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Research Article

Fuzzy Decision-Based Energy Management of Energy Grids with Hubs considering Participation of Hubs and Networks in the Energy Markets

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With the creation of competitive environments, such as electricity market, it is expected that energy networks and active consumers such as energy hubs participate in the market to promote their economic situation. So, the article proposes the optimal involvement of energy networks and hubs in energy markets in two wholesale and retail designs based on the energy management system at the same time. The proposed scheme is expressed as two-objective optimization. The first objective is to minimize the cost of different types of energy in electricity-gas-thermal networks. In another objective function, the cost of energy (which is the difference between the energy purchase cost and energy sale income) of energy hubs in the retail market is minimized. The scheme is bound to optimal power flow equations of the mentioned networks and operating model of power sources and active loads. Then, the Pareto optimization mixed with the sum of weighted functions helps extract an optimal compromise solution on the basis of fuzzy decision-making. Finally, the scheme is applied to a test system, and the obtained numerical results confirm that energy hubs are improved financially, and economic and operation conditions of the electricity-gas-thermal networks are enhanced simultaneously. So, significant profit can be achieved for EHs in the retail energy market. The economic situation of the networks enhances up to roughly 10% compared with that of power flow studies. Also, operating situation of the networks enhances by about 12% to 53% compared with a case without EHs.

1. Introduction

1.1. Motivation. One of the latest solutions to save energy is the adoption of ecofriendly and green demand response programs (DRPs) thanks to the emergence of recent advancements in power systems including renewable energy sources (RESs) and energy storage systems (ESSs). RESs and ESSs as new energy resources together with active load (AL) may help improve the grid from a technical viewpoint along with decreasing the operation cost [1]. To provide an example, renewables when assigned to power systems would drop the operating cost and electricity price up to an acceptable extent and, equivalently, enhance social welfare [2]. Additionally, with the amalgamation of such equipment, the amount of data submitted to the operator of the grid will increase so that suitable decisions can be made. When various types of power sources are integrated with ALs to establish energy hubs (EHs), virtual power plants (VPPs), and microgrids (MGs), it is called a smart grid, which is a preferred option to collect huge datasets to procure it to the grid operator. Yet, EHs are more desirable than VPPs and MGs as they help present a comprehensive energy management system with higher efficiency [3], in which power sources and ALs can actively communicate with the operator of the EH to provide energy management of energy networks more appropriately. In the cases that the EH operator has bilateral communication with the operators of energy networks, we call it a two-layer management system [4]. This assists to accelerate the processing speed compared to a case the grid operator is directly in communication with power sources and ALs. Another advantage of EHs is the injection of energy into energy networks. EHs can also get involved in energy markets and thus financially benefit [5]. One interesting role of energy networks is acting as a distribution company, where it can participate in energy transactions by purchasing energy from the main grid and selling it to the customers and EHs. One can predict that energy networks enjoy financially when adopting the mentioned strategy and using a suitable operation scheme when EHs are available across the grid, thereby enhancing technical and economic indicators.

1.2. Literature Review. The operation of EHs or energy networks has extensively been discussed in the literature. For instance, the authors in [6] considered the uncertain nature of renewable sources and the time-varying price of electrical energy by adopting a robust optimization technique. They also utilized Monte Carlo simulation to discriminate the coordinated/uncoordinated charging status of electric vehicles. In an attempt to drop the overall cost imposed by EHs, like operating cost and pollution cost, an optimal power flow was executed [7]. Such an EH consists of thermal storage equipment, combined heat and power (CHP) units, solar arrays, gas boilers, wind turbines, and electric vehicles, to name but a few. Ref. [8] adopts a chance-constrained optimization method so that the operation of EHs with various energy demands is optimally performed. This can also help grid and EH operators to make proper decisions. To address the uncertain and fluctuating nature of the operation points, some researchers use ESSs across the EH. The authors in [9] focus on the coordinated operation of several networks and provide optimal power flow solutions at the microgrid level. They also incorporate an EH structure in a sublevel, consisting of electricity and thermal/cooling hubs to establish an EH structure that combines renewables with ESSs and cooling/thermal energy systems. To address the challenge of congestion at the distribution level, several energy sources were deployed in EHs [10]. By integrating renewables and cooling-thermal power, a combined EH is first proposed. Then, EHs are optimally scheduled to supply the demand within peak hours. Ref. [11] discusses an EH that plays the role of a node at the distribution level. The inputs to this EH included electrical, gas, and wind energies, and the outputs are electrical, thermal, gas, and water energies. Optimal operation of the EH was ensured by adopting an objective function subject to the limitations concerning economics, emission, reliability, and efficiency. Ref. [12] extensively delves into the benefits of heat-power decoupling (HPD) advancements applied to CHPs, while various constraints related to energy demand, energy price, and renewable deployment are also taken into account. The energy of EHs is suitably managed in [13], in which the EHs are interconnected with electricity, gas, and thermal networks (EGTNs), and the role of the EH is proving coordination among generators and ESSs. Such a scheme helps minimize the operating cost of EGTNs. The paper also uses an adaptive robust optimization approach to properly model the uncertain parameters of the problem. With the involvement of EHs in day-ahead markets, their energy was managed for various energy networks [14], in which the structured formula was in the form of a linear objective function to maximize the profit earned by EHs in the market subject to the limitations of the problem. Also, uncertainties associated with the demand, renewable output, and energy price in the market are considered. Ref. [15] optimally modeled the operation of EHs in electricity-gas-thermal networks. The paper also utilized renewables and CHP systems together with storage and DRP to present flexible EH. The operating cost, reliability, and flexibility of networks were optimized in the same reference. The proposed optimization framework was subject to constraints of optimal power flow (OPF) as well as reliability and EH modeling.

