IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 22, 2020, accepted May 1, 2020, date of publication May 7, 2020, date of current version May 28, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2993035

Optimally Coordinated Expansion Planning of Coupled Electricity, Heat and Natural Gas Infrastructure for Multi-Energy System

HONG FAN[1,2], (Member, IEEE), QIANQIAN YUAN[2], SHIWEI XIA[1], (Senior Member, IEEE), JIAYANG LU[2], AND ZUYI LI[3], (Senior Member, IEEE)

[1]State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China
[2]Department of Electrical Engineering, Shanghai University of Electric Power, Shanghai 200082, China
[3]Electrical and Computer Engineering Department, Illinois Institute of Technology, Chicago, IL 60616, USA

Corresponding author: Shiwei Xia (s.w.xia@ncepu.edu.cn)

This work was supported in part by the National Key Research and Development Program under Grant 2018YFB0905105, in part by the Jiangsu Basic Research Project under Grant BK20180284, in part by the Fundamental Research Funds for the Central Universities under Grant 2019MS007, and in part by the China National Study Foundation under Grant 201906735013.

ABSTRACT Gas generation and heat storage are playing a prominent role to multi-energy systems (MES), and coordinated planning of integrated electricity, heat and gas infrastructures can highly benefit MES. In this context, a coordinated planning model of MES is proposed to determine the optimal expansion of conventional generators, transmission lines, gas boilers, combined heat and power units, and gas pipelines. In the model, the one-off investment cost of MES devices in the planning phase plus the operation cost and energy not served cost in the operation phase are considered in the objective, while the energy supply reliability, coupled operational security of multiple energy carriers, as well as the electricity, gas, and heat demand balance are comprehensively taken into account as the constraints. Afterwards, the Benders Decomposition method is adopted to solve the proposed expansion planning model in a divide and conquer manner. Finally three case studies on a 14-bus MES are conducted to demonstrate the effectiveness of the proposed expansion planning model. Simulation results indicate that the total cost of the proposed model in case 3 is saved by 9% and 2.8% compared with the separately planning scheme in case 1 and the coordinated planning scheme without candidate gas pipelines in case 2. Therefore, the proposed coordinated expansion model is very effective for MES Infrastructure planning.

INDEX TERMS Multi-energy system, coordinated expansion planning, electricity system, gas system, heating system.

NOMENCLATURE

INDICES

t	Index for years
h	Index for load blocks
b	Index for network nodes
i	Index for conventional generators
l	Index for transmission lines
c	Index for combined heat and power (CHP) units
p	Index for gas pipelines
g	Index for gas boilers

SETS

EG	Set of existed generators
ETL	Set of existed transmission lines
EGB	Set of existed gas boilers
EGP	Set of existed gas pipelines
CG	Set of planing candidate generators
CTL	Set of planing candidate transmission lines
CGB	Set of planing candidate gas boilers
CGP	Set of planing candidate gas pipelines
CHP	Set of planing candidate CHP
$r(l)$	Receiving node of line l
$s(l)$	Sending node of line l

PARAMETERS

λ_t	Coefficient of present value in year t
τ	Investment discount rate
γ	Investment salvage factor

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Wang.

u_i	Investment price of generator i
u_l	Investment price of transmission line l
u_c	Investment price of CHP c
u_p	Investment price of gas pipeline p
u_g	Investment price of gas boiler g
o_i	Unit operation cost of generator i
o_l	Unit operation cost of transmission line l
o_c	Unit operation cost of CHP c
o_p	Unit operation cost of gas pipeline p
o_g	Unit operation cost of gas boiler g
$DT_{h,t}$	Time duration of load block h in year t
PLL	Price of load lost
T^{com}	Commissioning year of multi-energy device
El_t^{max},	Electricity peak load demand in year t
R_t	System spinning reserve requirement in year t
X_l	Reactance of transmission line l
M	A large positive constant
$EL_{b,h,t}$	Electricity demand of node b in block h, year t
$GL_{b,h,t}$	Gas load demand of node b in block h, year t
$HL_{b,h,t}$	Heating load demand of node b in block h, year t

VARIABLES

C_{inv}	Investment cost
C_{op}	Operation cost
ENS_t	Energy not served in year t
P_i^{max}	Installation capacity of generator i
P_l^{max}	Installation capacity of transmission line l
P_c^{max}	Installation capacity of CHP c
P_p^{max}	Installation capacity of gas pipelines p
P_g^{max}	Installation capacity of gas boilers g
$x_{i,t}$	Binary variable of the investment state of generator i in year t
$x_{l,t}$	Binary variable of the investment state of transmission lines l in year t
$x_{c,t}$	Binary variable of the investment state of CHP c in year t
$x_{p,t}$	Binary variable of the investment state of gas pipelines p in year t
$x_{g,t}$	Binary variable of the investment state of gas boilers g in year t
θ	Voltage angle of reference bus in power network
$P_{i,h,t}$	Power output of generator i for load block h, year t
$P_{c,h,t}$	Power output of CHP c for load block h, year t
$P_{l,h,t}$	Power flow of transmission line l for load block h,year t
$\Delta P_{b,h,t}$	Load not served at bus b for load block h, year t
$G_{gs,h,t}$	Gas production of node gs for load block h, year t
$G_{p,h,t}$	Gas flow in pipeline p for load block h, year t
f_{mn}	Natural gas flow from node m to n
ω	Nodal pressure of gas pipeline
$G_{c,h,t}$	Gas consumption of CHP c in load block h, year t
$G_{g,h,t}$	Gas consumption of gas boiler g for load block h, year t
$H_{c,h,t}$	Heat power produced by CHP c for load block h, year t
$H_{g,h,t}$	Heat power produced by gas boiler g for load block h, year t

I. INTRODUCTION

With increasing concerns about the energy crisis and environmental pollution issues, multi-energy system (MES) has aroused widespread attention for its capability of effectively accommodating renewable energy resources [1]–[3]. MES could convert wind and solar power, natural gas, geothermal energy, biomass resources etc. into various directly used energy forms such as cooling, heating, electricity through advanced energy conversion technology, and thus improves the economy and environmental friendliness of energy utilization [4]–[5].

