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Economic Dispatch for Regional Integrated Energy System With District Heating Network Under Stochastic Demand

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ABSTRACT The strong interdependency of heat and power supply restricts the operational flexibility of combined heat and power (CHP) units, especially in cold seasons. More than that, such kind of coupling can conventionally cause massive power curtailment of renewable energy sources (RES) under stochastic heat demands. In this paper, these issues are resolved by the cooperation between the district heating network (DHN) and load-side thermal storages in a regional integrated energy system (RIES) model. In which, the DHN is formulated as an energy-storage-like (ESL) model, based on the dynamic characteristics of temperature and time delay effect of the medium within the pipeline system. The potential benefits of the proposed model, in terms of increasing the integration of RES and the total revenue of the entire system, have been demonstrated by the case studies.

INDEX TERMS District heating network (DHN), renewable energy sources (RES), regional integrated energy system (RIES).

NOMENCLATURE

INDICES AND SETS

$\mathcal{N}$	Set of nodes in the district heating network (DHN).
$\mathcal{N}_g/\mathcal{N}_d$	Set of source/demand nodes in theDHN.
P	Set of pipes in theDHN.
B	Set of buses in the distribution power system.
$\mathbf{Y}$	The network incidence matrix
$\mathbf{Y}_g/\mathbf{Y}_d$	The source/demand incidence matrix.

PARAMETERS

m_p	The mass flow rate within pipe section p.
ε_p	The time delay factor of pipe section p.
C_P	The specific heat of water.
$T_{a,t}$	The ambient temperature at time t.
$T_{o,t}$	The temperatures at the outlet of load nodes before mixing into the return network.
η_{ch}/η_{disch}	The charging/discharging efficiency of thermal energy storages (TES).
π	The energy price.
σ	Confidence level

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VARIABLES

$\mathbf{T}^s_{g,t}/\mathbf{T}^s_{d,t}$	The vector of the supply temperatures of source/demand nodes at time t.
$\mathbf{g}_t$	The vector of heat generations.
$\mathbf{d}_t$	The vector of thermal demands.
H_t	The charging and discharging rate of the DHN at time t.
E_t	The heat storage capacity of the DHN at time t.
b_t	The boundary power exchanged between the utility gridandthe regional integrated energy system (RIES) at time t.
$g_{k,t}$	The electricity generation of the CHP unit connected to bus k at time t.

$h_{k,t}$	The heat production of the CHP unit connected to bus k at time t.
$w_{k,t}$	The output of the wind turbine connected to bus k at time t.
$d^h_{n,t}$	The scheduled head demand of node n at time t.
$\tilde{d}^h_{n,r,t}$	The random real heat demand of node n at time t.
$\xi_{ch,n,t}\xi_{disch,n,t}$	The charging/discharging rate of the TES connected to node n at time t.
$S_{n,t}$	The storage capacity of theTES connected to the load node n at time t.
$Q_{n,t}$	The state variable of theTES connected to the load node n at time t.

I. INTRODUCTION

Currently, with the growth of global energy crisis, the increasing penetration of renewable energy sources (RES) in a distributed manner has garnered worldwide attention. However, the strong coupling between different energy sectors under the traditional energy structure has set up multiple barriers to the utilization of RES. For example, in the winter of severe cold or cold zones, such as Nordic countries and northern China, thehigher heat loads with lower electricity demands at off-peak hours can conventionally restrict the integration of RES. These issues have promoted the development of the regional integrated energy system (RIES), which enables the coordination and optimization of multiple energy carriers, including electricity, heat and gas. Normally, a RIES coordinates an intelligent power distribution system, a district heating system and other energy supply networks together, to provide the services of energy distribution and conversion.

One of the major concerns in research for RIES is how to decouple the strong interconnections between different energy carriers and between supplies and demands, to supply more flexibility for accommodating RES. Therefore, there are a number of projects focusing on exploiting the flexibility of multi-energy coordination in a RIES [1]. Among the solutions, thermal energy storages (TES) are considered asef-fective and practical options, and there are lots of researches focusing on the RIES containing CHP units and TES [2]–[9]. In these cases, TES supply buffer of time, which means they can capture the thermal energy that has not been used, and then deliver which to demand side when generation is not sufficient. In this way, TES can not only help CHP units to reduce cost and extend lifetime [4] but also create more flexibility for CHPs to better coordinate with other energy sources, e.g. RES. Then, better environmental and economic benefits for the whole energy system can be achieved.

However, after all the merits of TES, the utilization of TES is restricted by the limited capacity and high investment. In other words, the cost of TES is acceptable for a small-scale one, but which is too high to afford for a large-scale application. Therefore, a suitable replacement with less investment for large-scale TES is desperately needed. Fortunately, with an increasing interest in district heating network (DHN) [9]–[13], many facts have demonstrated that DHN system can be an excellent substitute of TES. The first reason is CHP units are usually connected to the source sides of a DHN, and DHNs have already become the indivisible infrastructures of urban communities in numerous countries, such as China, Denmark, et cetera, that is, DHN is instantly ready for the utilization. Secondly, in a general DHN, a considerable number of pipelines have already been thermal insulated with the medium in the form of hot water or steam [13], which can offer large amounts of thermal storage capacity without massive investments. Based on the above, DHN is considered as an excellent choice to provide additional flexibility just like TES.

However, up to now, the storage capacity of the DHN has not been fully used bythe practical operation. The reasons, on the one hand, a model of DHN that is applicable to the practical operation and can reflect the storage capacity of DHN still need to be drilled down into. In some previous studies, DHN is reduced to a single-node model [14], wherein the heat demands and supplies are balanced without modeling the pipeline system, so which is not applicable for exploring the storage characteristic of DHN. References [15]–[17] consider more detailed models of DHN with the losses of pressure heads and temperature, but the time delay effect of temperature was neglected. Moreover, although the effect of temperature dynamics in DHN has been studied in [13], it is hard to solve the model directly using off-the-shelf solvers, because the complicating variables are included in the operational constraints, and the convergence of the developed iterative algorithm is yet an open problem. Furthermore, the relative attenuation degree and lag time are made to describe DHN's dynamic characteristics in [18], but the calculation process is extremely complex. Summing up the above, a dynamic and easy-to-compute model of DHN is still necessary to be explored.