In [16], it is dedicated to studying and modeling the interdependence between the oil returns and exchange-rate movements of oil-exporting and oil-importing countries. Ref. [17] examines the impacts of Pakistani rupee volatility on monthly energy imports based on the nonlinear autoregressive distributed lag (NARDL) estimations. Ref. [18] proposes the improvement of mathematical modeling apparatus at the stage of technological processes' design and reconstruction. It used data from large restaurant-type catering enterprises typical for million-plus cities, some of which prepare fast-food dishes. The data gathered by collecting the carbon emission produced in the transport sector in China during 14 years between 2005 and 2019 was adopted [19] to examine the impact of energy efficiency on carbon dioxide emission level. According to the results, as the quality of energy and its efficiency is enhanced, the level of dioxide decreases significantly. Ref. [20] introduces a social index to analyze the impact of urbanization on energy generation and demand, economic situation, and the environment. In [21], it is devoted to model the corruption perception index in panel data framework. As corruption index is bounded from below and above, traditional econometric multiple regression will produce a bad quality model. The objective of [22] is to estimate small business development across regions of the Far Eastern District in Russia with regard to economic, social, and environmental dimensions of sustainability. Ref. [23] analyzes the relationship between triple bottom line (TBL) and corporate social responsibility (CSR) performance indicators: EBITDA; emissions score; resource use score; environmental, social, and governance (ESG) score; environmental innovation score; product responsibility score; CSR strategy score; management score; and shareholders score. The paper develops the 3-overlapping-circle sustainability model in the context of CSR performance indicators.

1.3. Research Gaps and Contributions. Based on the research background, a majority of studies have generally discussed EH operation, while EHs' involvement in energy markets has rarely been the focus of previous research. There are studies that provide an energy market model for EHs but do not apply it to energy networks. Nonetheless, regarding the financial achievements of competitive environments, distribution companies (DisCos) and energy hubs are encouraged to get involved in energy market to obtain the benefits besides enhancing the operating indicators of EGTNs. So, to solve this issue, the present research focuses on modeling of wholesale and retail energy markets in energy networks like EGTNs with EHs. This design is aimed at coordinating power sources and storage devices with the EH operator. Moreover, operators of EHs and energy networks will also be in contact and communication. In this design, EGTNs by playing the role of a private DisCo get involved in the wholesale market to transact energy. EGTNs then provide the purchased energy to the customers and EHs within the retail market. The mentioned design is expressed as a two-objective optimization problem. It tries to find the minimum weighted sum of energy cost of DisCos in the wholesale and retail markets and the energy cost of EHs in the retail market. This problem is bound to the constraints of OPF in EGTNs and operating model of power sources and storage devices in the form of EH. In continuation, the Pareto optimization with the help of fuzzy decision-making extracts an optimal compromise solution. Finally, the innovations of the mentioned design are summarized as follows:

(i) Presenting a model of wholesale and retail energy markets for EGTNs playing the role of DisCos with EHs

(ii) Obtaining financial benefits simultaneously for DisCos and EHs and

(iii) Presenting the model of operational and economic indicators of EHs for EGTNs

The hypotheses of the suggested scheme include the following:

(i) Simultaneous modeling of retail and wholesale energy markets for energy networks and hubs can improve economic situation of the networks and hubs

(ii) Optimal management of hubs can enhance the operating situation of various energy networks

(iii) Time variation of energy price can provide more suitable economic situation for energy networks and hubs

1.4. Paper Organization. The organization of the article is described as follows. Section 2 states the mathematical model of the proposed design. Then, Section 3 describes the process of extracting a compromise solution based on fuzzy decision-making. Section 4 provides the obtained results, and, eventually, conclusions are given in Section 5 of the article.

2. Model of the Proposed Scheme

The proposed scheme is an optimization problem. The optimization formulation includes objective function [24–28] and constraints [29–33]. Also, the optimization can be implemented on the energy network, if there are smart [34–40] and telecommunication [41–47] platform in this system.

In this section, the optimal operation of energy networks with EHs is formulated considering their involvement in energy markets. The objective function is responsible for minimizing the weighted sum of the energy cost of networks and EHs, and it must comply with the constraint of networks OPF and the model of power sources and active loads in the form of EH. Hence, the formulation of the design is as follows:

$$\min \varsigma_1 C_E + \varsigma_2 C_H, \tag{1}$$

$$\text{subject to } C_E = \sum_h \left(\gamma_{E\,h} P_{\mathrm{ES}\,s,h} + \gamma_{H\,h} H_{\mathrm{HS}\,s,h} + \gamma_{G\,h} G_{\mathrm{GS}\,s,h}\right) + \sum_h \sum_l \left(\gamma_{E\,h} P^{+}_{\mathrm{EH}\,l,h} + \gamma_{H\,h} H^{+}_{\mathrm{EH}\,l,h} + \gamma_{G\,h} G^{+}_{\mathrm{EH}\,l,h}\right), \tag{2}$$

$$C_H = \sum_h \sum_l \left\{ \left(\rho_{E\,h} P^{-}_{\mathrm{EH}\,l,h} + \rho_{H\,h} H^{-}_{\mathrm{EH}\,l,h} + \rho_{G\,h} G^{-}_{\mathrm{EH}\,l,h}\right) - \left(\gamma_{E\,h} P^{+}_{\mathrm{EH}\,l,h} + \gamma_{H\,h} H^{+}_{\mathrm{EH}\,l,h} + \gamma_{G\,h} G^{+}_{\mathrm{EH}\,l,h}\right) \right\}, \tag{3}$$

$$P_{\mathrm{ES}\,b,h} - P_{C\,b,h} + \sum_l I_{E\,b,l}\left(P^{+}_{\mathrm{EH}\,l,h} - P^{-}_{\mathrm{EH}\,l,h}\right) = \sum_k J_{E\,b,k} P_{F\,b,k,h} \quad \forall b, h, \tag{4}$$

$$Q_{\mathrm{ES}\,b,h} - Q_{C\,b,h} + \sum_l I_{E\,b,l} Q_{\mathrm{EH}\,l,h} = \sum_k J_{E\,b,k} Q_{F\,b,k,h} \quad \forall b, h, \tag{5}$$

$$P_{F\,b,k,h} = G_{b,k}(V_{b,h})^2 - V_{b,h} V_{k,h}\left\{G_{b,k} \cos\left(\upsilon_{b,h} - \upsilon_{k,h}\right) + B_{b,k} \sin\left(\upsilon_{b,h} - \upsilon_{k,h}\right)\right\} \quad \forall b, k, h, \tag{6}$$

$$Q_{F\,b,k,h} = -B_{b,k}(V_{b,h})^2 + V_{b,h} V_{k,h}\left\{B_{b,k} \cos\left(\upsilon_{b,h} - \upsilon_{k,h}\right) - G_{b,k} \sin\left(\upsilon_{b,h} - \upsilon_{k,h}\right)\right\} \quad \forall b, k, h, \tag{7}$$

$$G_{\mathrm{GS}\,n,h} - G_{C\,n,h} + \sum_l I_{G\,n,l}\left(G^{+}_{\mathrm{EH}\,l,h} - G^{-}_{\mathrm{EH}\,l,h}\right) = \sum_k J_{G\,n,k} G_{F\,n,k,h} \quad \forall n, h, \tag{8}$$

