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Stochastic electrical and thermal energy management of energy hubs integrated with demand response programs and renewable energy: A prioritized multi-objective framework

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ABSTRACT

Energy hubs (EH) are known as multi-carrier systems that integrate multiple energy resources to enable greater flexibility in the energy provision. In this study, a multi-objective decision-making framework is proposed to determine the optimal scheduling of EHs. The proposed model considers the total cost of the EH, emissions, power losses, and average reserve of EH, simultaneously. These objectives are prioritized based on the EH preference that can be different for each EH. In this strategy, the cost of the EH has the highest priority and is considered as the main objective. The emission, system losses, and system reserve simultaneously have been considered as secondary objectives. According to the prioritization made among objectives, a lexicography optimization is performed in which cost minimization is considered in the first step, and the secondary objectives are evaluated in the second step of optimization. The intermittency nature of the electrical and thermal loads, renewable generation, and market prices are applied to the model by stochastic techniques. The proposed multi-objective model has been tested on the non-real benchmark system (standard IEEE 5-bus test system). The simulation results show that the proposed model improves the reserve capacity, emission, and system losses.

1. Introduction

Multi-energy systems are flexible energy systems that can use energy sources to meet different energy needs. The energy hubs (EH) are multi-carrier energy systems that integrate the generation, consumption, conversion, and energy storage systems of different energy carriers [1]. The energy hubs combined the heat and power (CHP), distributed energy resources (DER), power electronic devices, energy storage systems (ESS), heat exchangers, boiler, and other equipment to provide an interface between different energy infrastructures [2, 3]. Depending on the type of fuel consumed by the resources, each resource has a different production cost and emits different greenhouse gases such as CO_2, SO_2, and NO_x to the atmosphere. In addition to economic performance, the environmental issues of the EHs have also been studied in related literature [4, 5]. The energy scheduling problem formed a large part of the researches area.

Eladl et al. [6] proposed multi-objective optimization to improve the social welfare and CO_2 emission simultaneously. The authors consider the uncertain nature of RES to investigate the impacts of RES on the total cost of EH. The optimal energy scheduling of the distribution system had been modeled by a three-layer optimization framework in [7]. The optimal islanding configuration of EHs was determined in the first layer, while optimal dispatch of the resources was defined in the second layer. Finally, the optimal locations of the phasor measurement units were studied in the third layer. In [8], a linear model is employed to present the optimal economic performance of a general grid-connected EH in the day-ahead market. The authors study the efficiency of the coordinated and uncoordinated framework on the energy management of the EH in an uncertain environment. However, the role of electrical and thermal DR programs is ignored. In [9], a robust planning-operational problem is presented considering the exact economic model of energy storage systems. In the proposed model, multiple energy storage systems had been studied to improve the flexibility and economy of the EH. In [10], the authors present a stochastic energy management strategy, which integrates the infrastructures of thermal, electrical, and natural gas