On the other hand, few studies have been made on considering the uncertainty of another side of DHN, i.e., heat demand. However, oversimplifying the uncertainties on the demand side [19], [20] may fail to reflect the real state of DHN. Although some published papers tried to predict daily heat load variations in a model, they still stated that the fast changes in heat loads are difficult to predict [21], [22], and it is nearly impossible for the operators to continually adjust their operation to meet the demand in real time [23]. Normally, the uncertain load are usually denoted by random variables that approximately obey some probability distributions, but most of which (e.g. Gaussian or Beta) cannot properly represent the accurate statistical characterization of such random variables for some forecast timescales [24]. More than that, most of the commonly used distributions do not have closed-form formulations, which directly expand the computing scale and increases the complexity of the problems. Therefore, a probability distribution model that canwell represent the random demand and can guarantee the dependability and feasibility of classical algorithms without increasing the nonlinearity and complexity should be explored. Besides, inspired by the conventional methods of eliminating the power load uncertainty through regulating reserve and automatic generation control (AGC) [25]in the electric grid, the heat demand uncertainty in DHN can also be managed by the small-capacity storages on load sides.

The main contributions of this paper are as follows:

1) Formulating a regional integrated energy system (RIES) model, which consists of a distribution power system and a district heating system connected with distributed generations and demands, to enable the coordination and optimization of multiple energy carriers, including electricity and heat.
2) Proposing an energy-storage-like (ESL) model to represent the storage characteristic of DHN, wherein the time delay effect of mass flow in pipelines are linearized by the generation and demands in neighboring time intervals. Moreover, the proposed ESL model can represent the storage characteristic of DHN by charging/discharging rate and storage capacity, which is just like a standard thermal storage device.
3) Proposing a chance-constrained approach to locally eliminate the uncertainty of heat demandsthrough regulating small-capacity TES installed on the demand side, and the characterization of the stochastic heat demand is denoted by the versatile probability distribution (VPD).

The remaining of this paper is organized as follows, the architecture of the RIES model is introduced in Section II. Section III gives the details of the ESL model of DHN, and Section IV shows the formulation of RIES. Case studies are conducted in Section V to demonstrate the effectiveness and benefit of the proposed model. Section VI gives the final conclusion.

II. ARCHITECTURE OF RIES

RIESs are the energy systems that contain generations and demands with multi-energy flows within a region. The operator of RIES is in charge of making the decision for local RES and conventional distributed generations (DGs) to meet multi-energy demands. The joint scheduling can always offer many economic and environmental benefits [23].

As shown in figure. 1, externally, a RIES connects to the boundary bus of the utility grid and exchanges boundary power at time-of-use (TOU) price, in pursuit of the regional optimal economic dispatch. Internally, a RIES consists of two main objects, one is the generation section that includes traditional DGs and RES, and the other is the load section with multi-energy demands. What's more, DHN is an inevitable existing part in RIES, so it can work as a supplementary heat storage part between the thermal generations and demands.

When considering the storage capacity of the DHN, the operation principle of RIES is explained as follows: when the generation of RES is high, or the time-of-use (TOU) power price from the utility grid is lower during off-peak times, the traditional distributed generations (DGs), such as CHP units, will reduce their power outputs to accommodate more power from RES. At the same time, there will be a drop in the heat production of the CHP units, and the temperature of the source node in DHN will be decreased within an adjustable range. Then the DHN is working in its "discharging" pattern, because demand nodes is keeping withdrawing heat from the medium within pipes. Similarly, when RES generate less power, or the utility grid raises electricity prices at peak times, CHP units must increase their power to balance the power demands. For the same reason mentioned before, the heat generation will be increased, and then DHN is going to work in its "charging" pattern. In this way, although the heat production from heat sources does not track the heat demands in real time, the real demands of customers at each time slot can be meet by the cooperation of the DHN and small-scaled TES. Therefore, the cogeneration system can obtain greater flexibility to increase the integration of RES and realize the optimal social welfare of the RIES.

III. THE ENERGY-STORAGE-LIKE MODEL OF DHN

A. BASIC ASSUMPTION

First of all, the pipeline network of DHN can be regarded as a closed heating system (no media exchange), which is entirely filled with the medium that carries the mission of delivering and storing energy in the process of flowing within pipes. Second, as there are fewer control devices at the end-user side, most of the DHNs are operated by quality regulation, i.e., with constant flow and variable temperatures [17]. In this paper, the medium is in the form of hot water, and quality regulation is used to regulate heat supply, which means keeping the mass flow rate fixed and regulating the heat in DHN through adjusting the supply temperatures of sources. Therefore, the energy change of the medium is mainly the change of its internal energy [26].

B. CHARACTERISTIC DESCRIPTION OF DHN

The thermodynamic system of DHN consists of three parts: heat generations from sources, heat demands, as well as the heat change rates of the pipeline system. The characteristics of DHN are described as follows.