$$G_{F\,n,k,h} = \xi_{n,k}\, \mathrm{sign}\left(\varpi_{n,h}, \varpi_{k,h}\right) \sqrt{\mathrm{sign}\left(\varpi_{n,h}, \varpi_{k,h}\right)\left((\varpi_{n,h})^2 - (\varpi_{k,h})^2\right)}, \tag{9}$$

$$H_{\mathrm{ES}\,t,h} - H_{C\,t,h} + \sum_l I_{H\,t,l}\left(H^{+}_{\mathrm{EH}\,l,h} - H^{-}_{\mathrm{EH}\,l,h}\right) = \sum_k J_{H\,t,k} H_{F\,t,k,h} \quad \forall t, h, \tag{10}$$

$$H_{F\,t,k,h} = \mu_{t,k}\left(T_{t,h} - T_{k,h}\right) \quad \forall t, k, h, \tag{11}$$

$$\underline{V}_b \le V_{b,h} \le \bar{V}_b \quad \forall b, h, \tag{12}$$

$$\sqrt{(P_{F\,b,k,h})^2 + (Q_{F\,b,k,h})^2} \le \bar{S}_{F\,b,k} \quad \forall b, k, h, \tag{13}$$

$$\sqrt{(P_{\mathrm{ES}\,b,h})^2 + (Q_{\mathrm{ES}\,b,h})^2} \le \bar{S}_{\mathrm{ES}\,b} \quad \forall b = s, h, \tag{14}$$

$$\underline{\varpi}_n \le \varpi_{n,h} \le \bar{\varpi}_n \quad \forall n, h, \tag{15}$$

$$\left|G_{F\,n,k,h}\right| \le \bar{G}_{F\,n,k} \quad \forall n, k, h, \tag{16}$$

$$\left|G_{\mathrm{GS}\,n,h}\right| \le \bar{G}_{\mathrm{GS}\,n} \quad \forall n = s, h, \tag{17}$$

$$\underline{T}_t \le T_{t,h} \le \bar{T}_t \quad \forall t, h, \tag{18}$$

$$\left|H_{F\,t,k,h}\right| \le \bar{H}_{F\,t,k} \quad \forall t, k, h, \tag{19}$$

$$\left|H_{\mathrm{HS}\,t,h}\right| \le \bar{H}_{\mathrm{HS}\,t} \quad \forall t = s, h, \tag{20}$$

$$\begin{aligned} P^{+}_{\mathrm{EH}\,l,h} - P^{-}_{\mathrm{EH}\,l,h} &= P_{\mathrm{CHP}\,l,h} + P_{\mathrm{RES}\,l,h} + (P_{D\,l,h} - P_{\mathrm{CH}\,l,h}) \\ &\quad - P_{C\,l,h} \quad \forall P^{+}_{\mathrm{EH}\,l,h}, P^{-}_{\mathrm{EH}\,l,h} \ge 0 \& l, h, \end{aligned} \tag{21}$$

$$Q_{\mathrm{EH}\,l,h} = Q_{\mathrm{CHP}\,l,h} + Q_{\mathrm{RES}\,l,h} + Q_{\mathrm{EES}\,l,h} - Q_{C\,l,h} \quad \forall l, h, \tag{22}$$

$$\begin{aligned} H^{+}_{\mathrm{EH}\,l,h} - H^{-}_{\mathrm{EH}\,l,h} &= H_{\mathrm{CHP}\,l,h} + H_{\mathrm{BO}\,l,h} \\ &\quad - H_{C\,l,h} \quad \forall H^{+}_{\mathrm{EH}\,l,h}, H^{-}_{\mathrm{EH}\,l,h} \ge 0 \& l, h, \end{aligned} \tag{23}$$

$$\begin{aligned} G^{+}_{\mathrm{EH}\,l,h} - G^{-}_{\mathrm{EH}\,l,h} &= -G_{\mathrm{CHP}\,l,h} - G_{\mathrm{BO}\,l,h} - G_{C\,l,h} \quad \forall G^{+}_{\mathrm{EH}\,l,h}, G^{-}_{\mathrm{EH}\,l,h} \\ &\ge 0, \& l, h, \end{aligned} \tag{24}$$

$$H_{\mathrm{CHP}\,l,h} = P_{\mathrm{CHP}\,l,h}\left(\frac{1-\eta_{tu}-\eta_{lo}}{\eta_{tu}}.\eta_{he}\right) \quad \forall l, h, \tag{25}$$

$$G_{\mathrm{CHP}\,i,t} = \frac{1}{\eta_{tu}}.P_{\mathrm{CHP}\,l,h} \quad \forall l, h, \tag{26}$$

$$\sqrt{(P_{\mathrm{CHP}\,l,h})^2 + (Q_{\mathrm{CHP}\,l,h})^2} \le \bar{S}_{\mathrm{CHP}\,l} \quad \forall l, h, \tag{27}$$

$$0 \le H_{\mathrm{CHP}\,l,h} \le \bar{H}_{\mathrm{CHP}\,l} \quad \forall l, h, \tag{28}$$

$$G_{\mathrm{BO}\,l,h} = \frac{1}{\eta_{bo}}.H_{\mathrm{BO}\,l,h} \quad \forall l, h, \tag{29}$$

$$0 \le H_{\mathrm{BO}\,l,h} \le \bar{H}_{\mathrm{BO}\,l} \quad \forall l, h, \tag{30}$$

$$0 \le P_{\mathrm{CH}\,l,h} \le \chi_{\mathrm{CH}\,l} \quad \forall l, h, \tag{31}$$

$$0 \le P_{D\,l,h} \le \chi_{D\,l} \quad \forall l, h, \tag{32}$$

$$\underline{E}_l \le E_{I\,l} + \sum_{\tau=1}^{h}\left(\eta_{\mathrm{ch}}P_{\mathrm{CH}\,l,\tau} - \frac{1}{\eta_{\mathrm{dis}}}P_{D\,l,\tau}\right) \le \bar{E}_l \quad \forall l, h, \tag{33}$$

$$\sqrt{(P_{D\,l,h} - P_{\mathrm{CH}\,l,h})^2 + (Q_{\mathrm{EES}\,l,h})^2} \le \bar{S}_{\mathrm{EES}\,l} \quad \forall l, h, \tag{34}$$

$$\sqrt{(P_{\mathrm{RES}\,l,h})^2 + (Q_{\mathrm{RES}\,l,h})^2} \le \bar{S}_{\mathrm{RES}\,l} \quad \forall l, h. \tag{35}$$

