td>
</tr>
</tbody>
</table>

In Table 4, compared with Case 1.1, Case 1.2 can reduce the operational cost and wind power curtailment by 6.44% and 2.02%, respectively, when the reserve of condensing CHP units is considered. In Case 1.3 and Case 1.4, introducing the EBs and introducing the HPs have similar wind curtailment rates. Compared with Case 1.1, EBs and HPs can reduce the wind power curtailment by 4.28% and 4.13%, respectively. However, the HPs can bring higher economic efficiency than the EBs with the same capacity. Compared with Case 1.2, EBs and HPs can reduce the operational cost by 10.87% and 12.90%, respectively. When the reserve of CHP units, STs, EBs, and HPs are all considered in Case 1.5, the scheduling achieves the lowest operational cost and wind power curtailment, reducing the wind curtailment and operational cost by 6.33% and 26.83%, respectively.

Fig. 10 shows the comparison between Case 1.1 and Case 1.5 for the expected value of deployed upward and downward reserve under all wind power scenarios. Compared with Case 1.1, Case 1.5 shows a great improvement in available reserve after considering the condensing CHP units, HPs, EBs, and STs, which improves the upward and downward reserves by 183.38% and 354.46%, respectively. It should be noted that the downward reserve is in low availability from period 16 to period 24 when the power load is in its valley while the wind power and heat demand is high. At these periods, both the thermal power units and CHP units are in their minimum outputs, leading them hard to release the downward reserve and accommodate the wind power.
In Case 1.5, apart from the STs, EBs, and HPs, the unit commitment of CHP1 also contributes additional flexibility compared with Case 1.1. The unit commitment plan of Case 1.1 and Case 1.5 are compared in Fig. 11. In Case 1.1, CHP1 is turned on during the whole horizon to produce heat. In comparison, Case 1.5 can turn off CHP1 in periods 10 and 16 due to the introduction of EBs, HPs, and EBs. By shutting down CHP1, more wind power can be accommodated to balance the power demand.

In addition, to validate the effectiveness of reserve modeling of the condensing CHP units, the feasibility of operating points of CHP1 after reserve deployment is tested. Fig. 12 shows that the operating points in different time periods under some wind power scenario are still within the operational region of CHP1 after reserve deployment. This validates the effectiveness of reserve modeling for condensing CHP units in the feasibility guarantee.

4.3 Case Study with NE integrated energy system

System 2: The second system is a practical regional energy system in the northeast part of China, abbreviated as the NE system. It covers the power grid of Liaoning province, Jilin province, Heilongjiang province, and east parts of Inner Mongolia. This system is mainly used to test the impact of introducing the reserve of condensing CHP units, HPs, EBs, and STs based on the analysis of operational cost and wind power curtailment. Fig. 13 shows the simplified composition of the NE system in 2025.
In Fig. 13, the equivalent Bus 1 in Liaoning province contains 29 thermal power units and 67 CHP units; the equivalent Bus 2 in Jilin province contains 20 thermal power units and 47 CHP units; the equivalent Bus 3 in Heilongjiang province contains 22 thermal power units and 47 CHP units; and the equivalent Bus 4 in Eastern Inner Mongolia contains 46 thermal power units and 19 CHP units.

The NE system has abundant wind sources, the predicted wind power capacities in 2025 in four equivalent buses are 10000, 8000, 8000, and 15000 MW, respectively. Bus 1 also contains 6250 MW nuclear power and 1500 MW DC outgoing power. Bus 4 has 10500 MW DC outgoing power. The capacities for EBs, HPs, and STs in each bus are all set as 300 MW. In this large-scale region energy system, the pipeline transmission constraints are neglected and only the heat balance between heat sources and heat load is considered.

The power demand, heat demand, and wind power forecast values for the case study are generated in two steps. Firstly, the power demand, heat demand, and wind power forecast values are generated for the full year of 2025. Secondly, the data on a typical day in winter are extracted for the case study.