1) NETWORK INCIDENCE MATRIX

Consider a DHN with N nodes collected in the set $\mathcal{N} = \{1, 2, ..., N\}$, and P pipe segments in the set $\mathcal{P} = \{1, 2, ..., P\}$, the topology of which can be described by a network incidence matrix $\mathbf{Y}$, and each element in $\mathbf{Y}$ can be described as

$$y_{np} = \begin{cases} 1 & \text{if the mess flow in pipe } p \text{ leaves node } n; \\ -1 & \text{if the mess flow in pipe } p \text{ comes into node } n; \\ 0 & \text{if no connection between pipe } p \text{ and node } n; \\ & \forall n \in \mathcal{N},\ p \in \mathcal{P}. \end{cases} \quad (1)$$

From the perspective of hydraulic analysis, with matrix $\mathbf{Y}$, the continuity of flow is expressed in the following equation.

$$\mathbf{Y} \times \mathbf{m}_{pipe} = \mathbf{m}_{node} \tag{2}$$

This equation illustrates the relationship between the mass flow rates through a node and within the pipe sections connected to it. In (2), $\mathbf{m}_{pipe} = \left[m^1_{pipe}, m^2_{pipe}, \ldots, m^P_{pipe}\right]^\dagger$ is the vector of the mass flow rates within pipe sections, and $\mathbf{m}_{node} = \left[m^1_{node}, m^2_{node}, \ldots, m^N_{node}\right]^\dagger$ is the vector of the mass flow rate through each node, where $\dagger$ indicates transposition.

2) HEAT SOURCE

$$\mathbf{g}_t = C_P \left(\mathbf{Y}_g \times \mathbf{m}_{pipe}\right) \cdot \left(\mathbf{T}^s_{g,t} - \mathbf{T}^r_{g,t}\right) \tag{3}$$

$\mathbf{g}_t = \left[g^1_t, g^2_t, \ldots, g^G_t\right]^\dagger$ represents the vector of the G generation heat sources defined in the set $\mathcal{N}_g = \{1, 2, \ldots, G\}$, and C_P is the specific heat of water. The generations can directly influence the mass flow rate $\mathbf{m}_{pipe}$, as well as the difference between the supply temperatures $\mathbf{T}^s_{g,t}$ and return temperature $\mathbf{T}^r_{g,t}$ of source nodes. It is worth mentioning that the source incidence matrix $\mathbf{Y}_g$ is defined by (1), except for that, all the nodes in $\mathbf{Y}_g$ are connected with heat sources. Moreover, in this paper, quality regulation is applied, and thereturn temperatures are specified at each time period, so only the supply temperatures are decision variables.

3) HEAT DEMAND

$$\mathbf{d}_t = C_P \left(\mathbf{Y}_d \times \mathbf{m}_{pipe}\right) \cdot \left(\mathbf{T}^s_{d,t} - \mathbf{T}_{o,t}\right) \tag{4}$$

$\mathbf{d}_t = \left[d^1_t, d^2_t, \ldots, d^D_t\right]^\dagger$ is the vector of the thermal energy withdrawn by D demand nodes in the set $\mathcal{N}_d = \{1, 2, \ldots, D\}$, which is directly decided by the mass flow rate $\mathbf{m}_{pipe}$ and the supply temperatures of the demand nodes $\mathbf{T}^s_{d,t}$, especially when the temperatures at the outlet of demand nodes before mixing into the return network $\mathbf{T}_{o,t}$ are controllable. Also, similar to $\mathbf{Y}_g$, the demand incidence matrix $\mathbf{Y}_d$ only considers demand nodes.

4) TEMPERATURE

Meanwhile, the dynamic characteristic of temperature variation can place considerable impacts on the operation of DHN, and the time delay effect cannot be neglected, both of them can be the critical factors in exploiting the storage capability of DHN.

a: TEMPERATURE DROP EQUATION

$$T_{end,p,t} = \left(T_{start,p,t-\varepsilon_p} - T_{a,t}\right) e^{-\frac{\lambda \varepsilon_p}{C_P A_p \rho}} + T_{a,t} \tag{5}$$

In the formula above,$T_{end,p,t}$ and $T_{start,p,t-\varepsilon_p}$ are the end and start node temperature of pipe section p at time t and $t - \varepsilon_p$, while $T_{a,t}$ is the ambient temperature at time t. Moreover, λ is the overall heat transfer coefficient, while ρ and A_p are, respectively, the density of water and the cross-sectional area of pipe section p. Additionally, the relationship between the time delay factor ε_p and the characteristics of pipe section p can be decided by

$$L_p = \int_{t-\varepsilon_p}^{t} \frac{m_p}{\pi \rho R_p^2} dt, \tag{6}$$

where L_p and R_p are the length and radius of pipe section p, and the mass flow rate through which is m_p. Considering (5)–(6), it is easy to conclude that the outlet temperature of a pipe section is decided by the temperature of its start node and the delay time.

Assuming there is a linear relationship between the temperature and time, then the temperature of each node at time slot $t - \varepsilon_p$ can be further described by the two time-adjacent temperatures of the same node as the following linear variations.

$$T_{end,p,t-\varepsilon_p} = (1 - \varepsilon_p) T_{end,p,t} + \varepsilon_p T_{end,p,t-1} \tag{7}$$

b: MIXTURE TEMPERATURE EQUATION

When more than one pipe is connected to the same node, the mixture temperature can be calculated as follows [27],

$$(\sum m_{out}) T_{out} = \sum (m_{in} T_{in}) \tag{8}$$

wherein T_{out} and m_{out} are, respectively, the temperature and the mass flow rate leaving the node; Meanwhile, m_{in} and T_{in} are the mass flow rate and the temperature of an incoming pipe.

Combining the temperature equations in (5)–(8), the supply temperatures of the DHN at time t can be represented by a linear function system as

$$\mathbf{T}^s_{d,t} = f_0 \left(\mathbf{T}^s_{g,t}, \mathbf{T}^s_{d,t-1}, \mathbf{T}^s_{g,t-1}\right). \tag{9}$$

Then, solving (3)–(4) and (9), the supply temperatures of demand nodes can be

$$\mathbf{T}^s_{d,t} = f_1(\mathbf{g}_t, \mathbf{d}_{t-1}, \mathbf{g}_{t-1}). \tag{10}$$

The above equation dedicates that the supply temperatures of demand nodes at time t can be decided by the current generations and the generations and demands at the previous dispatch period $t - 1$. The coupling between the supply temperatures and the two sides, i.e., sources and demands, at adjacent time slots is indicated by function f_1, which is established by exploiting the effect of time delay in the DHN.