Equation (1) presents the objective function, which is the weighted sum of the energy cost of EGTNs in wholesale and retail energy markets (C_E) and the energy cost of EHs in the retail market (C_H). It should be noted that the participation model of energy networks and EHs in the energy market is similar to that given in [48]. Energy networks purchase energy from the wholesale energy market and share it between consumers and EHs in the retail energy market. However, since EHs have energy generation and storage units, their energy management may assign the EH as a producer. So, EHs can sell energy to energy networks in the retail market. Therefore, according to Equation (2), cost of energy networks includes the cost of purchasing energy from the wholesale market (the first line of the equation) and EHs in the retail market (the second line of the equation). The second line of Equation (2) is an incentive case for EH provided by energy networks. Equation (3) presents the formulation of C_H, which is equal to the difference in the cost of the purchased energy of EHs and their sold energy in the retail market.

The constraints of energy networks can be observed in Equations (4)–(24) [14, 15]. In the meantime, Equations (4)–(7) represent the equations of AC power flow in the electrical network [49–51], which, respectively, denote the active-reactive power balance in electrical buses and active and reactive power flow through distribution lines [5]. Also, the constraints of gas network power distribution are presented in Equations (8) and (9). Constraint ((8)) refers to the balance of gas power in the gas node, and the amount of gas power passing through the gas pipe is formulated in Equation (9) [13]. In Equations (10) and (11), the heat network power distribution model is also expressed. Equation (10) shows the formulation of thermal power balance in the thermal node, and the amount of thermal power passing through the thermal pipe is calculated in Equation (20) [13]. The limits of operation of electricity, gas, and heat networks are modeled in constraints ((12))-((14)), ((15))-((17)), and ((18))-((20)), respectively, [13–15]. Constraints ((12))-((14)), respectively, present the constraints on voltage magnitude of the electrical buses and distribution line and substation power flow [52, 53]. Constraints ((15))-((17)) also refer to limitations on gas node pressure and gas power through pipe and gas station, respectively. Finally, the limitations on the temperature of the thermal node and the thermal power flow through the thermal pipe and station are specified in Equations (18)–(20), respectively.

The operating models of power sources, storage devices, and responsive loads are presented in constraints ((21))-((35)). In these relationships, constraints ((21))-((24)), respectively, present the active-reactive-gas-thermal power balance the EH. Also, + and − signs for active, thermal, and gas powers denote the performance model of the supply and demand of EHs for the said powers. Constraints ((25))-((28)) provide the CHP operating model [54, 55]. Equations (25) and (26) give the thermal and gas power of CHP, which depend on active power of the CHP. Also, the limits of CHP output in the electrical and thermal sectors are modeled in constraints ((27)) and ((28)), respectively, which represent the apparent and thermal power limits of CHP, respectively. In constraints ((29)) and ((30)), the boiler operating model is presented, which, respectively, refers to the calculation relationship of the boiler gas power and the limitation of the thermal power generated by the boiler [54]. The performance model of electric energy storage is specified in relations (31)–(34) [56]. In these relationships, the limitation of charging and discharging rates of the storage device is stated in constraints ((31)) and ((32)), respectively. The limitation of the energy stored in this storage device is modeled as in ((33)). Then, the limit on apparent power flowing through the storage charger has a model similar to ((34)). Relationships ((31))-((34)) are true for mobile storage devices such as electric vehicles (EVs) [2, 5, 55]. Nevertheless, the number and type of EVs connected to EH are different in each operating hour [57, 58]. Therefore, the parameters χ_{CH} and χ_D, E_I and $\bar{E}$, and $\bar{S}_E$ will have a subscript h. The values of χ_{CH}, χ_D, and $\bar{S}_E$ at each instant are, respectively, equal to the sum of the charging rate, discharge rate, and charging capacity of EVs connected to EH, and E_I at each moment can be found by summing up the initial energy of newly connected vehicles to the EH, and $\bar{E}$ is the sum of final energy of vehicles disconnected from EH [2]. In this article, it is assumed that each of the EVs fully charges its battery [5, 55]. In the following, the apparent power limit of the renewable source is formulated in constraint ((35)) [2].

Note that this scheme considers economic, environmental, and operation conditions, so that economic model is considered an energy cost [59] of networks and EHs. To reduce environmental pollution [60], the RES such as wind turbine and photovoltaic is used in EH. Finally, to achieve optimal situation for these indices, an optimization problem [61–63] obtains for the proposed scheme.

3. Determining the Compromise Solution Based on Fuzzy Decision-Making

In Equation (1), the parameters ς_1 and ς_2 are weighting coefficients of C_E and C_H functions, and according to [64], their sum should be equal to 1. Therefore, by choosing different values for these parameters, different values are extracted for C_E and C_H functions, which are plotted in a two-dimensional (2D) coordinate representing the Pareto front for the proposed design. Next, in order to obtain an optimal compromise solution to the mentioned functions, fuzzy decision-making was adopted [54]. The problem ((1))-((35)) is solved for two study cases with $\varsigma_1 = 1$ and $\varsigma_2 = 1$, and the output of these two problems leads to extracting the minimum ($f_{\min}$) and maximum ($f_{\max}$) values of C_E and C_H functions. Then, for a specific value of weight coefficients, the linear membership function (f_l) is calculated for C_E and C_H functions. The value of f_l for a given function (f) is equal to 1 (0), if the value of the function is less (more) than its minimum (maximum) value. Otherwise, f_l is equal to $(f - f^{\max})/(f^{\min} - f^{\max})$. In the following, the minimum value of f_l obtained for the C_E and C_H functions is calculated, which is indicated here by the letter Δ. Finally, the compromise solution corresponds to a point (with specified ς_1 and ς_2) that has the largest value. Therefore, the steps of implementing fuzzy decision-making are as follows [54]:

(1) Calculate $f_{\max}$ and $f_{\min}$ for C_E and C_H functions for two study cases $\varsigma_1 = 1$ and $\varsigma_2 = 1$

(2) Set $\varsigma_1 = 1$ and $\varsigma_2 = 0$

(3) Calculate f_l for C_E and C_H functions

(4) Calculate Δ, where $\Delta = \min\,(f_l(C_E), f_l(C_H))$

(5) $\varsigma_1 = \varsigma_1 - \varepsilon$ and $\varsigma_2 = \varsigma_2 + \varepsilon$, where ε has a specific step, e.g., 0.05

(6) Implement steps 3 and 4

(7) If $\varsigma_2 = 1$, implement step 8, otherwise return to step 5

(8) Determine the compromise solution corresponding to the point with max (Δ)

Finally, Figure 1 shows the flowchart problem solution.