At present, some achievements have been made in MES planning field. For example, based on an energy hub model, a MES expansion method was proposed to plan the combined heating and power (CHP) units, gas boilers (GBs) and other energy carriers in [6], [7]. In [8], the CHP units and natural gas distribution network are jointly optimized to ensure the maximization of electricity and heat supply for satisfying flexible customer need. In [9], the electricity distribution network and natural gas network were co-planned to optimize the site and size of micro-gas turbine, resulting in a reduced total investment cost for the integrated system. Authors of [10] proposed an optimal planning model for the interconnected energy centers and multiple energy infrastructures. A long-term, multi-region and multi-stage planning model was also established in [11] to analyze the economy of electricity-gas hybrid networks. The author mainly focused on traditional coal-fired and gas-fired generation units, but the CHP units were not considered. A distributed energy system of combined cooling, heating and power (CCHP) units, photovoltaic and heat pumps was established in [12], [13], and optimization results indicated that CCHP integrated with solar energy has advantages over the single CCHP in terms of both energy saving and CO2 emission reductions. Authors of [14] proposed a multi-stage flexible planning model of integrated electricity-gas system to maximize the social well-being for increased load demands. An energy hub based optimal planning framework was put forward in [15] to optimize the sizing of CCHPs, boilers, electricity and heat storage for an interconnected electricity and natural gas network. A robust scheduling model with consideration of $N-1$ contingencies was presented in [16] for co-expanding power transmission lines and natural gas pipelines, and the case studies demonstrated the presented model was quite robust against wind power uncertainty. However, the authors mainly discussed the optimal operation of MES without taking the planning problem into consideration. Shao *et al.* [17] established a two-level scheduling model for a heat-electricity integrated system considering electric and thermal load demand response, and revealed that the integrated system could flexibly fulfill customers' energy consumption. In [18], [19], the reliability and security constraints are considered in the gas-electricity coupled planning model, and the solutions have ensured the desired power system reliability requirement. The optimal design and operation of distributed energy systems and heating network layouts is investigated in [20], and afterward a mixed integer linear programming model is established to minimize total cost and carbon emissions. In [21] the expansion of power substations, CCHP, GBs and air conditioning equipment are conducted in an active distribution network, and the influence of extreme load scenario on power supply reliability is analyzed. Yu *et al.* [22] considered the regional geographical resource endowment and put forward the optimal scheme to coordinate energy suppliers and demands in a micro integrated energy system. In [23], a demand response scheme was tailored to coordinate the power to gas devices, heat pumps, storage and flexible loads, subsequently the optimal dispatch solution with considering interactions among multiple energy carriers was achieved. In [24], based on a two-stage stochastic optimization model, Dr. Yang *et al.* evaluated the effect of uncertain load demands, energy prices and renewable energy intensity on system planning cost. In [25], a mixed integer linear programming model was proposed to optimally design a combined heat and electricity generation system by small-size CHPs, and thereby the benefits of energy saving and CO2 emission reduction were achieved. In [26] various operation schemes are compared and verified that the mutual network coordination and power co-generation have the highest economic and environmental benefits.

To sum up, the references mentioned above have established various models for MES planning and indeed enriched the MES planning theory. However, none of them has addressed the coupling of electricity, gas and heat networks simultaneously with the energy supply reliability requirement. To fill this research gap, a coordinated MES expansion planning model is proposed as a mixed integer linear programming (MILP) problem in this paper. The coupling of electricity-gas-heat networks and energy reliability etc. are taken into account as operation constraint, while device investment cost, MES operation cost and energy not served cost are considered in the objective. Afterwards, Benders decomposition algorithm is adopted to solve the proposed high-dimensional MILP problem. Finally case studies are conducted on a hybrid 14-node MES with extensive discussions to check performance of the proposed model.

The main contributions of this paper are threefold.

1) A long-term coordinated planning model is proposed to determine the optimal expansion plans of generation units, transmission lines, gas boilers, combined heat and power units, and gas pipelines for MES. In the model, the one-off investment cost of MES devices, the operation cost and energy not served cost are considered in the objective, while the energy reliability requirement, the coupled operation constraints among multiple energy carriers, the demand balances of electricity, gas, and heat are taken into account as constraints.
2) Benders decomposition algorithm is tailored to decompose the proposed high-dimension model into a master problem for optimizing investment cost and sub-problems for optimizing operation related costs, and thereby the optimal MES expansion solution is effectively obtained.
3) Simulation results and comparisons have validated the benefits of the proposed coordinated expansion planning model, which can enhance the economic and reliability of a coupled electricity, heat and natural gas system.

The rest of this paper is organized as follows. The MES architecture and its general mathematical formula are introduced in section II. Section III presents the coordinated expansion planning model, and numerical case studies are conducted in Section IV with the conclusion provided in the last Section.

II. GENERAL FORMULATION OF MULTI-ENERGY SYSTEM

MES can effectively improve energy efficiency and is the main supplier in next-era energy paradigm, which is the key transformation medium coupling different energy flow through energy conversion devices. For example the most commonly used CHP and gas boiler (GB) are sources in electricity and heat network but consumers in the natural gas system. Fig. 1 shows the typical structure of a MES.

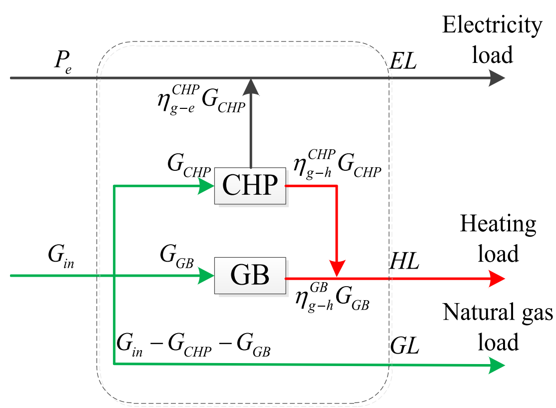

FIGURE 1. Paradigm of MES with a CHP and GB.

According to Fig.1, the input P and output L are connected via energy conversion coefficients by Eqs. (1)-(3).

$$EL = P_e + \eta_{g-e}^{CHP} G_{CHP} \tag{1}$$

$$HL = \eta_{g-h}^{CHP} G_{CHP} + \eta_{g-h}^{GB} G_{GB} \tag{2}$$

$$GL = G_{in} - G_{CHP} - G_{GB} \tag{3}$$

where η_{g-e}^{CHP} and η_{g-h}^{CHP} are the gas-to-electricity and gas-to-heat conversion coefficients of CHPs, and η_{g-h}^{GB} is the gas-to-heat coefficient of GBs.

III. PROPOSED MULTI-ENERGY SYSTEM PLANNING MODEL

This section presents the mathematical formulation of the coordinated expansion planning model, which considers the investment and operation costs as well as the coupled operation constraints of electricity, gas and heat system. For proposed long term planning model, the electricity load demand during each year is represented by a total number of h blocks with different load levels as shown Fig.2. The block h is with a load consumption level $\mathrm{EL}_{b,h,t}$ and time duration $\mathrm{DT}_{h,t}$, which means that the h^{th} load level (in MW) will last $\mathrm{DT}_{h,t}$ hours at bus b in year t, and it will be used to maintain the power balance in Eq. (III-C.1). Similarly, the gas and heat load demand during each planning year is also represented by a total number of h blocks with h load levels.

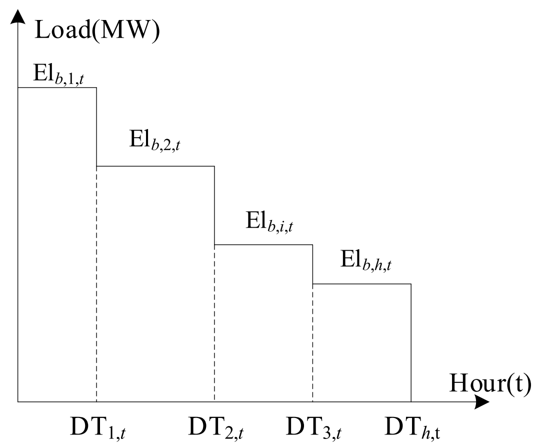

FIGURE 2. Load demand of node *b* in year t.