5) CHARGING/DISCHARGING RATE

As is known to all, it is difficult to measure the change rate of thermal energy within the DHN system. Then the authors drew their inspiration from the concept of enthalpy change, which can be used to denote the charging/discharging rate of DHN.

Enthalpy is a quantity used to measure the energy in a thermodynamic system, which consists of the internal energy of the system, as well as the products of pressure and volume [28]. However, it is nearly impossible to measure enthalpy directly, and just a difference or change of enthalpy have physical meaning. To be specific, the positive change of enthalpy indicates endothermic reaction, and an exothermic process is corresponding to a negative one.

The general formulation of the enthalpy change of the medium within the pipe section p can be expressed as follows,

$$\begin{aligned}\Delta H_{p,t} &= m_p \Delta h_{p,t} \\ &= m_p \left(\int_{T_{end,p,t}}^{T_{start,p,t}} C_P dT + \int_{R_{end,p,t}}^{R_{start,p,t}} \left[v - T_{end,p,t} \left(\frac{\partial v}{\partial T} \right) \right] dR \right) \end{aligned} \quad (11)$$

where $\Delta h_{p,t}$ represents the enthalpy change of pipe section p, which is formulated by the temperature and pressure changes of the medium. Moreover, $R_{start,p,t}$ and $R_{end,p,t}$ represent the pressure of the start node and end node of pipe section p, and v is the specific volume of the medium. When the medium is hot water in our cases, the second term for the integral of pressure is negligibly small, so the enthalpy change equation of pipe section p can be a formulation of temperatures.

Then, as for the entire DHN, the enthalpy change can be expressed as

$$H_t = C_p \left[\left(\mathbf{Y}_d \times \mathbf{m}_{pipe} \right)^{\dagger} \cdot \mathbf{T}^s_{d,t} + \left(\mathbf{Y}_g \times \mathbf{m}_{pipe} \right)^{\dagger} \cdot \mathbf{T}^s_{g,t} \right] + H^r, \quad (12)$$

where H_t represents the charging/discharging rate of the whole DHN network, i.e., when H_t is positive, the DHN is in the charging process, otherwise, it is working in the discharging process. H^r represents the change rate of the return network, which can be known previously as the return temperatures and mess flow rates are specified in this paper. Thus, the change of enthalpy can be directly decided by the supply temperatures. Additionally, it should be noted that this model is easy to be extended into a complex one with more decision variables involved.

To simplify the expression, the formulation of H_t in (12) can be transformed into an equation of the supply temperatures at load nodes and generation of sources at time t as follows.

$$H_t = f_2(\mathbf{T}^s_{d,t}, \mathbf{g}_t) \quad (13)$$

Seemingly, H_t is only related to the variables at time slot t, i.e.,$\mathbf{T}^s_{d,t}$ and $\mathbf{g}_t$, but when we consider the characteristic of $\mathbf{T}^s_{d,t}$ that has been given in (10), it is easy to find out that H_t essentially also relates to the generations and demands in the previous time slot.

6) THE STORAGE CAPACITY

The formulation of the thermal energy stored in pipe section p is showing below,

$$e_{p,t} = C_P M_p \overline{T_{p,t}} = C_P \rho A_p L_p \overline{T_{p,t}} \quad (14)$$

where M_p is the mass of hot water within the pipe section p, and $\overline{T_{p,t}}$ is the average temperature of the medium within pipe section p at time t.

For the entire DHN, when the cross-sectional area of all pipe sections equals to A, the total storage capacity at period t is

$$E_t = \frac{C_P \rho A}{2} \left[(\mathbf{Z}_d \times \mathbf{L})^{\dagger} \times \mathbf{T}^s_{d,t} + \left(\mathbf{Z}_g \times \mathbf{L} \right)^{\dagger} \times \mathbf{T}^s_{g,t} \right] + E^r, \quad (15)$$

where E^r is the storage capacity of the return network that can be previously calculated. $\mathbf{L}$ is the vector of the lengths of all pipe sections in the DHN. Meanwhile, the matrices $\mathbf{Z}_d$ and $\mathbf{Z}_g$ are respectively for demand nodes and source nodes, and their definitions are given by the following equation.

$$z_{np} = |y_{np}| \quad \forall n \in \mathcal{N},\ p \in \mathcal{P} \quad (16)$$

Apparently, the formula of the storage capacity of DHN has a strong physical meaning that the energy stored in DHN is limited by the size of pipelines and under the control of the medium temperature.

Similar as H_t in (13), the storage capacity of the entire DHN can also be described by supply temperatures of demand nodes and generations at time t.

$$E_t = f_3 \left(\mathbf{T}^s_{d,t}, \mathbf{g}_t \right) \quad (17)$$

Also, the storage capacity of DHN can be formulated as a function of the charging/discharging rate of DHN,

$$E_t = f_4 \left(H_t \right) \quad (18)$$

which is just the same as the characteristic of the general model of standard TES, and the ESL model of DHN is established.

IV. FORMULATION OF RIES

In the RIES, distributed generations (i.e., CHP units, wind turbines) coordinately meet multi-type demands within the district, while considering the flexibility supplied by the DHN. The operator of the RIES aims to seek the optimal dispatch of different generation units under the security and physical constraints.