4. Numerical Results

4.1. Case Study. A sample system with electricity, gas, and heat networks is tested by the suggested scheme (refer to Figure 2). The electricity network has 9 buses, while the gas and thermal networks include 4 and 7 nodes, respectively [15, 55]. The base power of the electricity network is set at 1 MVA, while it is 1 MW for the gas and thermal networks [14]. Additionally, the base voltage, base pressure, and base temperature are set at 1 kV, 10 Bar, and 100°C, bounded between [0.9, 1.1] p.u. [13, 65–70]. The date related to distribution lines of the electricity network and gas and heat pipelines in the gas and thermal networks, as well as the peak demand of the mentioned energies, can be found in [14]. The only consumers in the gas network are the CHP and boiler, and there is no passive gas demand. The hourly demand can be calculated by multiplying the peak load and load factor [13, 55]. The daily load factor curves of electricity and thermal networks are available in [14]. The daily energy price curve in the wholesale market for various energy networks can also be extracted from [14]. It is assumed that energy networks can escalate the energy price in the retail market by up to 20% in comparison with the wholesale market so the amount of profit will be $\rho = 1.2 \times \lambda$ [55].

The system consists of seven EHs located at different points of the grids (Figure 2). The demand can be found in [14]. EHs 1, 2, 3, and 5 consist of electrical power sources and storage devices, including renewable sources, EVs, and battery units. Hub #4 contains a CHP and a boiler. EHs #6 and #7 are equipped with the aforementioned devices. The maximum electricity generation output and maximum heat output of the CHP are 1 MVA and 1 MW, where η_{tu}, η_{lo}, and η_{he} are 40%, 9%, and 40%, respectively [54, 55]. The maximum heat output of the boiler, whose efficiency is 0.8, is 0.3 MW [14]. The EHs are also equipped with a solar system and a wind turbine with apparent power of 0.25 and 0.2 MVA [14]. The capacity of a renewable source multiplied by its rate of power gives the hourly power of that source [15]. Ref. [55] provides the daily power curve of the solar and wind systems.

A battery with 2 MWh capacity and 0.88 charging and discharging efficiency is 88% that is assigned to EHs 1-3 and 5-7 [15]. The charging and discharging rates of the battery are set at 0.5 MW, the charger's capacity is 0.6 MVA, and the minimum storable energy and initial energy are assumed at 0.2 MWh [15]. The capacity of EHs 1-3 and 5-7 is sixty electric vehicles, and the data of these vehicles is provided in [1, 2]. The number of vehicles connected to the EH at hear hour can be found by multiplying the number of vehicles in the parking lot and the penetration rate of vehicles [55]. The expected daily penetration rate curve of vehicles is shown in Figure 3 [5].

4.2. Results. The design applied to the data of Section 4.1 was implemented using the GAMS environment, and the IPOPT solver was used to find solutions to the problem [71].

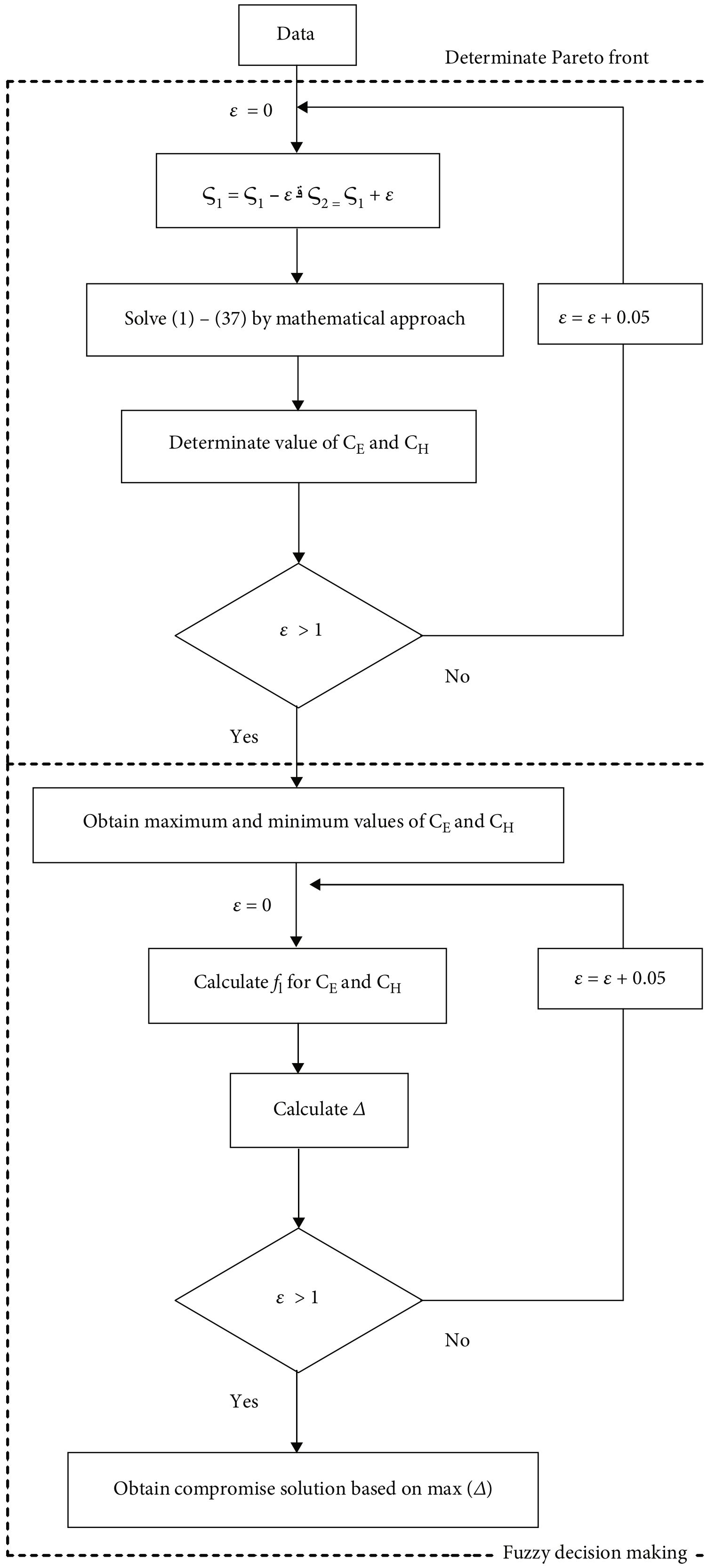

Figure 1: The problem solution flowchart.