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Nomenclature

Sets

s	index of scenarios
t	index of time slot
p, q	index of nodes

Parameters

A_{PV}	area of PV panel
B_{PV}	number of PV panel
$B_{p,q}, F^{max}_{p,q}$	susceptance/ Maximum flow of line p-q
$C^{Grid}_{s,t}$	price of the main grid at time *t* and scenario *s*
$C^{PV}_{O\&M}, C^{WT}_{O\&M}$	O&M cost of PV/WT
$C^{ES}_{O\&M},\ C^{HS}_{O\&M}$	O&M cost of electrical and heat storages
$C^{CHP}_{O\&M}$	O&M cost of CHP
$C^{boiler}_{O\&M}$	O&M cost of boiler
$C^{E,up}_{DR},\ C^{H,up}_{DR}$	cost of upward regulation of the electrical/ thermal DR program
$C^{E,down}_{DR},\ C^{H,down}_{DR}$	Ccst of downward regulation of the electrical/ thermal DR program
$C^{Emission}$	treatment cost of the pollutant emission
$E^{ES,min},\ E^{ES,max}$	minimum/maximum capacity of electric storage
$E_s,\ H_s$	capacity of electrical/heat storage
$G^{Boiler}_{max},\ G^{CHP}_{max}$	maximum allowable natural gas in the input of boiler/ CHP
$H^{HS,min},\ H^{HS,max}$	minimum/maximum capacity of heat storage
$I_{t,s}$	solar radiation at time t and scenario s
$K^{Boiler}_{CO_2}$	CO_2 emission coefficient of boiler
$K^{Boiler}_{NO_x}$	NO_x emission coefficient of boiler
$K^{Boiler}_{SO_2}$	SO_2 emission coefficient of boiler
$K^{Grid}_{CO_2}$	CO_2 emission coefficient of the main grid
$K^{Grid}_{NO_x}$	NO_x emission coefficient of the main grid
$K^{Grid}_{SO_2}$	SO_2 emission coefficient of the main grid
$K^{CHP}_{CO_2}$	CO_2 emission coefficient of CHP
$K^{CHP}_{NO_x}$	NO_x emission coefficient of CHP
$K^{CHP}_{SO_2}$	SO_2 emission coefficient of CHP
LHV	low calorific value of natural gas
$MR^E_{up},\ MR^E_{down}$	maximum ratios of shifted up and shifted down of electrical load
$MR^H_{up},\ MR^H_{down}$	maximum ratios of shifted up and shifted down of thermal load
N^{MPT}	maximum power temperature coefficient of PV
$P^{ES,ch}_{max}, P^{ES,dch}_{max}$	maximum charging/ discharging power of electrical storage
$P^{HS,ch}_{max},\ P^{HS,dch}_{max}$	maximum charging/ discharging power of heat storage
$P^{EL}_t,\ P^{HL}_t$	electrical/thermal load of EH at time t
P^{H}_{max}	maximum thermal transmission limit of heat pipe
P^{Grid}_{max}	maximum purchasing power of the main grid
P_r	rated power of WT
$T^{out}_t,\ T^c$	ambient and standard temperature at time t
$v_{t,s}$	wind speed at time t and scenario s
$v_{ci},\ v_{co},\ and\ v_r$	cut-in, cut-out, and rated speed of WT
λ^G_t	price of natural gas
$\delta_{p,t},\ \delta_{slack,t}$	voltage angle of node p /slack at time t
η_{PV}	efficiency of PV
$\eta^{ES,ch},\ \eta^{ES,dch}$	efficiency of charging/discharging power of electric storage
$\eta^{HS,ch}, \eta^{HS,dch}$	efficiency of charging/discharging power of heat storage
η^{boiler}	efficiency of boiler
$\eta^{CHP}_e,\ \eta^{CHP}_h$	electrical/thermal efficiency of CHP
ρ_s	probability of scenario s
ΔT	length of time slot

Variables

$Cost_{Grid}$	cost of purchasing power from the main grid
$Cost_{PV}$	total cost of PV
$Cost_{WT}$	total cost of WT
$Cost_{CHP}$	total cost of CHP unit
$Cost_{Boiler}$	total cost of boiler
$Cost_{EDR}$	cost of electrical DR program
$Cost_{HDR}$	cost of thermal DR program
$Cost_{Storage}$	cost of energy storage systems
$Cost_{Emission}$	penalty cost of greenhouse gas emission
$P^{ECHP}_t,\ P^{HCHP}_t$	electrical/thermal output power of CHP
$P^{E,down}_t,\ P^{H,down}_t$	shifted down electric/thermal power by DR program
$P^{E,up}_t,\ P^{H,up}_t$	shifted up electric/thermal power by DR program
$P^{Hboiler}_t$	thermal output power of boiler
P^{Grid}_t	purchasing power from the main grid
P^{BGrid}_t	base purchasing power from the main grid
$P^{PV}_{s,t},\ P^{WT}_{s,t}$	output power of PV/WT at time t and scenario s
$G^{CHP}_t,\ G^{Boiler}_t$	consumed natural gas by CHP/boiler
$P^{HS,ch}_t,\ P^{HS,dch}_t$	charging/discharging power of heat storage at time t
$P^{ES,ch}_t,\ P^{ES,dch}_t$	charging/discharging power of electric storage at time t
$E^{ES}_t,\ H^{HS}_t$	stored energy in electrical/heat storage at time t
$I^{E,up}_t, I^{E,down}_t$	up/down shifting indicator of electrical load
$I^{H,up}_t, I^{H,down}_t$	up/down shifting indicator of thermal load
μ_k	membership function of objective functions k
$z^{ES,ch}_t,$	binary variable of charging state of electric storage
$z^{ES,dch}_t$	binary variable of discharging state of electric storage
$z^{HS,ch}_t, z^{HS,dch}_t$	binary variable of charging and discharging state of heat storage

Abbreviation

ARI	Average reserve index
CHP	Combined heat and power
DR	Demand response program
ESS	Energy storage system
IPI	Independence performance index
LII	Loss improvement index
PV	Photovoltaic cells
RES	Renewable energy resources
WT	Wind turbine

networks. Uncertainties related to the RES and demand loads are applied to the model by the corresponding probability distribution functions.