A. OBJECTIVE FUNCTION

The objective of the proposed coordinated expansion planning model is to minimize MES total cost during the 10-year planning horizon in (4), and the coefficient of present value λ_t is calculated as $\lambda_t = 1/(1+\tau)^{t-1}$. Eq. (5) represents the investment cost of generators, transmission lines, CHP, and GBs respectively. Eq. (6) represents the operation costs of generators, CHP, and GBs. The cost of Energy Not Served (ENS) is calculated by multiplying the amount of ENS with the price of lost load (PLL) as in (7).

$$\min F = \sum_{t=1}^{T} \lambda_t \left[(1-\gamma \frac{\lambda_T}{\lambda_t}) C_{inv}(t) + C_{op}(t) + C_{eens}(t) \right] \tag{4}$$

$$\begin{aligned} C_{inv}(t) = & \sum_{i \in \mathrm{CG}} u_i P_i^{\max}(x_{i,t} - x_{i,t-1}) \\ & + \sum_{l \in \mathrm{CTL}} u_l P_l^{\max}(x_{l,t} - x_{l,t-1}) \\ & + \sum_{c \in \mathrm{CCHP}} u_c P_c^{\max}(x_{c,t} - x_{c,t-1}) \\ & + \sum_{p \in \mathrm{CGP}} u_p P_p^{\max}(x_{p,t} - x_{p,t-1}) \\ & + \sum_{g \in \mathrm{CGB}} u_g P_g^{\max}(x_{g,t} - x_{g,t-1}) \end{aligned} \tag{5}$$

$$\begin{aligned} C_{op}(t) = & \sum_h DT_{h,t} (\sum_{i \in \mathrm{EG}} o_i P_{i,h,t} + \sum_{i \in \mathrm{CG}} o_i P_{i,h,t} \\ & + \sum_{c \in \mathrm{CCHP}} o_c P_{c,h,t} + \sum_{g \in \mathrm{EGB}} o_g H_{g,h,t} \\ & + \sum_{g \in \mathrm{CGB}} o_g H_{g,h,t}) \end{aligned} \tag{6}$$

$$C_{eens}(t) = PLL \times ENS_t \tag{7}$$

B. INVESTMENT CONSTRAINTS

The coordinated expansion planning model considers investment constraints of generators, transmission lines, CHPs, gas boilers, and gas pipelines. Once a candidate device is installed, its investment state is fixed to 1 for the remaining years (8)-(12). Besides, commissioning time is imposed on a newly installed MES device by (13)-(17). Constraint (18) ensures that the total power generation capacity meets the predicted electricity load demand and reserve requirement.

$$x_{i,t-1} \le x_{i,t} \quad \forall i \in \mathrm{CG} \tag{8}$$
$$x_{l,t-1} \le x_{l,t} \quad \forall l \in \mathrm{CTL} \tag{9}$$
$$x_{c,t-1} \le x_{c,t} \quad \forall c \in \mathrm{CHP} \tag{10}$$
$$x_{p,t-1} \le x_{p,t} \quad \forall p \in \mathrm{CGP} \tag{11}$$
$$x_{g,t-1} \le x_{g,t} \quad \forall g \in \mathrm{CGB} \tag{12}$$
$$x_{i,t} = 0 \quad \forall i \in \mathrm{CG},\ \forall t < T_i^{com} \tag{13}$$
$$x_{l,t} = 0 \quad \forall l \in \mathrm{CTL},\ \forall t < T_l^{com} \tag{14}$$
$$x_{c,t} = 0 \quad \forall c \in \mathrm{CHP},\ \forall t < T_c^{com} \tag{15}$$
$$x_{p,t} = 0 \quad \forall p \in \mathrm{CGP},\ \forall t < T_p^{com} \tag{16}$$
$$x_{g,t} = 0 \quad \forall g \in \mathrm{CGB},\ \forall t < T_g^{com} \tag{17}$$

$$\begin{aligned} \sum_{i \in EG} P_i^{\max} + \sum_{i \in CG} P_i^{\max} x_{i,t} + \sum_{c \in CHP} P_c^{\max} x_{c,t} \\ \ge EL_t^{\max} + R_t \forall t \end{aligned} \tag{18}$$

C. OPERATION CONSTRAINTS

The proposed planning model takes into account the coupled operation constraints of electricity, gas and heat networks as follows.

1) ELECTRICITY NETWORK RELATED CONSTRAINTS

Electricity network related constraints are setting for the operation conditions of generators, transmission lines, and buses. Eq. (III-C.1) represents power balance of node b for load level h in year t. Eqs. (20)-(III-C.1) enforce the power flow limits of adding the candidate line on existed transmission lines based on DC power flow calculation, and Eqs. (III-C.1)-(23) are the power flow limits of adding the candidate line as a completed new transmission branch. Constraint (24) is the reference bus voltage angle. Eqs. (25)-(26) enforce capacity limits for existed and candidate generators.

$$\sum_{i\in b} P_{i,h,t} + \sum_{c\in b} P_{c,h,t} + \sum_{r(l)\in b} P_{l,h,t} - \sum_{s(l)\in b} P_{l,h,t} + \Delta P_{b,h,t} = EL_{b,h,t} \tag{19}$$

$$P_{l,h,t} = \frac{\theta_{m,h,t} - \theta_{n,h,t}}{X_l}(1+x_{l,t}) \quad \forall l \in \text{ETL},\ \forall h,\ \forall t \tag{20}$$

$$\left|P_{l,h,t}\right| \le (1 + x_{l,t})P_{l,\max} \quad \forall l \in \text{ETL},\ \forall h,\ \forall t \tag{21}$$

$$\left|P_{l,h,t} - \frac{\theta_{m,h,t} - \theta_{n,h,t}}{X_l}\right| \le M(1 - x_{l,t}) \quad \forall l \in \text{CTL},\ \forall h,\ \forall t \tag{22}$$

$$\left|P_{l,h,t}\right| \le x_{l,t}P_l^{\max} \quad \forall l \in \text{CTL},\ \forall h,\ \forall t \tag{23}$$

$$\theta_{ref} = 0 \tag{24}$$

$$0 \le P_{i,h,t} \le (1 + x_{i,t})P_i^{\max} \quad \forall i \in \text{EG} \tag{25}$$

$$0 \le P_{i,h,t} \le x_{i,t}P_i^{\max} \quad \forall i \in \text{CG} \tag{26}$$

2) GAS NETWORK RELATED CONSTRAINTS

The natural gas flow through a pipeline with nodes m and n is stated as a quadratic term of terminal pressure of both ends by (27)-(28), where the sgn(*) indicates the gas flow direction. When the pressure of node m is larger than n, the gas flows from m to n, otherwise from n to m. Similar to bus voltage limits in power transmission network, the natural gas network has to maintain the nodal pressure within an appropriate range by (29). Gas flow balance constraint (30) describes that the total gas flow injection is equal to the total gas outflow at each node. The gas flow capacity of a pipeline is restricted by (31).

$$G_{p,h,t} = f_{mn} = sgn(\omega_m, \omega_n)C_{mn}\sqrt{\left|\omega_m^2 - \omega_n^2\right|} \tag{27}$$

$$sgn(\omega_m, \omega_n) = \begin{cases} 1 & \omega_m \ge \omega_n \\ -1 & \omega_m > \omega_n \end{cases} \tag{28}$$

$$\omega_{\min} \le \omega \le \omega_{\max} \tag{29}$$

$$\sum_{gs\in b} G_{gs,h,t} + \sum_{r(p)\in b} G_{p,h,t} - \sum_{s(p)\in b} G_{p,h,t} - \sum_{c\in b} G_{c,h,t} - \sum_{g\in b} G_{g,h,t} = GL_{b,h,t} \tag{30}$$

$$\left|G_{p,h,t}\right| \le G_p^{\max} x_{p,t} \tag{31}$$

3) HEAT NETWORK RELATED CONSTRAINTS

Heat balance Eq. (32) indicates that the total heat produced is equal to the total outflow at each node.