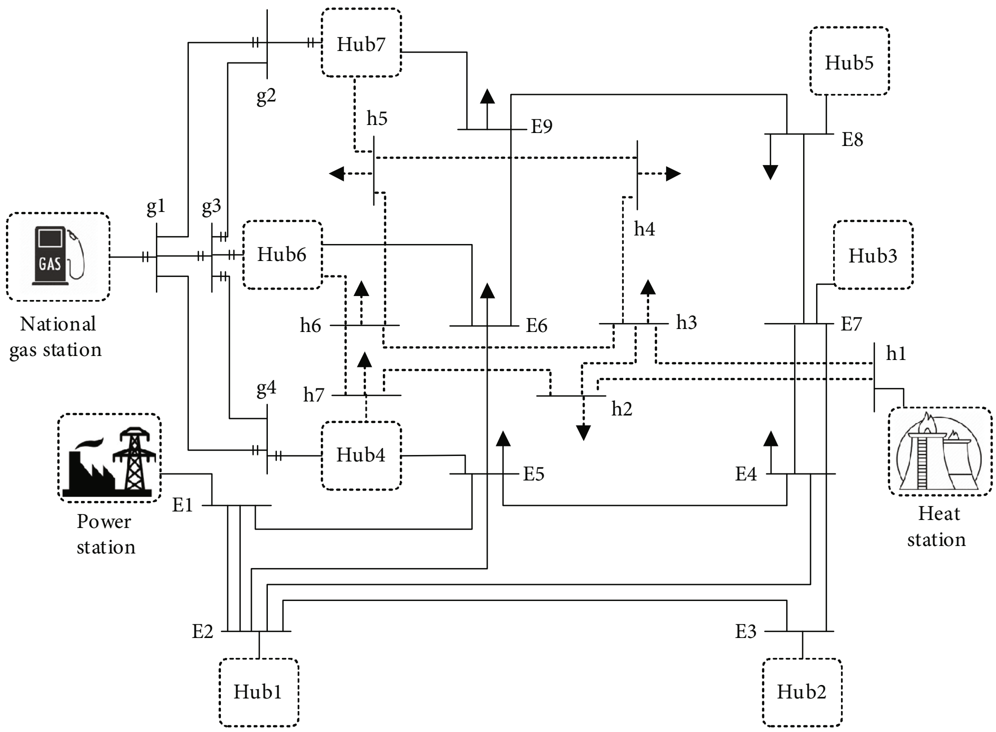

Figure 2: Test system [14, 55].

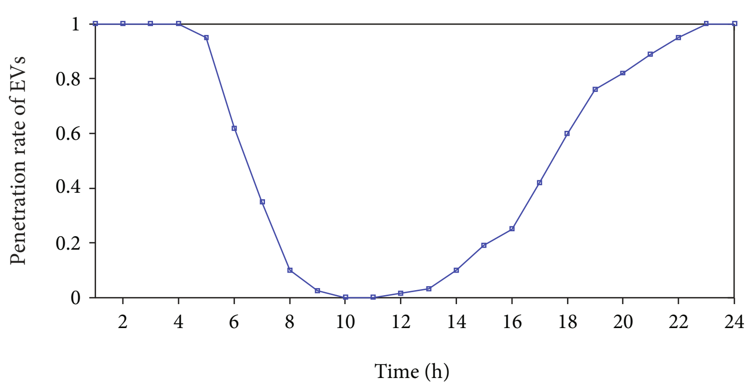

Figure 3: Daily curves of EV penetration rate [5].

Numerical results obtained from different study cases are presented in detail as follows:

(A) Determining the compromise solution of the proposed scheme: Figure 4 depicts the Pareto front curve for the proposed design. Based on this figure, the minimum and maximum values of C_E are \$5778.5 and \$23039.6. These values for C_H are \$53.931 and \$45.071, respectively. Therefore, the range of changes in C_E and C_H is equal to \$17261.1 (23039.6-5778.5) and \$99.002, respectively. In addition to this, based on Figure 4, it is seen that the trends of changes in C_E and C_H functions are opposite in terms of increase and decrease. That is, the increase in C_E is proportional to the decrease in C_H because, according to Equation (3), to obtain the minimum amount of C_H, the hubs must produce more energy. Since this produced energy is sold to energy networks in the retail market, C_E will be high as per Equation (2). Finally, fuzzy decision-making obtains a compromise solution for the proposed design, which is reported in Table 1 for different solvers such as IPOPT, CONOPT, DISOPT, KNITRO, and OQNLP [71]. KNITRO and DISOPT algorithms are not able to extract the optimal solution. The solution extracted in other algorithms is not the same. This is because the problem is nonconvex, which is because of power flow constraints in electricity and gas networks. In the meantime, the results of an algorithm that obtains a more optimal point (minimum for the proposed design) are confirmed because it is expected to obtain a local

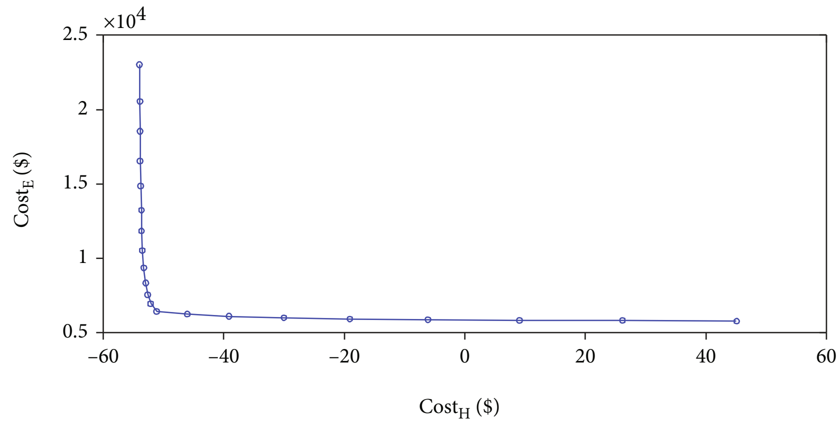

Figure 4: The Pareto front of the proposed design.

Table 1: The compromise point of the proposed design obtained from fuzzy decision-making based on different solution algorithms.