Najafi et al. [11] modeled the short-term energy scheduling of EH in restructured power systems. Although the uncertain natures of the market prices and renewable resources had been applied, the role of demand response programs was not investigated. In [12], a rolling horizon framework was utilized to model the real-time scheduling of EH. However, the role of DR programs in the operation of EH was ignored. The cooperation of multi-carrier microgrids as networked EHs had been investigated in [13]. In the proposed model, the bi-directional interaction between electricity and gas networks are provided by the power-to-gas (P2G) converters. Nevertheless, the uncertainties of electrical and thermal demand load and renewable generation were ignored. Also, the impacts of electrical and thermal DR programs on the daily operation of EH were not studied.

Mirzapour et al. [14] studied the transactive energy among the EHs in the distribution system by bi-level multi-follower optimization. The cost of the distribution system operator had been minimized at the upper-level of optimization, while the total daily cost of EHs had been optimized at the lower-level. Although the RESs are integrated into the EHs, the uncertain natures of RESs and the role of DR programs have been ignored. Bostan et al. [15] investigated the optimal day-ahead scheduling of networked EHs considering electric vehicles and DR programs. Although the emission of greenhouse gases has been studied in the same work, reliability and supply security have been ignored. A robust optimization problem had been proposed in [16] to consider the uncertainties of RES and market prices. An environmental optimization had been presented in [17] to reduce the operation cost and CO_2 emission in a general EH. However, the uncertain behavior of the renewable generation and electrical and thermal demands were not studied. Lu et al. [18] proposed robust technique to consider the uncertain behavior of EVs in the networked energy hubs. Nevertheless, the reserve capacity and power losses had not been studied.

The probabilistic scheduling of EH systems integrated with RES and DR programs were also investigated in [19-21]. In [19], the authors use the P2G converter system to make a connection between the electricity system and the natural gas network. The authors only consider the operational cost of the EH, and the reliability and reserve system had been ignored. The flexibility of DR programs on the operation scheduling of the EH system in the presence of load and RES uncertainty was investigated in [20]. The authors in [21] studied the effects of the implementation of the electrical and thermal DR programs on the operation of EH by stochastic optimization.

The interaction among the EHs in the distribution systems has been formulated as a multi-level optimization framework [22-24]. The effect of auxiliary equipment on wind power consumption had been studied in [22]. The total profit of the EHs had been maximized at the upper-level, while the heating bills of the residents had been minimized at the lower-level. However, the effects of the uncertain behavior of RES and the DR programs are not investigated in that work. Luo et al. [23] proposed a three-level Stackelberg game to model interaction among the utility company, operator of EH, and users. Although the DR programs had been considered, the role of energy storage systems was ignored. Damavandi et al. [24] presented a bi-level framework to study the multi-energy players' behavior in the distribution system. The proposed model considers the economic aspects, as well as the profit and social welfare. In contrast, the reliability, independence, and security of the system are not studied.

According to the literature, the main focus of the previous research works has been on the cost/profit minimization/maximization, while less attention has been paid to the operation scheduling of the EH system in terms of security, system losses, emission, and independence. In this paper, we focus on the operation scheduling of EH, considering both demand-side management and generation management. The proposed energy scheduling considers the total daily cost, reserve capacity, power losses, and greenhouse gasses emission to present a comprehensive framework in the energy management problem. In the proposed model, the operator of the EH prioritizes its objective based on its preferences. The economic aspects, such as the daily cost of EH, have the highest preference and are considered as the main objective. The emission of greenhouse emission, loss improvement index (LII), and average reserve index (ARI) of the energy hub are the secondary objectives. The EH considers the reserve capacity as one of the secondary objectives to increase its security of supply. The higher reserve capacity creates more security, but it increases the cost of the system. Therefore, the EH should make a trade-off among different and even competing objectives. The main objective of the operator is optimized at first, where the optimal cost and optimal operation scheduling of EH are determined. The operator of EH considers a safe margin for itself to keep the daily cost in the acceptable range and optimizes the secondary objectives simultaneously. The EH has various electrical and thermal resources as well as boiler, RES, CHP unit, electrical storage, and heat storage to supply its load. Besides, it is able to participate in the electrical and thermal demand response programs. Table 1 compares the related works in the energy scheduling of EHs. The major contributions of this work are summarized as follows:

1. The daily energy management of an energy hub has been modeled by multi-objective optimization. The objective functions have been prioritized to the main and the secondary objectives based on the EH operator's preference. The total cost of the energy hub is the main objective, while the power loss, emission, and reserve capacity are the secondary objective functions.
2. The modified fuzzy approach is utilized to convert the multi-objective optimization to a single objective. The proposed framework has a compensatory behavior and can select the best solution in different working scenarios.
3. The proposed scheme provides a safe margin for the cost of the EH to keep it within the budget range. The proposed model is flexible in considering different values for the safe margin based on the trade-off between the main and secondary objectives.
4. The uncertain natures of market prices, thermal and electric loads, and RESs are investigated using stochastic optimization. The scenario-generation technique is applied to generate possible scenarios for each parameter. The generated scenarios are decreased by a scenario-reduction method to reduce the computational burden and make the problem tractable.

The rest of this paper is organized as follows: The mathematical formulation of the proposed strategy is presented in section II. The lexicography-fuzzy approach (LFA) is described in section III. The simulation results and evaluating the efficiency of the proposed model are defined in section IV. Finally, the conclusion and future works have been presented in section V.

2. Mathematical formulation of the proposed model

The formulation of the objective functions and operating constraints have been defined in this section.

2.1. Main objective function

The main objective of the EH is cost minimization and formulated as (1). The total cost consists of the cost of transactive energy with the main grid, cost of RES, generation cost of CHP and boiler, electrical and thermal DR program costs, electrical and thermal energy storage system costs, and the emission cost of greenhouse gases [18].

$$\begin{aligned} Min\ Cost = {} & Cost_{Grid} + Cost_{PV} + Cost_{WT} + Cost_{CHP} + Cost_{Boiler} + Cost_{EDR} \\ & + Cost_{HDR} + +Cost_{Storage} + Cost_{Emission} \end{aligned} \tag{1}$$

The cost of imported energy from the upstream network is shown in (2). Besides, the cost of renewable resources (i.e., photovoltaic units and wind turbines) are demonstrated in (3)-(4) [25].

$$Cost_{Grid} = \sum_{t} \sum_{s} \rho_s P_t^{Grid} C_{s,t}^{Grid} \Delta T \tag{2}$$

$$Cost_{PV} = \sum_{t} \sum_{s} \rho_s P_{s,t}^{PV} C_{O\&M}^{PV} \Delta T \tag{3}$$

$$Cost_{WT} = \sum_{t} \sum_{s} \rho_s P_{s,t}^{WT} C_{O\&M}^{WT} \Delta T \tag{4}$$

The generation costs and O&M costs of CHP and boiler are presented

Table 1
The comparison of the proposed model and related papers.