In the first step, the per-unit value of the load is the same as that of 2012. The load capacity is calculated with the actual annual growth rate of the four parts of the NE system in 2015, which are 2.7%, 2.2%, 2.8%, and 7.0%, respectively. The per-unit curves of heat demand and wind power forecast values are obtained from the publicly accessible meteorological data, population distribution, and administration area data [46]. Their capacity in 2025 is set according to the planned values. The selected profiles of power demand, heat demand, and wind power values are shown in Fig. 14.
In System 2, wind power is negatively correlated with power demand. The wind production accounts about 48% of the peak power demand. The cost and operational characteristics are consistent with the statistics of the power plants in China. The cost parameters for wind curtailment, load shedding, and reserve capacity and deployment are the same as those in Section 4.2.

Five cases, Case 2.1, Case 2.2, Case 2.3, Case 2.4, and Case 2.5, which are similar to Case 1.1 to Case 1.5, are simulated for a comprehensive comparison about the impact of utilizing flexible devices to improve wind power utilization and reduce operational cost, as shown in Table 5. In Table 5, the improvement of economic efficiency of Cases 2.2, 2.3, 2.4 and 2.5 are all calculated with Case 2.1 as the base case. The heat and power production of units and flexible devices for the five cases are illustrated in Fig. 15.

**Table 5 Operational cost and wind curtailment rate of NE system**

<table>
<thead>
<tr>
<th>Cases</th>
<th>Case 2.1</th>
<th>Case 2.2</th>
<th>Case 2.3</th>
<th>Case 2.4</th>
<th>Case 2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible resources</td>
<td>Thermal units</td>
<td>Thermal units, CHP units, STs</td>
<td>Thermal units, CHP units, STs, EBs</td>
<td>Thermal units, CHP units, STs, HPs</td>
<td>Thermal units, CHP units, STs, EBs, HPs</td>
</tr>
<tr>
<td>First-stage cost/$</td>
<td>4.8610×10^7</td>
<td>4.8164×10^7</td>
<td>4.6811×10^7</td>
<td>4.5206×10^7</td>
<td>4.4633×10^7</td>
</tr>
<tr>
<td>Second-stage cost/$</td>
<td>4.6269×10^6</td>
<td>4.4314×10^6</td>
<td>3.2283×10^6</td>
<td>2.8297×10^6</td>
<td>2.2188×10^6</td>
</tr>
<tr>
<td>Total cost/$</td>
<td>5.3237×10^7</td>
<td>5.2595×10^7</td>
<td>5.0039×10^7</td>
<td>4.8046×10^7</td>
<td>4.6852×10^7</td>
</tr>
<tr>
<td>Improvement of economic efficiency</td>
<td>--</td>
<td>1.21%</td>
<td>6.01%</td>
<td>9.75%</td>
<td>11.99%</td>
</tr>
<tr>
<td>Wind curtailment rate</td>
<td>8.77%</td>
<td>8.06%</td>
<td>5.77%</td>
<td>4.60%</td>
<td>3.58%</td>
</tr>
</tbody>
</table>
In Case 2.1, only the reserve of conventional thermal units is considered. Due to the limited flexibility, Case 2.1 has the highest wind curtailment and operational cost, which is illustrated in Fig. 15 (a). In Fig. 15 (a), the wind power is mainly curtailed at periods when the load is in its valley while the wind power has high availability. During those time periods, the heat demand is at a high level due to the lower ambient temperature at night. On the one hand, to supply the high-level heat demand, a large amount of CHP units needs to be online. On the other hand, Case 2.1 does not consider reserve of CHP units, leading extra committed thermal power units to provide the required reserve. Both factors limit the operational flexibility of the system and result in the high wind curtailment rate and operational cost.

In Case 2.2, after considering the reserve of condensing CHP units and heat regulation of the STs, the total cost decreases by 1.21% than that of Case 2.1. The wind curtailment rate decreases by 0.71% than that of Case 2.1. As can be seen from Fig. 15 (b), after using CHP units to provide reserve, the committed thermal power units have been reduced from period 1 to period 5. Besides, when the STs are integrated, the heat production of CHP units can be changed. Even though this can reduce the wind curtailment rate to some extent, the effect is not as significant as Case 2.3 and Case 2.4.