Algorithm	C_E (\$)	C_H (\$)	Convergence iteration	Calculation time (sec)
IPOPT	6437.3	-51.063	56	27.4
CONOPT	6508.5	-48.871	71	29.9
DISOPT			Infeasible solution	
KNITRO				
OQNLP	6612.1	-43.566	98	33.5

optimum point that is closer to the global optimum point. Hence, in these IPOPT, CONOPT, and OQNLP algorithms, the IPOPT solver provides the most optimal point (the minimum value of C_E and C_H). So, this algorithm is suitable for solving the proposed problem. Moreover, this algorithm has fewer convergence iterations and low computing time compared with other algorithms. In the following, considering the values of C_E and C_H functions at the compromise point obtained from IPOPT and comparing it with Figure 4, it can be stated that the aforementioned fuzzy decision-making can obtain values for the proposed objective functions so that the values are close to their minimum values. For example, C_E at the compromise point is far from its minimum value of about 3.8% $((6437.4 - 5778.5)/17261.1)$. This value for C_H is about 2.9%

(B) Economic evaluation of EHs: the economic status of EHs is reported for five different study cases in Figure 5, which are as follows.

Case 1. The proposed design is in accordance with the problem ((1))-((35)).

Case 2. The same Case 1 with assuming that the prices of buying and selling energy for EHs in the retail market both are equal to ρ.

Case 3. Case 1 with constant price of buying and selling energy for EHs in the retail market during all operating hours. In this situation, the purchase price of electrical, thermal, and gas energy is 32 \$/MWh, 30 \$/MWh, and 18 \$/MWh, respectively, and the sale price of energy is 20% lower than the purchase price.

Case 4. The same Case 3 with a 10% reduction in the price of buying and selling energy in the retail market.

Case 5. The same Case 3 with a 20% increase in the price of buying and selling energy in the retail market.

Further, based on Figure 5, it is observed that by considering the difference in the price of buying and selling energy of EHs in the retail markets in Case 1compared to Case 2, a higher income has been obtained in the former case for EHs. In Case 2, since the buying and selling prices in the retail market are equal and, generally, have a higher value than the energy price in the wholesale market, the energy networks are not inclined to purchase energy from EHs. They do this only under critical conditions like during peak load hours when voltage drops, and high heat and pressure are more probable. Therefore, EH benefit is minimum in Case 2 according to Figure 5. In Cases 3 to 5, for a high energy price (Case 5), more income can be obtained for EHs than in Case 1. Although this issue has favorable social welfare for EHs, it leads to low social of customers as they are obliged to buy energy at a high price. Therefore, regarding the social welfare of producers and end-users based on Figure 5, it is desirable to have a changing energy price over time.

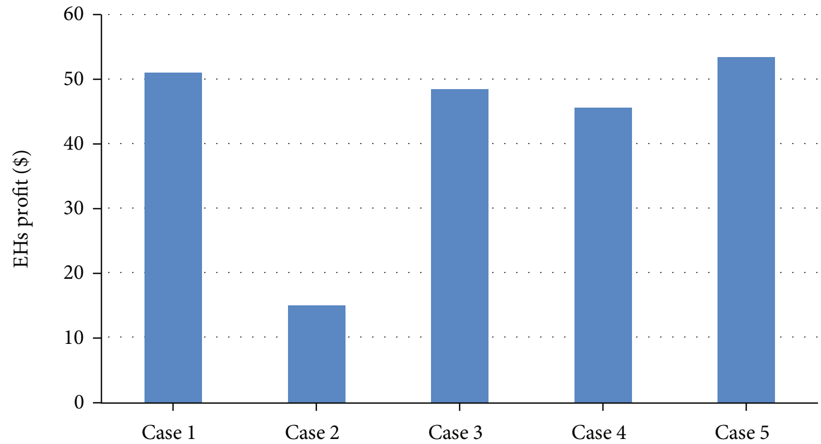

Figure 5: Profit of EHs (-C_H) in different study cases.

(C) Investigating the economic and operation status of energy networks: in Table 2, the values of economic and operation indicators of energy networks for the proposed design (Case 1) and power flow studies (Case 6) are reported. Operation indicators include energy losses in different energy networks, maximum voltage drop, pressure and temperature, maximum overvoltage, pressure, and temperature. Regarding economic indicators, the term C_E is also presented. In power flow studies of energy networks, the energy cost of networks is around \$7184.8, but the design with proper management of EHs has been able to reduce it to \$6437.3. In other words, Case 1 enhanced the economic condition of energy networks by about 10.4% ((7184.8 – 6437.3)/7184.8) compared to power flow studies. In terms of operation, no overvoltage, overpressure, and overtemperature were observed in Case 6 for energy networks. Also, since gas energy consumers (EHs with CHP and boilers) were discarded in this case, energy losses and pressure drop are zero for the gas network. Nonetheless, in Case 6, maximum drops of voltage and temperature are 0.112 and 0.116 per unit (p.u.), respectively, and their upper limit is 0.1 (1-0.9) p.u. Also, the electrical and thermal networks in the mentioned studies have energy losses of more than 3.7 MWh and 2.8 MWh, respectively. But, in Case 1, even though the energy losses in the gas network have increased to 1.44 MWh, the energy losses in the electrical and thermal networks have decreased by approximately 35.71% ((3.78 – 2.43)/3.78) and 31.45% ((2.83 – 1.94)/2.83) compared with Case 6. This has caused the total energy loss in the mentioned energy networks to decrease from 6.61 MWh in Case 6 to 5.81 MWh in Case 1. So, the proposed design can reduce energy losses by 12.1% compared to the power flow studies. Also, in Case 1, even though the maximum overvoltage and overtemperature have increased around 0.01 p.u. and the maximum pressure drop has increased to 0.038 p.u., the maximum voltage drop and temperature drop have values of 0.052 and 0.079, respectively. Thus, the proposed design has been able to reduce the maximum drops of voltage and temperature by 53.7% and 31.9%, respectively, compared with Case 6

Table 2: Values of economic and operation indicators of energy networks in different study cases.