$$\sum_{c\in b} H_{c,h,t} + \sum_{g\in b} H_{g,h,t} = HL_{b,h,t} \tag{32}$$

4) COUPLED OPERATION CONSTRAINTS OF ELECTRICITY HEAT AND GAS NETWORK

Coupled operation constraints of electricity, heat and gas network are mainly dependent on the energy conversion process. CHP electricity and heat power output are presented in Eqs. (33)-(34) and limited by Eqs. (35)-(36). The heat power provided by GB is shown in Eq. (37) and constrained by Eqs. (38)-(39).

$$P_{c,h,t} = \eta_{g-e}^{CHP} G_{c,h,t} \quad \forall c \in \text{CHP} \tag{33}$$

$$H_{c,h,t} = \eta_{g-h}^{CHP} G_{c,h,t} \quad \forall c \in \text{CHP} \tag{34}$$

$$0 \le P_{c,h,t} \le x_{c,t}P_c^{\max} \quad \forall c \in \text{CHP} \tag{35}$$

$$0 \le H_{c,h,t} \le x_{c,t}H_c^{\max} \quad \forall c \in \text{CHP} \tag{36}$$

$$H_{g,h,t} = \eta_{g-h}^{GB} G_{g,h,t} \quad \forall g \in \text{EGB} \cup \text{CGB} \tag{37}$$

$$0 \le H_{g,h,t} \le H_{g,\max} \quad \forall g \in \text{EGB} \tag{38}$$

$$0 \le H_{g,h,t} \le x_{g,t}H_{g,\max} \quad \forall g \in \text{CGB} \tag{39}$$

5) RELIABILITY CONSTRAINTS

The ENS calculated in (40) is adopted to measure the amount of electricity not served during each year, and the corresponding system reliability is constrained by (41).

$$ENS_t = \sum_h DT_{h,t} \sum_b \Delta P_{b,h,t} \tag{40}$$

$$ENS_t \le ENS_t^{\max} \quad \forall t \tag{41}$$

IV. SOLUTION METHODS

The proposed optimization model (4)-(41) is a mixed integer linear programming (MILP) problem with a large number of coupling variables. In this paper, the Benders decomposition is adopted to solve the MILP. General steps of using Benders Decomposition method for solving this problem are demonstrated in Fig. 3.

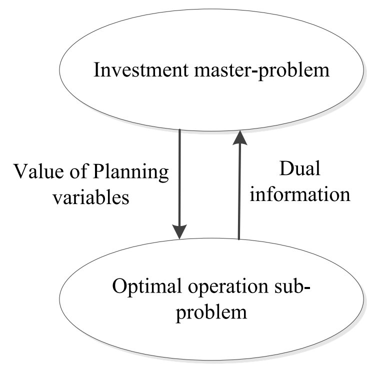

FIGURE 3. Benders decomposition general step for solve MES model.

By using the Benders decomposition method, the proposed MILP model can be decomposed into an investment planning master problem and an optimal operation sub-problem. The master problem sends the solved planning variables to the sub-problem, while sub-problem feedback the dual variables to master problem for generating Benders cut, and these two procedures execute iteratively until reach the convergence criterion.

For the proposed MES model, the master problem comprises the objective (42)-(43) and constraints (8)-(18).

$$\min \alpha \tag{42}$$

$$\begin{aligned}\alpha \geq & \sum_{t=1}^{T} \lambda_t \left(1-\gamma \frac{\lambda_T}{\lambda_t}\right) \\ & \times \left(\begin{array}{l} \sum_{i\in CG} u_i P_i^{\max}(x_{i,t}-x_{i,t-1}) \\ +\sum_{l\in CL} u_l P_l^{\max}(x_{l,t}-x_{l,t-1}) \\ +\sum_{c\in CC} u_c P_c^{\max}(x_{c,t}-x_{c,t-1}) + \sum_{p\in CP} u_p P_p^{\max}(x_{p,t}-x_{p,t-1}) \\ +\sum_{g\in CGB} u_g P_g^{\max}(x_{g,t}-x_{g,t-1}) \end{array}\right) \\ & +\sum_{t=1}^{T} \lambda_t \sum_{h} DT_{h,t} \\ & \times \left(\begin{array}{l} \sum_{i\in EG} o_i P_{i,h,t}^{*} + \sum_{i\in CG} o_i P_{i,h,t}^{*} + \sum_{c\in CC} o_c P_{c,h,t}^{*} \\ +\sum_{g\in EGB} o_g H_{g,h,t}^{*} + \sum_{g\in CGB} o_g H_{g,h,t}^{*} \end{array}\right) \\ & +\sum_{t=1}^{T} \lambda_t PLL \times ENS_t^{*} \\ & +\sum_{t=1}^{T} \left[\begin{array}{l} u_t^{*}\left(\begin{array}{l} \sum_{i\in b} P_{i,h,t}^{*} + \sum_{c\in b} P_{c,h,t}^{*} + \sum_{r(l)\in b} P_{l,h,t}^{*} \\ -\sum_{s(l)\in b} P_{l,h,t}^{*} + \Delta P_{b,h,t}^{*} - P_{b,h,t} \end{array}\right) \\ +\upsilon_t^{*}\left(\begin{array}{l} \sum_{gs\in b} G_{gs,h,t}^{*} + \sum_{r(p)\in b} G_{p,h,t}^{*} - \sum_{s(p)\in b} G_{p,h,t}^{*} \\ -\sum_{c\in b} G_{c,h,t}^{*} - \sum_{g\in b} G_{g,h,t}^{*} - G_{b,h,t} \end{array}\right) \\ +\omega_t^{*}\left(\begin{array}{l} \sum_{c\in b} H_{c,h,t}^{*} + \sum_{g\in b} H_{g,h,t}^{*} + \sum_{r(hl)\in b} H_{hl,h,t}^{*} \\ -\sum_{s(hl)\in b} H_{hl,h,t}^{*} - H_{b,h,t} \end{array}\right) \end{array}\right] \end{aligned} \tag{43}$$

where $P_{i,h,t}^*$, $P_{c,h,t}^*$, $P_{l,h,t}^*$, $\Delta P_{b,h,t}^*$, $G_{gs,h,t}^*$, $G_{p,h,t}^*$, $G_{c,h,t}^*$, $G_{g,h,t}^*$, $H_{c,h,t}^*$, $H_{g,h,t}^*$, and $H_{hl,h,t}^*$ are the optimal solutions obtained from the sub-problem; u_t^*, υ_t^*, and ω_t^* are the corresponding Lagrange multipliers. The master problem is solved to obtain the upper bound (UB) of the original MILP model, i.e. the optimal value of α, and its optimal solution $x_{i,t}^*$, $x_{l,t}^*$, $x_{c,t}^*$, $x_{g,t}^*$, $x_{p,t}^*$ are transferred to the sub-problem.