A. OBJECTIVE FUNCTION

The objective of the RIES is meeting the load demands at the maximum social welfare of the whole system.

$$\text{maximize} \sum_{t \in T} U_t - C_t \quad (19)$$

The details of the objective function are

$$U_t = \pi^g_t \sum_{k \in B} g_{k,t} + \pi^w_t \sum_{k \in B} w_{k,t} + \pi^h_t \sum_{n \in \mathcal{N}} d^h_{n,t} \quad (20)$$

$$\begin{aligned} C_t = &\sum_{k \in B} a_k (g_{k,t} + C_V h_{k,t})^2 + b_k (g_{k,t} + C_V h_{k,t}) + c_k \\ &+ \sum_{n \in \mathcal{N}} \rho^{tes}_{n,t} (\xi_{ch,n,t} + \xi_{disch,n,t})^2 + \pi^b_t b_t \end{aligned} \quad (21)$$

where a_k, b_k and c_k are the cost coefficients, and C_V is the operation parameter of the CHP unit that is connected to the distribution bus k. π_t^g,π_t^w and π_t^b are the electricity prices of the power from CHPs, wind turbines, and utility grid, while π_t^h is the heat price of the scheduled head demand $d_{n,t}^h$, and $\rho_{n,t}^{tes}$ is the penalty factor of the TES connected to node n at time t.

B. CONSTRAINTS

1) CHP

$$g_{k,t} = f(h_{k,t}) \tag{22}$$
$$0 \leq h_{k,t} \leq h_{k,\max} \tag{23}$$
$$0 \leq g_{k,t} \leq g_{k,\max} \tag{24}$$

The feasible region of a CHP unit can be a convex polygon region described by constraints in (22)–(24) [26], where $h_{k,\max}$ and $g_{k,\max}$ are respectively the upper limits of the heat and power outputs of the CHP unit connected to bus k.

2) WIND TURBINES

$$(1-\delta)w_{k,\max,t} \leq w_{k,t} \leq (1+\delta)w_{k,\max,t} \tag{25}$$

In order to take into account the uncertainty of wind generation while guaranteeing the security and stability of the power system, the generation of a wind turbine should stand in a generation interval decided by the predicted values $w_{k,\max,t}$. The uncertainty factor δ equals to 5% in our cases, which means the lower and upper bound of the generation interval is, respectively, 95% and 105% of the prediction.

3) POWER BALANCE

$$b_t + \sum_{k\in B} g_{k,t} + w_{k,t} - d_{k,t} = 0 \tag{26}$$

In addition to the generations from CHPs and wind turbines within the RIES, the boundary power exchanged with the utility grid is another crucial factor in guaranteeing the real-time power balance.

4) DHN

The DHN can be represented by the ESL model as follows.

$$\mathrm{I}^T \mathbf{g}_t = \sum_{k\in B} h_{k,t} \tag{27}$$
$$\mathrm{I}^T \mathbf{d}_t = \sum_{n\in\mathcal{N}} d_{n,t}^h \tag{28}$$
$$\mathbf{T}_{d,t}^s = f_1(\mathbf{g}_t, \mathbf{d}_{t-1}, \mathbf{g}_{t-1}) \tag{29}$$
$$\underline{\mathbf{T}}_{d,t}^s \leq \mathbf{T}_{d,t}^s \leq \overline{\mathbf{T}}_{d,t}^s \tag{30}$$
$$H_t = f_2(\mathbf{T}_{d,t}^s, \mathbf{g}_t) \tag{31}$$
$$\underline{H}_t \leq H_t \leq \overline{H}_t \tag{32}$$
$$E_t = f_4(H_t) \tag{33}$$
$$\underline{E_t} \leq E_t \leq \overline{E_t} \tag{34}$$

As a unique characteristic of the hot water medium, the supply temperature of each node should not be lower than a threshold to make sure the load-serving quality or exceed an upper limit to prevent generating steam. Moreover, unlike a conventional TES device, the charging/discharging rates and the storage capacity of the DHN is directly decided by the nodes temperature, which is under the control of the heat production and consumption of the connected sources and demands. Therefore, the feasible region of the ESL model may be different in different cases.

5) THERMAL ENERGY STORAGE

$$\xi_{ch,n,t} \leq Q_t \times M \tag{35}$$
$$\xi_{disch,n,t} \leq (1-Q_t) \times M \tag{36}$$
$$S_{n,t} = S_{n,t-1} + \xi_{ch,n,t}\eta_{ch,n} - \xi_{disch,n,t}/\eta_{disch,n} \tag{37}$$
$$\underline{S_n} \leq S_{n,t} \leq \overline{S_n} \tag{38}$$

The small-scale TES installed at the demand sides are described by a solvable model, in which the big M method is applied in (35)–(36). Where M is defined as a big enough positive value and Q is a binary variable that guarantees TES not charge and discharge simultaneously.

6) HEAT BALANCE

$$\mathrm{I}^T \mathbf{g}_t - H_t - \mathrm{I}^T \mathbf{d}_t = 0 \tag{39}$$

Under the help of DHN, total heat generation and heat demand should be balanced at each time slot.

7) THE UNCERTAINTY OF HEAT DEMANDS

$$\Pr\left\{\xi_{ch,n,t} \geq d_{n,t}^h - \tilde{d}_{n,r,t}^h\right\} \geq \sigma_{ch} \tag{40}$$
$$\Pr\left\{\xi_{disch,n,t} \geq \tilde{d}_{n,r,t}^h - d_{n,t}^h\right\} \geq \sigma_{disch} \tag{41}$$

As the real heat demands are uncertain and difficult to precisely predict, it is much more economical to eliminate this kind of uncertainty by storage devices, such as small capacity TES near the loading side, rather than adjusting the scheduling of the whole DHN. Here a chance-constrained approach is applied to the constraints (40) and (41), in which,the uncertainty is described as the difference between the expected value of the predicted heat load $d_{n,t}^h$ and the random real heat demand $\tilde{d}_{n,r,t}^h$ of each node. The physical meaning of these equations is that the probabilities of the small-scale TES can adequately handle the heat demand uncertainty should satisfy the confidence level $\sigma_{ch}/\sigma_{disch}$.