Ref.	Proposed model	Pros	Cons
[11]	• Single-objective optimization • Stochastic optimization	• The uncertainty of EV patterns was studied • Discharging cost of BESs had been considered	• The electrical and thermal DR programs were not studied • The power losses and reserve capacity were not considered • The uncertainty of demand load wad ignored
[12]	• Single-objective optimization • Chance constrained optimization	• Considering the uncertainties of EV and renewable generation • Presenting a rolling horizon model to model real-time energy scheduling of EH	• The emission of greenhouse gases was not considered • The power losses and reserve capacity were not studied • The impacts of DR programs on the operation of EH were not studied
[13]	• Single-objective optimization • Deterministic approach	• The operation of multi-carrier networked microgrids had been modeled as multi EH • The planning of the system was studied	• The power losses and reserve capacity were not studied • The uncertainties of demand loads, renewable generation, and market prices were not applied to the proposed model • The impacts of DR programs on the operation of EH were not studied
[14]	• Single-objective optimization • Deterministic approach • Bi-level framework	• The transactive energy among EHs and distribution system was investigated • Renewable energy resources had been integrated into the model	• The effects of the presented model on the CO_2 emission had not been studied • The loss improvement index had not been studied • The electrical and thermal storage systems were not considered
[17]	• Multi-objective optimization • Deterministic approach	• The CO_2 emission was studied • The electrical and thermal storage systems were considered • Real-time DR programs had been applied to reduce operating costs	• The uncertainties of demand loads, renewable generation, and market prices were not applied to the proposed model • The power losses and reserve capacity were not studied • The thermal DR program was not considered
[19]	• Single-objective optimization • Stochastic optimization	• Considering the uncertain nature of market prices, load demand, and RES • Providing the connection between electric and natural gas network using P2G converter • Considering the electrical and thermal energy storage systems	• The power losses and reserve capacity were not investigated • The efficiency of the proposed model on the CO_2 emission was not studied • The independence of EH was not calculated
[21]	• Single-objective optimization • Stochastic optimization	• The impact of DR programs had been studied • Using stochastic optimization to apply the uncertainty of market prices and renewable generation • Electrical and thermal energy storage systems had been utilized	• The effects of the presented model on the CO_2 emission had not investigated • The efficiency of the proposed model on the multi-microgrid systems was not studied • The reserve capacity of EH was not considered
This study	• Multi-objective optimization • Stochastic optimization • Two-stage framework	• Considering the uncertainties of demand loads, market prices, and renewable generation • The proposed model provides a safe margin for the cost of EH • The power losses, emission, and reserve capacity of EH has been considered as the secondary objectives	• The efficiency of the proposed model on the multi-carrier multi-microgrid systems will be studied in the future work

in (5)-(6) [18]:

$$Cost_{CHP} = \sum_t G_t^{CHP} \lambda_t^G \Delta T + \left(P_t^{ECHP} + P_t^{HCHP}\right) C_{O\&M}^{CHP} \Delta T \quad (5)$$

$$Cost_{Boiler} = \sum_t G_t^{Boiler} \lambda_t^G \Delta T + \left(P_t^{Hboiler}\right) C_{O\&M}^{boiler} \Delta T \quad (6)$$

Eqs. (7) and (8) show the cost of electrical and thermal DR programs, respectively [18].

$$Cost_{EDR} = \sum_t \left(C_{DR}^{E,down} P_t^{E,down} + C_{DR}^{E,up} P_t^{E,up}\right) \Delta T \quad (7)$$

$$Cost_{HDR} = \sum_t \left(C_{DR}^{H,down} P_t^{H,down} + C_{DR}^{H,up} P_t^{H,up}\right) \Delta T \quad (8)$$

The O&M costs of battery energy storage and heat storage are defined as (9) [18]:

$$Cost_{Storage} = \sum_t \left(P_t^{HS,ch} + P_t^{HS,dch}\right) C_{O\&M}^{HS} \Delta T + \left(P_t^{ES,ch} + P_t^{ES,dch}\right) C_{O\&M}^{ES} \Delta T \quad (9)$$

The CO_2 emission treatment cost of EH is modeled as (10) [18]:

$$Cost_{Emission} = \sum_t C^{Emission} \left(P_t^{Grid} u^{Grid} + \left(P_t^{ECHP} + P_t^{HCHP}\right) u^{CHP} + P_t^{Hboiler} u^{Boiler}\right) \Delta T \quad (10)$$

where u^{Grid}, u^{CHP}, and u^{Boiler} are the CO_2 emission coefficients of the main grid, CHP unit, and boiler, respectively.

2.2. Secondary objective functions

The average reserve index (ARI) of the EH, loss improvement index (LII), and emission are the secondary objectives. The model of the secondary objectives have presented in (11)-(13):

$$Max\ ARI = \frac{1}{NT} \sum_t \left(E_t^{ES} + H_t^{HS}\right) \quad (11)$$

$$Max\ LII = \frac{1}{NT} \sum_t \left(\frac{\left(P_t^{BGrid}\right)^2 - \left(P_t^{Grid}\right)^2}{\left(P_t^{BGrid}\right)^2} \right) \times 100 \quad (12)$$

$$\begin{aligned} Min\, Emission = & \sum_t P_t^{Hboiler} \left(K_{CO_2}^{Boiler} + K_{NO_x}^{Boiler} + K_{SO_2}^{Boiler}\right) \\ & + P_t^{Grid} \left(K_{CO_2}^{Grid} + K_{NO_x}^{Grid} + K_{SO_2}^{Grid}\right) \\ & + \left(P_t^{ECHP} + P_t^{HCHP}\right) \left(K_{CO_2}^{CHP} + K_{NO_x}^{CHP} + K_{SO_2}^{CHP}\right) \end{aligned} \quad (13)$$