The sub-problem comprises the objective (44)-(45) and the constraints (III-C.1)-(41).

$$\min \beta \tag{44}$$

$$\begin{aligned}\beta = & \sum_{t=1}^{T} \lambda_t \sum_{h} DT_{h,t} \\ & \times \left(\begin{array}{l} \sum_{i\in EG} o_i P_{i,h,t}^{*} + \sum_{i\in CG} o_i P_{i,h,t}^{*} + \sum_{c\in CC} o_c P_{c,h,t}^{*} \\ +\sum_{g\in EGB} o_g H_{g,h,t}^{*} + \sum_{g\in CGB} o_g H_{g,h,t}^{*} \end{array}\right) \\ & +\sum_{t=1}^{T} \lambda_t PLL \times ENS_t \end{aligned} \tag{45}$$

It should be noted that the variables $x_{i,t}$, $x_{l,t}$, $x_{c,t}$, $x_{g,t}$, $x_{p,t}$ in constraints (22-23), (26), (31), (35-36) and (39) should be replaced by the investment variables $x_{i,t}^*$, $x_{l,t}^*$, $x_{c,t}^*$, $x_{g,t}^*$, $x_{p,t}^*$ optimized from the master problem. By solving the sub-problem, the solutions $P_{i,h,t}^*$, $P_{c,h,t}^*$, $P_{l,h,t}^*$, $\Delta P_{b,h,t}^*$, $G_{gs,h,t}^*$, $G_{p,h,t}^*$, $G_{c,h,t}^*$, $G_{g,h,t}^*$, $H_{c,h,t}^*$, $H_{g,h,t}^*$, $H_{hl,h,t}^*$ and the corresponding Lagrange multipliers are return to the master problem for generating Benders cut (43), and the lower bound (LB), i.e. the optimal value of β of the original MILP model can be updated.

The master problem and sub-problem are solved iteratively until the termination condition is satisfied that the gap of master and sub-problem objective is smaller than a threshold, i.e. Benders decomposition is an exact algorithm for the MILP problem, and thus they could guarantees solution optimality for large-scale MILP model as discussed in [27]. The effectiveness of the same strategy has been verified in [18], [19] and will also be validated by the three case studies in Section V.

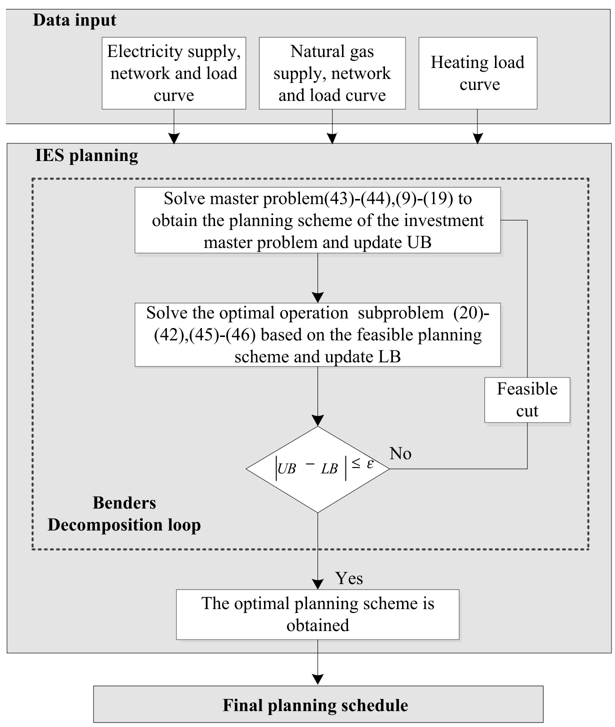

FIGURE 4. Flow chart of the Benders decomposition method.

With a flowchart shown in Fig. 4, the main steps of using Benders decomposition to solve the proposed model are described as follows.

Step 1: System initialization. Input system parameters including electricity supply and load, natural gas supply and load, heat load demand and network data.

Step 2: Solve the master problem (8)-(18) and (42)-(43), afterward update the *UB* of the original MILP model as well as transfer the solution $x^*_{i,t}$, $x^*_{l,t}$, $x^*_{c,t}$, $x^*_{g,t}$, $x^*_{p,t}$ to the sub-problem.

Step 3: Solve the sub-problem (III-C.1)-(41) and (44)-(45), and update the *LB* of the original MILP model.

Step 4: Stop Benders decomposition loop and go to Step 5 if the termination condition ($|UB - LB| \leq \varepsilon$) is satisfied; otherwise, add feasible cut to the master problem and go to Step 2.

Step 5: The optimal planning scheme is obtained.

V. CASE STUDIES

A. PARAMETER DESCRIPTION OF TEST SYSTEM

The proposed coordinated expansion planning model was validated by a MES network as showed in Fig. 5. The electricity network comprises 14 buses, 5 generators and 20 transmission lines, while 6 candidate generators and 10 candidate transmission lines are considered for expansion. Heat and natural gas systems are composed of 14 nodes, 4 GBs, 11 gas pipelines, and 3 natural gas suppliers. 3 candidate GBs and 4 candidate CHPs are considered to enhance the heat and natural gas system. Parameters of all the candidate generators, lines, GBs and CHPs are provided in Tables 1-5.

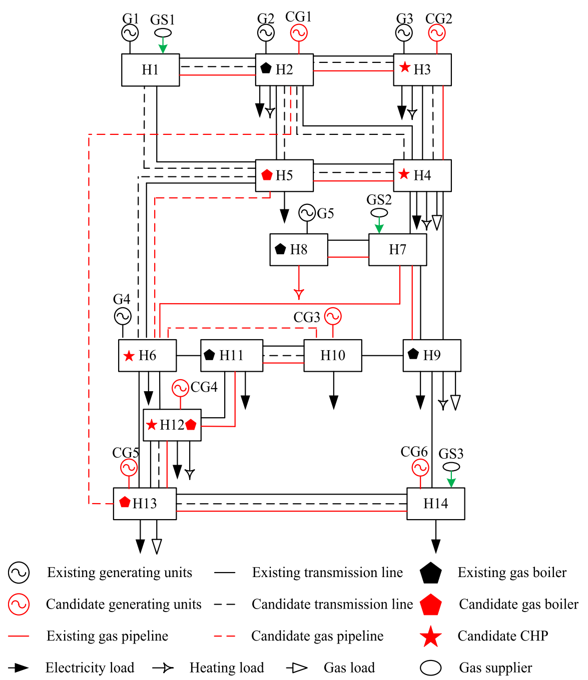

FIGURE 5. Topology of integrated energy network.

A 10-year planning horizon is applied for the following case studies, and each candidate device is considered for installing at the beginning of each year. The annual electricity load demand is divided into 3 load blocks to represent the base, medium, and peak load level according to Fig. 2. The electricity peak load of the first year is 178.8 MW with an average annual growth rate of 3% for the next 9 years. The spinning reserve requirement of electricity load is 5% [22]. The investment discount rate is 5% and the PLL is 10000\$/MWh [13]. The heat and gas peak loads are 120.3 MW and 88.5 MW with an annual growth rate of 2% and 5% respectively.

TABLE 1. Parameters of candidate generation units.

No	Bus	Capacity (MW)	Operation cost (10^3\$/MW)	Investment price (10^3\$/MW)	T^{com}_{CG} (*year*)
CG1	2	40	0.12	917	1
CG2	3	20	0.08	908	3
CG3	10	12	0.13	920	6
CG4	12	16	0.1	914	5
CG5	13	20	0.09	909	6
CG6	14	16	0.12	918	8

TABLE 2. Parameters of candidate transmission lines.