In Case 2.3 and Case 2.4, the EBs and HPs are introduced on the basis of Case 2.2, respectively. Even though with the same integrated capacity, they present different impacts on reducing the operational cost and wind curtailment. When the EBs are introduced, the total cost decreases 6.01% than Case 2.1 and 4.86% than Case 2.2; while the wind curtailment decreases by 3.00% than Case 2.1 and 2.29% than Case 2.2. In comparison, when the HPs are introduced, the total cost decreases by 9.75% than Case 2.1 and 8.65% than Case 2.2; while the wind curtailment decreases by 4.11% and 3.46% than Case 2.2.

As can be seen from Fig. 15 (c) and (d), when the EBs and HPs are introduced, the heat supply originally from CHP units can be replaced by the EBs and HPs, then the fuel cost of units can be saved, and more wind power can be used to supply the power consumption of the EBs and HPs. By comparison, the HPs in Case 2.4 can produce more heat than the EBs in Case 2.3 and save more fuel cost for the system.

It should be noted that, the advantage of HPs in reducing wind power curtailment and operational cost is more obvious than the EBs in the NE system, compared with the 6-bus system. In the 6-bus system, only one CHP unit and one thermal unit are committed. There is not enough system flexibility for HPs and EBs to exploit their flexibility capability. In comparison, the NE system has a larger system flexibility to coordinate CHP units and flexible devices due to the large number of CHP units. Therefore, the HPs have more advantage than the EBs on reducing wind power curtailment and operational cost in the NE system.

In Case 2.5, when the HPs and EBs are both introduced on the basis of Case 2.2, the system has the lowest operational cost and wind curtailment, reducing the wind curtailment and operational cost by 5.19% and 11.99%, respectively. As can be seen from Fig. 15 (e), the heat production from CHP units has been reduced compared with other cases due to the simultaneous integration of EBs, HPs, and STs, releasing more flexibility for the system to accommodate wind power.

Fig. 16 shows the comparison between Case 2.1 and Case 2.5 for the expected value of deployed upward and downward reserve under all wind power scenarios. Compared with Case 2.1, Case 2.5 can improve the upward and downward reserves by 70.54% and 100.17%, respectively. The improvement of the downward reserve at periods 1-6 is the main reason for accommodating more wind power.
5. Conclusions

In this paper, a two-stage stochastic optimal dispatching scheme is proposed for the integrated electricity and heat system, which considers detailed reserve modeling of condensing combined heat and power units, heat pumps, electric boilers, and heat storage tanks and takes into account the spatial-temporal correlation of wind power scenario set. A 6-bus small-scale energy system and a regionally integrated energy system in China were simulated under different scenarios. The main conclusions are as follows:

- The proposed Gaussian mixture model-exponential scenario generation method is able to account for the spatial and temporal correlations simultaneously. It outperforms the Copula-exponential method in the coverage rate and envelope area. In addition, it saves the scenario generation time by 95% and reduces the operational cost by 12.40% than the Copula-exponential method.

- The proposed reserve modeling of condensing combined heat and power units is effective at guaranteeing a feasible operating point after reserve deployment. Compared with the EBs, the HPs with the same capacity can save more operational cost due to its high energy conversion efficiency.

- The two-stage stochastic optimal dispatching scheme of the integrated electricity and heat system can bring more flexibility by coordinating the conventional thermal units, condensing combined heat and power units, heat pumps, electric boilers, and heat storage tanks, improving the upward reserve of the two systems by 183.38% and 70.54%, respectively, and downward reserve by 354.46% and 100%, respectively, reducing the wind curtailment of two systems by 6.33% and 5.19%, respectively, saving the operational cost of two systems by 26.83% and 11.99%, respectively.

For the future work, the distributed operation of the integrated electricity and heat system under uncertainty and the corresponding solution algorithm will be studied to protect the privacy of all subsystems and improve the computational efficiency.

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### References