Case	1	6
C_E (\$)	6437.3	7148.9
Energy loss (MWh) in electricity network	2.43	3.81
Energy loss (MWh) in heating network	1.94	2.91
Energy loss (MWh) in gas network	1.44	0
Total energy loss (MWh)	5.81	6.72
Upper drop of voltage (p.u.)	0.052	0.109
Upper drop of temperature (p.u.)	0.079	0.118
Upper drop of pressure (p.u.)	0.038	0
Upper overvoltage (p.u.)	0.012	0
Upper overtemperature (p.u.)	0.009	0
Upper overpressure (p.u.)	0	0

5. Conclusion

The study presented the problem energy networks and energy hubs involvement in day-ahead energy markets at the same time, where energy networks purchase energy from the wholesale energy market to supply EHs and consumers in retail energy markets. Following this, the design was expressed in the form of two-objective optimization to minimize the energy cost of energy networks in wholesale and retail markets and to minimize the energy cost of EHs in the retail market. The problem was constrained by optimal power flow equations of energy networks and the operating model of power sources and ALs in the form of EH. The Pareto optimization together with the sum of weighted function method and fuzzy decision-making was used to achieve a compromise solution. The obtained results indicate that the suggested design achieves the highest profit for EHs according to the time-varying energy price. Also, optimal energy management of EHs assists to reduce energy cost of energy networks by about 10% compared with power flow studies. It also was capable of reducing the energy losses of energy networks and maximum drop of voltage and temperature by roughly 12%, 53%, and 32%, respectively, in comparison to power flow studies when incorporating optimal scheduling of EHs. Furthermore, fuzzy decision-making selected a compromise solution where objective functions are almost minimized. Thus, the energy costs of energy networks and EHs are about 3.8% and 2.9% away from their minimum values at the compromise point, respectively. The IPOPT algorithm can obtain a proposed design with a high convergence speed (lower convergence iteration and lower computing time) so that its solution is the most optimal among other mathematical solution algorithms.

Therefore, the advantages of the proposed scheme compared to the previous research are as follows:

(i) In this scheme, the economic goals of energy networks and EHs were met with their simultaneous participation in the energy market. Energy networks gain financial benefit by purchasing energy from the wholesale market and share it in the retail market, and EHs gain financial benefit by selling energy in the retail market. This scheme created a competitive environment on different levels of the power system such as energy networks and active consumers

(ii) At the same time, the proposed scheme is able to improve the economic situation and network operation with the optimal energy management of EHs, and in addition to this, it also extracts the optimal economic situation for EHs

(iii) The implementation time step is short in operation problems; especially in the problems where the market model is needed, the implementation step is under one hour. Therefore, in these conditions, low computation time is of special importance. In this design, the IPOPT algorithm was able to achieve this goal

In the end, based on the stated advantages, the problems in the field of research have been resolved in the proposed scheme.

Nomenclature

Variables

C_H, C_E: Cost of energy for energy hubs (EHs) and energy networks ($)
G_{BO}, H_{BO}: Gas and heat power of boiler (MW)
G_{CHP}, H_{CHP}: Gas and heat power (MW) of combined heat and power (CHP)
G^+_{EH}, G^-_{EH}: Gas power of EH in production and consumption mode (MW)
G_{GS}, H_{HS}: Gas power of gas station and heat power of heat station (MW)
G_F, H_F: Gas and heat power of the pipeline (MW)
H^+_{EH}, H^-_{EH}: Heat power EHs in production and consumption mode (MW)
P_{CHP}, Q_{CHP}: Active (MW) and reactive (MVAr) power of the CHP (MW, MVAr)
P_{CH}, P_D: Active power of electricity energy storage (EES) in charging and discharging mode (MW)
P_{ES}, Q_{ES}: Active (MW) and reactive (MVAr) power of electrical substation
P_F, Q_F: Active (MW) and reactive (MVAr) power of electrical distribution
P^+_{EH}, P^-_{EH}: Active power of EHs in production and consumption mode (MW)
Q_{EES}: Reactive power of EES charger (MVAr)
Q_{EH}: Reactive power of EH (MVAr)
Q_{RES}: Reactive power (MVAr) of renewable energy source (RES)
T: Temperature in per unit (p.u.)
V, υ: Voltage magnitude (p.u.) and voltage angle (rad)
ϖ: Pressure (p.u.).

Constants

$\underline{E}$, $\bar{E}$: Minimum and maximum energies (MWh) in EES
E_I: Initial energy (MWh) of ESS
G, B: Conductance and susceptance (p.u.) of electrical distribution line
G_C, H_C: Gas and heat load (MW)
$\bar{G}_{GS}$, $\bar{G}_F$: Maximum gas capacity (MW) of gas station and pipeline
$\bar{H}_{CHP}$, $\bar{H}_{BO}$: Maximum heat capacity (MW) of CHP and boiler
$\bar{H}_{HS}$, $\bar{H}_F$: Maximum heat capacity (MW) of heat station and pipeline
I_E, I_G, I_H: Incidence matrices of bus and EH, gas node and EH, and heat node and EH
J_E, J_G, J_H: Incidence matrices of electrical bus and line, gas node and pipeline, and heat node and pipeline
P_C, Q_C: Active (MW) and reactive (MVAr) load
P_{RES}: Active power (MW) of RES
$\bar{S}_{CHP}$, $\bar{S}_{EES}$, $\bar{S}_{RES}$: Maximum apparent power (MVA) of CHP, ESS, and RES
$\bar{S}_{ES}$, $\bar{S}_F$: Maximum apparent power (MVA) of electrical substation and line
sign (ϖ_n, ϖ_k): Sign function (=1 if ϖ_n is greater than ϖ_k; otherwise = −1)
$\underline{T}$, $\bar{T}$: Minimum and maximum allowable values of temperature (p.u.)
$\underline{V}$, $\bar{V}$: Minimum and maximum allowable voltage magnitude (p.u.)
χ_{CH}, χ_D: Charging and discharging rate of EES (MW)
γ_E, γ_G, γ_H: Price of electrical, gas, and heat energy in the wholesale market ($/MWh)
η_{bo}: Efficiency of boiler
η_{ch}, η_{dis}: Charging and discharging efficiency of EES

η_{tu}, η_{lo}, η_{he}: Efficiency of turbine, losses, and heat in CHP
μ: Constant of heat pipeline (p.u.)
ρ_E, ρ_G, ρ_H: Price of electrical, gas, and heat energy in the retail market ($/MWh)
$\underline{\varpi}$, $\bar{\varpi}$: Minimum and maximum allowable pressure (p.u.)
ξ: Constant of gas pipeline (p.u.)
ζ: Weighting factor.

Indices

b: Electrical buses
H: Heat nodes
n: Gas nodes
K: Bus or node
L: EH
s: Slack bus (node)
t: Hour.

Data Availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest

The authors declare that they have no conflict of interest to the publication of this article.

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