It should be noted that managing the uncertainty by such approach can ensure the feasibility and security of the system operation in most cases. More importantly, under some specially designed probability distribution, such chance-constraints can have closed forms and the complex stochastic problem can be convert into a simpler deterministic model with less computational burden. The versatile probability distribution (VPD) is such a probability distribution that can realize such conversion. VPD has been proved that it can better represent the distribution probability of the random wind power output [24], so it can also be applied to giving a more accurate probability distribution of the random real heat demand. That is because the basic idea of VPD is adjusting the shape parameters depend on data. Which means, with the data over a specific time-scale, the adjustable shape parameters for the random heat demands can be uniquely determined.

The CDF of the VPD can be expressed as [24],

$$F(x) = \left(1 + e^{-\alpha(x-\gamma)}\right)^{-\beta} \tag{42}$$

where $\alpha > 0$, $\beta > 0$ and γ are shape parameters. Such parameters are uniquely decided by the forecast and historical data. More details are shown in Table 1.

In this case, the standardized forecast of heat demands varied from 0.5 to 0.8 per unit (p.u.)of maximum load. Then the shape parameters ofVPD for the random heat demand, are obtained from the 1-hour-ahead forecast based on the CDF curve fitting approach, the look-up table of shape parameters is shown below.

TABLE 1. The look-up table of shape parameters.

Forecast span (p.u.)	α	β	γ
[0.5,0.6]	76.081	0.354	0.533
[0.6,0.7]	66.364	0.623	0.635
[0.7,0.8]	34.211	1.063	0.752

The inverse function of CDF is a function of the confidence level σ as follows.

$$F^{-1}(\sigma) = \begin{cases} \gamma - \frac{1}{\alpha}\ln(\sigma^{-1/\beta} - 1) & 0 < \sigma < 1 \\ -\infty/+\infty & \sigma = 0,\ \sigma = 1 \end{cases} \tag{43}$$

Based on the characteristics of VPD, the chance-constrained equations in (40) and (41) can be simplified to the following linear constraints,

$$d^h_{n,t} - \xi_{ch,n,t} \le F^{-1}(1 - \sigma_{ch}) \tag{44}$$

$$d^h_{n,t} + \xi_{disch,n,t} \ge F^{-1}(\sigma_{disch}) \tag{45}$$

where $F^{-1}(\cdot)$ is the inverse function of CDF for the real heat demand of node n. In this way, the stochastic problem with random variables can be converted into a deterministic problem. Therefore, in our cases, the VPD can apparently enhance the computation efficiency. Although this paper only demands, other types of uncertainties, such as which of RES, can also be modeled similarly.

Taking all the aforementioned formulations into account, such a RIES model is a MILP problem and can be solved by MATLAB or the sophisticated optimization software Cplex.

V. CASE STUDY

In this section, study cases with the practical operational parameters of generators and DHN are presented to demonstrate the effectiveness of the proposed RIES model.

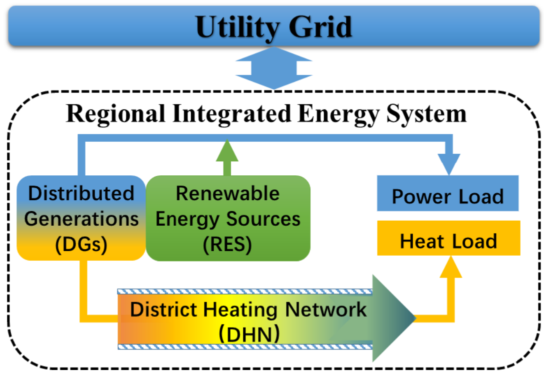

FIGURE 1. The regional integrated energy system model.

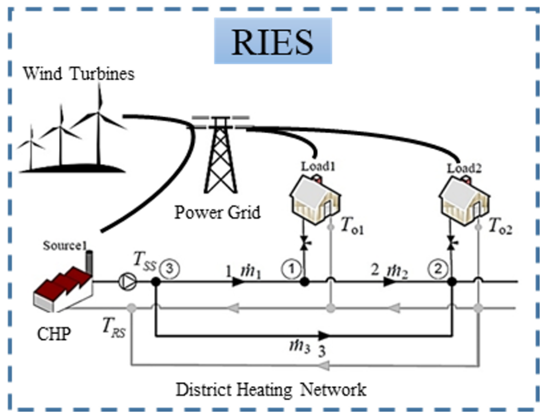

FIGURE 2. The topology of RIES.

A. SIMULATION PARAMETERS OF RIES

In this paper, DHN consists of supply and return networks with the medium in the form of hot water [27]. As quality regulation is applied, the mass flow rates and the return temperatures at each node, as well as the ambient temperature T_a and the outlet temperatures T_o of demand nodes can be set to the measurements [27]. All these parameters can be easily collected in a practical DHN system. Additionally, the real predicted values of wind power generation $w_{k,\max,t}$ are from [29], [30].

B. SIMPLE CASE

In the simple case, the RIES containing a 4-node DHN has been used to illustrate the preference of the proposed ESL model. Meanwhile, a CHP unit and wind turbines are also considered in the RIES model shown in figure.2.

To give a more direct understanding of the charging or discharging rates of the DHN, the simulation results of which is shown in figure.3. What can be noticed from the figure below is that the two curves have similar trends, which just coincides with the modeling in Section III. Said differently, the charging/ discharging rate of a pipe section depends on the temperature difference between the two ends of it. Moreover, in the practical operation, the node temperatures can be easily collected in the real DHN by a large number of existed sensors. Therefore, the charging/discharging rate of the entire

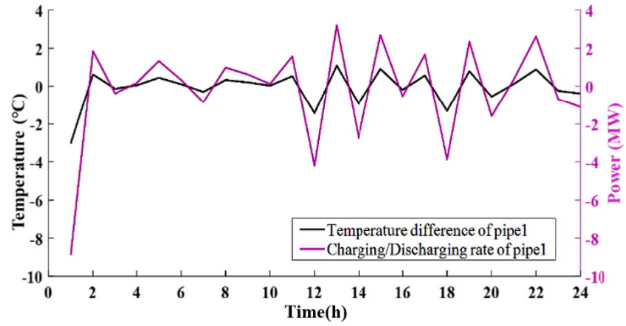

FIGURE 3. The relationship between the temperature and charging/discharging rate of pipe 1.