No	From	To	Capacity (MW)	Investment price (10^3\$/MW)	T^{com}_{CL} (*year*)
CTL1	1	2	15	82.5	5
CTL2	2	3	10	80	2
CTL3	2	4	15	83	4
CTL4	1	5	15	82.5	6
CTL5	2	5	15	82.5	5
CTL6	3	4	10	70	3
CTL7	4	5	10	60	2
CTL8	10	11	10	62	4
CTL9	12	13	10	100	5
CTL10	13	14	10	75	3

TABLE 3. Parameters of candidate gas boilers.

No	Node	Capacity (MW)	$\eta^{GB}_{g\text{-}h}$	Operation cost (10^3\$/MW)	Investment price (10^3\$/MW)	T^{com}_{CGB} (*year*)
CGB1	5	25	0.91	0.032	700	1
CGB2	12	21	0.91	0.034	600	3
CGB3	13	25	0.91	0.033	800	3

TABLE 4. Parameters of candidate CHPs.

No	CHP1	CHP2	CHP3	CHP4
Node	3	4	6	12
Capacity(MW)	32	24	24	30
$\eta^{CHP}_{g\text{-}e}$	0.31	0.31	0.3	0.33
$\eta^{CHP}_{g\text{-}h}$	0.46	0.45	0.47	0.44
Operation price (10^3\$/MW)	0.0865	0.0885	0.0895	0.0905
Investment price (10^3\$/MW)	600	600	600	600
Tcom CC	2	3	2	4

TABLE 5. Parameters of candidate gas pipelines.

No	From	To	Capacity (MW)	Investment cost (10^3\$/MW)	T^{com}_{gas} (*year*)
CGP1	2	13	15	340	3
CGP2	5	6	10	340	5
CGP3	6	10	15	340	6

B. SIMULATION RESULTS AND DISCUSSIONS

Three cases are tested and compared here to illustrate the effectiveness of the proposed model.

Case 1: the electricity, gas, and heat systems are planned separately. Electricity loads are supplied by generators, while heating loads are supplied by gas boilers.

Case 2: the coordinated expansion planning of coupled electricity, gas, and heat system is considered, but gas pipelines are not considered to be installed during the 10-year planning horizon [20].

Case 3: the coordinated expansion planning of coupled electricity, heat and natural gas systems is considered with a full set of candidate devices including generators, transmission lines, GBs, CHPs and gas pipelines.

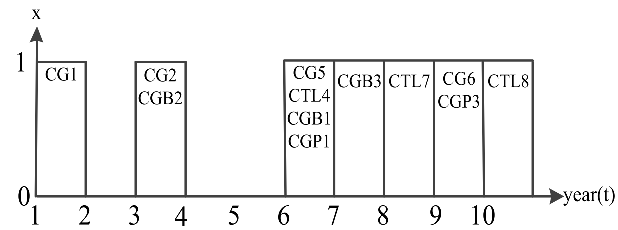

FIGURE 6. Planning results of case 1.

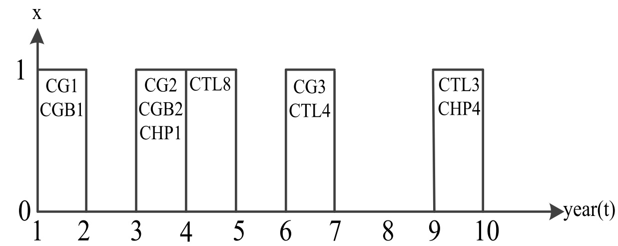

FIGURE 7. Planning results of case 2.

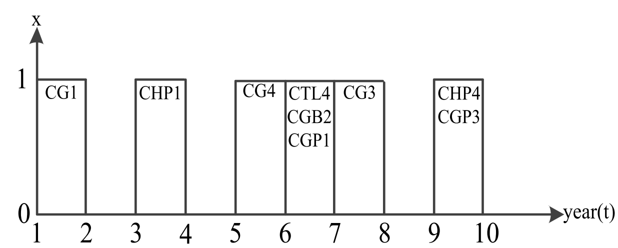

FIGURE 8. Planning results of case 3.

1) CASE 1

In this case, electricity, heat and gas systems are planned separately. As shown in Fig.6, four candidate generators including CG1, CG2, CG5 and CG6 are constructed at year 1, 3, 6, and 9 to meet the growing electricity load demand, and three transmission lines including CTL4, CTL7, CTL8 are built at year 6, 8, 10 respectively to enhance the electricity transferring capacity. It can be seen that the planed generators and transmission lines have a positive correlation with the growing electricity load demand. For the planning

TABLE 6. Planning results of different cases.

Case	Case1	Case2	Case3
CG	(CG1,1), (CG2,3), (CG5,6), (CG6,9)	(CG1,1), (CG2,3), (CG3,6)	(CG1,1), (CG4,5), (CG3,7)
CTL	(CTL4,6), (CTL7,8), (CTL8,10)	(CTL4,6), (CTL3,9), (CTL8,4)	(CL4,6)
CHP	/	(CHP1,3), (CHP4,9)	(CHP1,3), (CHP4,9)
CGB	(CGB2,3), (CGB1,6), (CGB3,7)	(CGB1,1), (CGB2,3)	(CGB2,6)
CGP	(CGP1,6), (CGP3,9)	/	(CGP1,6), (CGP3,9)

Note: (x, y) means the candidate device x installed at year y.

of heat and gas system, three gas boilers CGB2, CGB1 and CGB3 are developed at year 3, 6, 7, and two gas pipelines CGP1 and CGP3 are established at year 6 and 9 respectively. At the end of the planning horizon, a total of 3 transmission lines and 96 MW generators are installed at buses 2, 3 14 for the electricity network, while 3 gas boilers are installed at nodes 5, 12 and 13 for the natural gas-heating system. The total cost of decoupled planning of the electricity, gas, and heat system to supply the increasing load is 11.082×10^6\$ for 10 years.

2) CASE 2

In case 2, we consider a coupling plan of electricity, heat and natural gas systems without taking the gas pipeline expansion into account. Due to the coupling relationship between electricity, heating and gas system, two CHPs are planned to construct at year 3 and 9. With the CHPs installation, fewer generators are built compared with case 1, such as candidate generators CG1, CG2 and CG3 constructed in year 1, 3 and 6 respectively. With the expansion of CG1, CG2 for the growing electricity load demand, the transmission line CTL8 is built in year 4 and the other two transmission lines CTL4 and CTL3 are built in year 6 and 9 respectively to transmit more electricity power. In addition, since CHP can provide electricity and heat simultaneously, fewer gas boilers in terms of CGB1 and CGB2 are constructed at year 1 and 3 in case 2. At the end of the 10-year planning, 72 MW of new generators and three transmission lines are installed for the electricity network, while 46 MW of Gas boilers and two CHPs are constructed for the heat and gas network. The topology of the expanded network at the end of planning horizon is shown in Fig. 9.

In Table 7, though CHPs involved with 0.27×10^6\$ investment cost in case 2, the expanded CHPs reduce the operation cost by 0.707×10^6\$ compared with that in case 1. This is because the utilization of a high efficient CHP requires less fuel for producing the same amount of energy than that in case 1. In addition, the energy not served cost and total costs are reduced by 0.017×10^6\$ and 0.774×10^6\$ compared with case 1.