DHN is relatively easy to calculate and under the control of dispatchable sources.

Moreover, with the help of DHN,the performance of RIES can be improved. The comparison of the heat generation of sources and the heat demands is shown below.

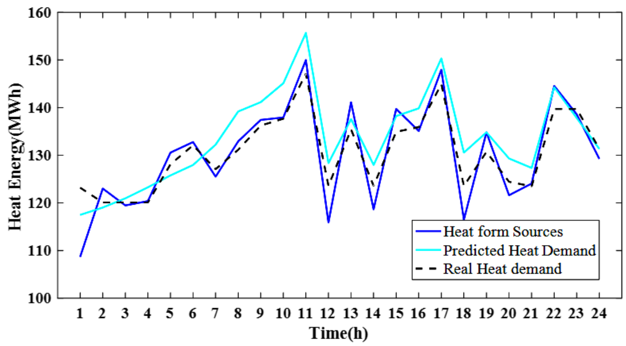

FIGURE 4. Difference between heat generations and demands.

The results in Figure.4 illustrate that in the proposed RIES model, the heat source has got more flexibility, so that it does not need to precisely follow the predicted or actual heat demands, though in most cases, they still have similar trends. This finding also indicates that after considering the storage capacity of the DHN through the proposed ESL model, the strong restriction placed by the heat demands on the generation can be alleviated, even under the uncertainty caused by customers.

C. REAL CASE

The 24-hour integrated economic dispatch for the RIES has been performed based on a real DHN in figure. 5 consists of 33 nodes and 33 pipes, wherein three CHP units work as the heat sources that are connected to node 1, 32 and 33. More details can refer to [27]. According to the actual TOU price mentioned in [31], the valley period of load is from 23:00 to 07:00 with the price of 48.3 \$/MWh, and the price for peak load that appears during 10:00–15:00and 18:00–21:00 is set to 180.6 \$/MWh. Besides, the remaining periods with flat load are under the electricity price of 112.5 \$/MWh.

The results in Table 2 show that when considering the thermal storage capacity of DHN, the total profit of the RIES has been increased, and the majority of the aforementioned increment is from the improvement of the CHP units' profits.

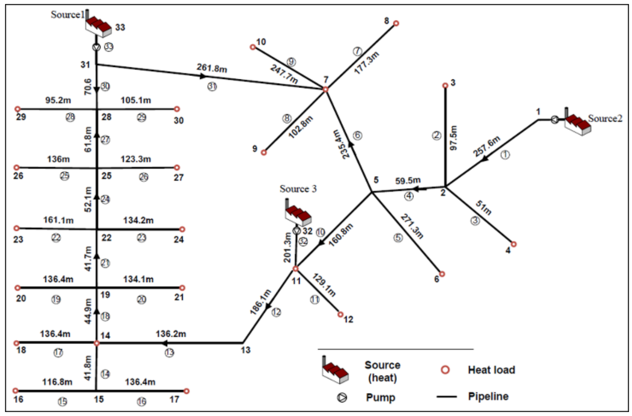

FIGURE 5. The topology of the DHN in Barry Island [27].

Such facts make the proposed RIES with ESL model be attractive to heat sources or cogeneration energy plants, (e.g., CHP units) and motivate them to join the integrated dispatch. More than that, this case also proved that the proposed model can effectively reduce the wind power curtailment with a negligible investment of DHN. Taken together, the RIES with ESL model have strong potential benefit and can be conveniently used for the practical application.

TABLE 2. The impact of DHN.

Items	Without DHN	With DHN	Difference
Profit of CHP(USD)	424398.8	402810.8	21588.0
Profit of RIES(USD)	552481.6	530558.9	21922.7
Wind curtailment(MWh)	189.8	164.2	-25.6

VI. CONCLUSION

In this paper, an ESL model of DHN is proposed to present the thermal storage capacity of DHN. The simulation results show that with the proposed ESL model, the overall economic efficiency of the RIES model has been effectively enhanced, meanwhile, wind power curtailment can be significantly reduced. The outstanding advantages of the ESL model are that it not only can reduce the complexity of modeling based on the collectable parameters during the practical operation, but also can be described by two state variables (charging/discharging rate and storage capacity), which is just like the commonly used storage devices. Therefore, the proposed model can help system operators in optimal power flow calculation for RIESs and has good prospect in engineering applications.

Several interesting and relevant fields are open for future research. For example, to improve the measurement accuracy of the thermal storage capacity of DHN and promote its utilization, except the uncertainty of wind power and load demands that have already been considered in the proposed RIES model, other types of uncertainties in the operation processes are also worth further study. Another important field of research is the compensation mechanism for stimulating conventional generators to supply ancillary service in the RIES, which can make the proposed RIES model be more applicable under the energy market background.

REFERENCES

[1] B. Rezaie and M. A. Rosen, "District heating and cooling: Review of technology and potential enhancements," *Appl. Energy*, vol. 93, pp. 2–10, May 2012.

[2] J. Yu, X. Shen, T. Sheng, H. Sun, W. Xiong, and L. Tang, "Wind-CHP generation aggregation with storage capability of district heating network," in *Proc. IEEE Conf. (EI2)*, Beijing, China, Nov. 2017, pp. 1–6.

[3] J. Yu, H. Sun, and X. Shen, "Optimal operating strategy of integrated power system with wind farm CHP unit and heat storage device," *Electr. Power Automat. Equip.*, vol. 37, no. 6, pp. 139–145, 2017.

[4] D. Haeseldonckx, L. Peeters, L. Helsen, and W. D'haeseleer, "The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO_2 emissions," *Renew. Sustain. Energy Rev.*, vol. 11, no. 6, pp. 1227–1243, Aug. 2007.

[5] D. Lindenberger, T. Bruckner, H.-M. Groscurth, and R. Kümmel, "Optimization of solar district heating systems: Seasonal storage, heat pumps, and cogeneration," *Energy*, vol. 25, no. 7, pp. 591–608, Jul. 2000.

[6] A. P. Prato, F. Strobino, M. Broccardo, and L. P. Giusino, "Integrated management of cogeneration plants and district heating networks," *Appl. Energy*, vol. 97, no. 3, pp. 590–600, Sep. 2012.

[7] J. V. C. Vargas, J. C. Ordonez, E. Dilay, and J. A. R. Parise, "Modeling, simulation and optimization of a solar collector driven water heating and absorption cooling plant," *Sol. Energy*, vol. 83, no. 8, pp. 1232–1244, Aug. 2009.

[8] S. I. Gustafsson and B. G. Karlsson, "Heat accumulators in CHP networks," *Energy Convers. Manag.*, vol. 33, no. 12, pp. 1051–1061, Dec. 1992.

[9] H. F. Ravn and J. M. Rygaard, "Optimal scheduling of coproduction with a storage," *Eng. Optim.*, vol. 22, no. 4, pp. 267–281, May 1994.

[10] U. Persson and S. Werner, "Heat distribution and the future competitiveness of district heating," *Appl. Energy*, vol. 88, no. 3, pp. 568–576, Mar. 2011.

[11] P. E. Grohnheit and B. O. G. Mortensen, "Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies," *Energy Policy*, vol. 31, no. 9, pp. 817–826, Jul. 2003.

[12] K. Difs and L. Trygg, "Pricing district heating by marginal cost," *Energy Policy*, vol. 37, no. 2, pp. 606–616, Feb. 2009.

[13] Z. Li, W. Wu, M. Shahidehpour, J. Wang, and B. Zhang, "Combined heat and power dispatch considering pipeline energy storage of district heating network," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 12–22, Jan. 2016.

[14] N. Yildirim, M. Toksoy, and G. Gokcen, "Piping network design of geothermal district heating systems: Case study for a university campus," *Energy*, vol. 35, no. 8, pp. 3256–3262, Aug. 2010.

[15] B. Awad, M. Chaudry, J. Wu, and N. Jenkins, "Integrated optimal power flow for electric power and heat in a MicroGrid," in *Proc. CIRED IET*, 2009, pp. 1–4.

[16] X. S. Jiang, Z. X. Jing, Y. Z. Li, Q. H. Wu, and W. H. Tang, "Modelling and operation optimization of an integrated energy based direct district water-heating system," *Energy*, vol. 64, no. 1, pp. 375–388, Jan. 2014.

[17] Z. Pan, Q. Guo, and H. Sun, "Feasible region method based integrated heat and electricity dispatch considering building thermal inertia," *Appl. Energy*, vol. 192, pp. 395–407, Apr. 2017.

[18] P. Jie, Z. Tian, S. Yuan, and N. Zhu, "Modeling the dynamic characteristics of a district heating network," *Energy*, vol. 39, no. 1, pp. 126–134, Mar. 2012.

[19] K. Mařík, Z. Schindler, and P. Stluka, "Decision support tools for advanced energy management," *Energy*, vol. 33, no. 6, pp. 858–873, Jun. 2008.

[20] E. Dotzauer, "Simple model for prediction of loads in district-heating systems," *Appl. Energy*, vol. 73, pp. 277–284, Nov./Dec. 2002.

[21] M. B. Simonović, V. D. Nikolić, E. P. Petrović, and I. T. Ćirić, "Heat load prediction of small district heating system using artificial neural networks," *Thermal Sci.*, vol. 20, pp. 1355–1365, Nov. 2016.

[22] H. Gadd and S. Werner, "Daily heat load variations in Swedish district heating systems," *Appl. Energy*, vol. 106, no. 11, pp. 47–55, 2013.

[23] K. M. Powell, A. Sriprasad, W. J. Cole, and T. F. Edgar, "Heating, cooling, and electrical load forecasting for a large-scale district energy system," *Energy*, vol. 74, no. 5, pp. 877–885, Sep. 2014.

[24] Z.-S. Zhang, Y.-Z. Sun, D. W. Gao, J. Lin, and L. Cheng, "A versatile probability distribution model for wind power forecast errors and its application in economic dispatch," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3114–3125, Aug. 2013.

[25] J. Li, F. Liu, Z. Li, C. Shao, and X. Liu, "Grid-side flexibility of power systems in integrating large-scale renewable generations: A critical review on concepts, formulations and solution approaches," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 272–284, Oct. 2018.

[26] C. Lin, W. Wu, B. Zhang, and Y. Sun, "Decentralized solution for combined heat and power dispatch through benders decomposition," *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1361–1372, Oct. 2017.

[27] X. Liu, J. Wu, N. Jenkins, A. Bagdanavicius, "Combined analysis of electricity and heat networks," *Appl. Energy*, vol. 162, pp. 1238–1250, Jan. 2016.

[28] M. W. Zemansky and R. H. Dittman, "Heat and thermodynamics," *Amer. J. Phys.*, pp. 164–167, 1998.

[29] P. Pinson, "Wind energy: Forecasting challenges for its operational management," *Statist. Sci*, vol. 28, no. 4, pp. 564–585, Nov. 2013.

[30] W. A. Bukhsh, C. Zhang, and P. Pinson, "An integrated multiperiod OPF model with demand response and renewable generation uncertainty," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1495–1503, May 2016.

[31] Y. Cao *et al.*, "An optimized EV charging model considering TOU price and SOC curve," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 388–393, Mar. 2012.

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