3) CASE 3

In this case, new gas pipelines are considered to be installed in the gas network. As shown in Table 6, candidate gas

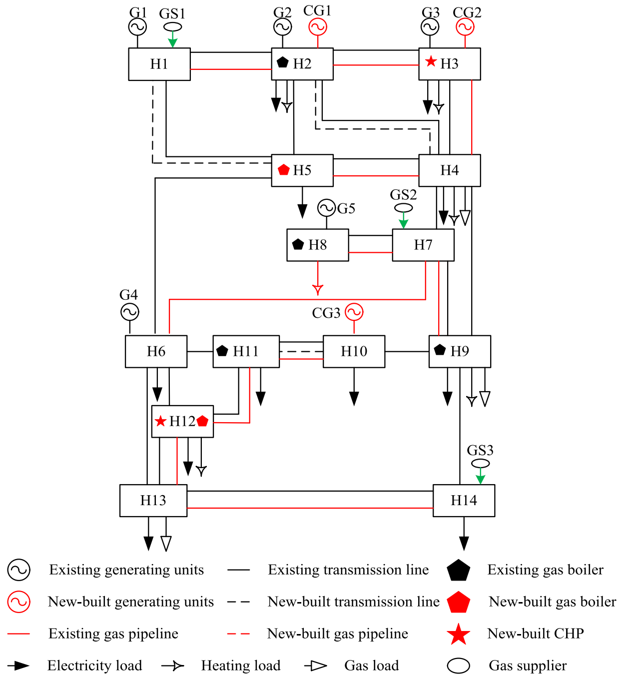

FIGURE 9. Planning results of case 2.

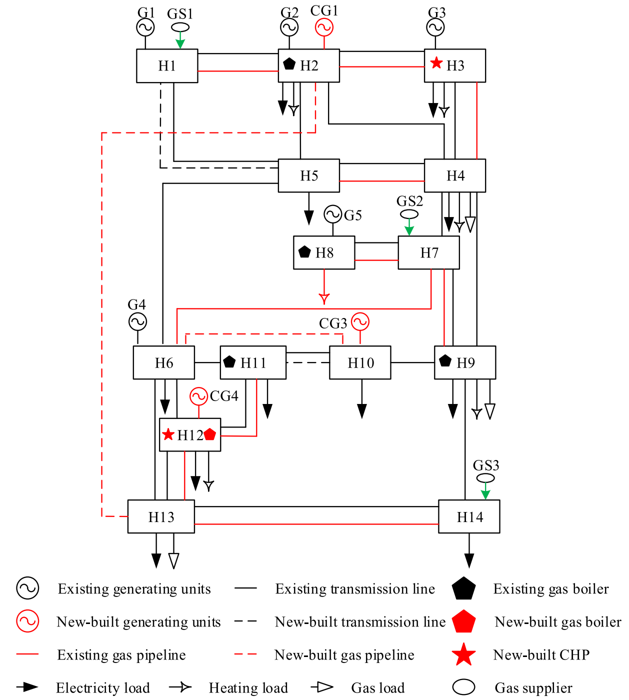

FIGURE 10. Planning results of case 3.

pipelines CGP1 and CGP3 are installed in year 6 and 9 respectively, which would provide extra gas supply capacity. With the construction of these gas pipelines, CHP can convert more natural gas into electricity and heat. As a result, the installation of power generators and gas boilers is delayed compared with case 2 [20]. For example, only generators CG1, CG4, and CG3 are installed in year 1, 5, and 7 respectively, while only the gas boiler CGB2 is installed in year 6. The final MES topology at the end of 10-year planning is shown in Fig. 10.

Table 7 also lists the operation cost, investment cost, operation cost, unserved energy cost and total cost in case 3. As indicated by Table 6 and 7, since the gas network congestion is alleviated by the newly expanded gas pipelines CGP1 and CGP6 which enhance the natural gas supply capacity for gas boilers and CHPs, the unserved energy cost in case 3 is reduced by 0.006 × 10^6\$ compared with case 2. This indicates that the coupled planning of electricity, heat and natural gas system can reduce the amount of load lost and thus effectively improve power supply reliability. In case 3, the total cost of the coordinated planning model is 11.052 × 10^6\$ which is the cheapest among these three case studies.

When make detailed comparisons among these three cases according to the results in Table 7, we can clearly observe that: 1) the total cost of case 2 [20] is lower than that of case 1 by 6.4%. This is because the electricity system, natural gas system and heat system are planned independently in case 1, while in case 2 these systems are planned jointly and thus they are coordinated to improve the planning economy. 2) In case 3, due to the installation of candidate gas

TABLE 7. Cost of different cases.

Cost(10^6\$)		Case1	Case2[20]	Case3
Investment cost of devices	CG	0.72	0.58	0.53
	CTL	0.02	0.01	0.01
	CHP	0	0.27	0.27
	CGB	0.37	0.27	0.09
	CGP	0.07	0	0.07
Investment cost		1.18	1.13	0.97
Operation cost		10.872	10.165	9.986
unserved energy cost		0.092	0.075	0.069
Total cost		12.144	11.37	11.052

pipelines CGP1 and CGP3, its total cost is further reduced by 2.8% compared with case 2, which means new pipelines are effective investment candidates for reducing the total operation cost of interdependent electricity, heat and natural gas infrastructures. Based on these discussions, the proposed coordinated expansion planning model in case 3 is most cost-effective to meet the growing electricity and heat load demand of MES.

VI. CONCLUSION

This paper proposes a long-term coordinated expansion model to determine the optimal planning of candidate generators, transmission lines, gas boilers, CHP, and gas pipelines for MES. The one-off investment cost during the planning phase plus the MES operation coast and energy not served cost during the operation phase are designed in the objective, while the coupled gas, heat and electricity system operation constraints and the reliability requirement are also considered in the model. Consequently, the Benders decomposition algorithm is utilized to solve the proposed coordinated expansion model. Simulation results of the

14-bus electricity, heat and natural gas integrated network have demonstrated that the proposed coordinated planning of MES in case 2 and 3 has a better economy compared with the decoupled planning system in case 1, while the investment of gas pipelines in case 3 can further improve MES energy utilization efficiency and reliability benchmarked with case 2. Therefore, the proposed coordinated model is very effective to optimize the expansion planning of MES.

REFERENCES

[1] Y. Li and R. Hu, "Exergy-analysis based comparative study of absorption refrigeration and electric compression refrigeration in CCHP systems," *Appl. Thermal Eng.*, vol. 93, pp. 1228–1237, Jan. 2016.
[2] X. Lu, K. W. Chan, S. Xia, X. Zhang, G. Wang, and F. Li, "A model to mitigate forecast uncertainties in distribution systems using the temporal flexibility of EVAs," *IEEE Trans. Power Syst.*, vol. 35, no. 3, pp. 2212–2221, May 2020, doi: 10.1109/TPWRS.2019.2951108.
[3] D. Xu, B. Zhou, K. W. Chan, C. Li, Q. Wu, B. Chen, and S. Xia, "Distributed multienergy coordination of multimicrogrids with Biogas-Solar-Wind renewables," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3254–3266, Jun. 2019.
[4] M. Henderson and M. Shahidehpour, "Continuing to grow: Natural gas usage rising in electricity generation," *IEEE Power Energy Mag.*, vol. 12, no. 6, pp. 12–19, Nov. 2014.
[5] S. Xia, S. Bu, C. Wan, X. Lu, K. W. Chan, and B. Zhou, "A fully distributed hierarchical control framework for coordinated operation of DERs in active distribution power networks," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 5184–5197, Nov. 2019.
[6] X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Optimal expansion planning of energy hub with multiple energy infrastructures," *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2302–2311, Sep. 2015.
[7] D. A. Savi, J. Bicik, and M. S. Morley, "A DSS generator for multiobjective optimisation of spreadsheet-based models," *Environ. Model. Softw.*, vol. 26, no. 5, pp. 551–561, May 2011.
[8] X. Zhang, G. G. Karady, and S. T. Ariaratnam, "Optimal allocation of CHP-based distributed generation on urban energy distribution networks," *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 246–253, Jan. 2014.
[9] C. A. Saldarriaga, R. A. Hincapie, and H. Salazar, "A holistic approach for planning natural gas and electricity distribution networks," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4052–4063, Nov. 2013.
[10] X. Zhou, C. Guo, Y. Wang, and W. Li, "Optimal expansion co-planning of reconfigurable electricity and natural gas distribution systems incorporating energy hubs," *Energies*, vol. 10, no. 1, p. 124, 2017.
[11] C. Unsihuay-Vila, J. W. Marangon-Lima, A. C. Z. de Souza, I. J. Perez-Arriaga, and P. P. Balestrassi, "A model to long-term, multiarea, multistage, and integrated expansion planning of electricity and natural gas systems," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1154–1168, May 2010.
[12] W. Ma, S. Fang, and G. Liu, "Hybrid optimization method and seasonal operation strategy for distributed energy system integrating CCHP, photovoltaic and ground source heat pump," *Energy*, vol. 141, pp. 1439–1455, Dec. 2017.
[13] H. Yousefi, M. H. Ghodusinejad, and A. Kasaeian, "Multi-objective optimal component sizing of a hybrid ICE + PV/T driven CCHP microgrid," *Appl. Thermal Eng.*, vol. 122, pp. 126–138, Jul. 2017.
[14] J. Qiu, Z. Y. Dong, J. H. Zhao, Y. Xu, Y. Zheng, C. Li, and K. P. Wong, "Multi-stage flexible expansion co-planning under uncertainties in a combined electricity and gas market," *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 2119–2129, Jul. 2015.
[15] M. Salimi, M. Adelpour, S. Vaez-ZAdeh, and H. Ghasemi, "Optimal planning of energy hubs in interconnected energy systems: A case study for natural gas and electricity," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 8, pp. 695–707, May 2015.
[16] L. Bai, F. Li, T. Jiang, and H. Jia, "Robust scheduling for wind integrated energy systems considering gas pipeline and power transmission N-1 contingencies," *IEEE Trans. Power Syst.*, vol. 32, no. 2, pp. 1582–1594, Mar. 2017.
[17] C. Shao, Y. Ding, J. Wang, and Y. Song, "Modeling and integration of flexible demand in heat and electricity integrated energy system," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 361–370, Jan. 2018.
[18] X. Zhang, M. Shahidehpour, A. S. Alabdulwahab, and A. Abusorrah, "Security-constrained co-optimization planning of electricity and natural gas transportation infrastructures," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 2984–2993, Nov. 2015.
[19] C. He, L. Wu, T. Liu, and Z. Bie, "Robust co-optimization planning of interdependent electricity and natural gas systems with a joint N-1 and probabilistic reliability criterion," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 2140–2154, Mar. 2018.
[20] B. Morvaj, R. Evins, and J. Carmeliet, "Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout," *Energy*, vol. 116, pp. 619–636, Dec. 2016.
[21] X. Shen, Y. Han, S. Zhu, J. Zheng, Q. Li, and J. Nong, "Comprehensive power-supply planning for active distribution system considering cooling, heating and power load balance," *J. Modern Power Syst. Clean Energy*, vol. 3, no. 4, pp. 485–493, Dec. 2015.
[22] H. Yu, C. Zhang, Z. Deng, H. Bian, C. Sun, and C. Jia, "Economic optimization for configuration and sizing of micro integrated energy systems," *J. Modern Power Syst. Clean Energy*, vol. 6, no. 2, pp. 330–341, Mar. 2018.
[23] L. Ni, W. Liu, F. Wen, Y. Xue, Z. Dong, Y. Zheng, and R. Zhang, "Optimal operation of electricity, natural gas and heat systems considering integrated demand responses and diversified storage devices," *J. Modern Power Syst. Clean Energy*, vol. 6, no. 3, pp. 423–437, May 2018.
[24] Y. Yang, S. Zhang, and Y. Xiao, "Optimal design of distributed energy resource systems based on two-stage stochastic programming," *Appl. Thermal Eng.*, vol. 110, pp. 1358–1370, Jan. 2017.
[25] S. Bracco, G. Dentici, and S. Siri, "Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area," *Energy*, vol. 55, pp. 1014–1024, Jun. 2013.
[26] A. Maroufmashat, A. Elkamel, M. Fowler, S. Sattari, R. Roshandel, A. Hajimiragha, S. Walker, and E. Entchev, "Modeling and optimization of a network of energy hubs to improve economic and emission considerations," *Energy*, vol. 93, pp. 2546–2558, Dec. 2015.
[27] C. A. Floudas, A. Aggarwal, and A. R. Ciric, "Global optimum search for nonconvex NLP and MINLP problems," *Comput. Chem. Eng.*, vol. 13, no. 10, pp. 1117–1132, Oct. 1989.

HONG FAN (Member, IEEE) received the master's degree in electrical engineering from Guangxi University, in 2004, and the Ph.D. degree from Shanghai Jiaotong University, in 2009. In the same year, she taught at the School of Electrical Engineering, Shanghai University of Electric Power. In 2018, she went to the Illinois University of Technology as a Visiting Scholar. Her main research interests include distribution network planning, operation, integrated energy systems, and electricity market.

QIANQIAN YUAN received the B.S. degree in automation engineering from the Nanjing Institute of Technology, Nanjing, China, in 2017. She is currently pursuing the M.S. degree in electrical engineering with the Shanghai University of Electric Power, Shanghai, China. Her research interest includes optimization on power system operation and planning.

SHIWEI XIA (Senior Member, IEEE) received the Ph.D. degree from The Hong Kong Polytechnic University, Hung Hom, Hong Kong, in 2015. He is currently with the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing, China, and also with the Yangzhong Intelligent Electrical Research Center, North China Electric Power University. His research interests include security and risk analysis for power systems with renewables, and distributed optimization and control of ac–dc distribution grid. He is an Associate Editor of IEEE ACCESS journal.

JIAYANG LU received the B.S. degree from Hehai University, Nanjing, China, in 2017. He is currently pursuing the M.S. degree in electrical engineering with the Shanghai University of Electric Power. His current research interests include power system planning and secure operation of electric power systems.

ZUYI LI (Senior Member, IEEE) received the B.S. degree from Shanghai Jiaotong University, Shanghai, China, in 1995, the M.S. degree from Tsinghua University, Beijing, China, in 1998, and the Ph.D. degree from the Illinois Institute of Technology (IIT), Chicago, IL, USA, in 2002, all in electrical engineering. He is currently a Professor with the Electrical and Computer Engineering Department, IIT. His research interests include economic and secure operation of electric power systems, cyber security in smart grid, renewable energy integration, big data analytics, electric demand management of data centers, and power system protection.