The ARI in a system indicates the average electrical and thermal reservation capacity. Actually, the ARI shows the average electrical and thermal stored energy in the storage systems. The higher value of ARI provides more flexibility for the system to overcome the uncertainties. Also, the LII shows the total improvement for loss reduction. In the proposed model. The P_t^{BGrid} is the amount of transactive energy with the upstream network at a general optimization framework. While P_t^{Grid} shows the amount of transactive energy with the upstream network in the prioritized model. LII shows that system losses are improved by reducing the energy exchanged with the upstream network. This improvement has occurred because the required energy has been supplied by the local resources and the energy pass from the shorter lines. The P_t^{BGrid} is the base value of the imported power from the upstream network. The value of P_t^{BGrid} is defined by performing a single objective optimization problem that only considers the total cost of the energy hub as the objective function.

2.2.1. Renewable energy storage

The generated power of PV and WT can be calculated as follows [25]:

$$P^{PV}_{t,s} = B_{PV\,PV} A_{PV} I_{t,s} \left(1 + N^{MPT}\left(T^{c} - T^{out}_{t}\right)\right) \tag{14}$$

$$0\ 0 \le v_{t,s} \le v_{ci}\ or\ v_{co} \le v_{t,s}$$

$$P^{WT}_{t,s} = \{\ P_r \frac{v^2_{t,s} - v^2_{ci}}{v^2_r - v^2_{ci}}\ v_{ci} \le v_{t,s} \le v_r \tag{15}$$

$$P_r\ v_r \le v_{t,s} \le v_{co}$$

Eqs. (14) and (15) show the generating power of PV and WT at time t and scenario s, respectively. Parameters T^{out}_{t} and T^{c} are the ambient and standard temperatures of the PV unit. Also, $N^{MPT}$is the maximum power temperature coefficient of PV. To consider the uncertain nature of WT and PV units, Weibull and Beta probability distribution function (PDF) can be used, respectively [25, 26]. The Weibull PDF is defined as (16)-(17) [26]:

$$PDF(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)\right) | k = \left(\frac{\delta}{\mu}\right)^{-1.086} \tag{16}$$

$$c = \frac{\mu}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{17}$$

where c, k, δ, and μ are the scale index, shape index, standard deviation, and mean value of the wind speed. The Beta PDF is applied to model the behavior of PV as (18)-(20) [26]:

$$PDF(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1} \tag{18}$$

$$\beta = (1-\mu)\left(\frac{\mu(1-\mu)}{\delta^2} - 1\right) \tag{19}$$

$$\alpha = \frac{\mu\beta}{1-\mu} \tag{20}$$

where α, β, and Γ are shape parameters and the gamma function (α, $\beta \ge 0$).

2.3. The electrical energy storage system

The constraints of ESS are defined as follows [27, 28]:

$$E^{ES}_{t} = E^{ES}_{t-1} + \Delta t\left(\frac{\eta^{ES,ch} P^{ES,ch}_{t}}{E_s} - \frac{P^{ES,dch}_{t}}{\eta^{ES,dch} E_s}\right) \tag{21}$$

$$0 \le P^{ES,ch}_{t} \le z^{ES,ch}_{t} P^{ES,ch}_{max} \tag{22}$$

$$0 \le P^{ES,dch}_{t} \le z^{ES,dch}_{t} P^{ES,dch}_{max} \tag{23}$$

$$E^{ES,min} \le E^{ES}_{t} \le E^{ES,max} \tag{24}$$

$$z^{ES,ch}_{t} + z^{ES,dch}_{t} \le 1 \tag{25}$$

$$E^{ES}_{t1} = E^{ES}_{t24} \tag{26}$$

The energy update function of ESS is given by (21). The maximum charging and discharging power of ESS are shown in (22) and (23), respectively. The minimum and maximum bounds of stored electric energy are shown in (24). Eq. (25) guarantees that at a time slot, the ESS cannot be charged and discharged simultaneously. Finally, Eq. (26) enforces that the stored energy in the beginning and at the end of the day must be equal.

2.4. Thermal energy storage

The following constraints have been imposed on the operating of the heat storage unit [19]:

$$H^{HS}_{t} = H^{HS}_{t-1} + \Delta t\left(\frac{\eta^{HS,ch} P^{HS,ch}_{t}}{H_s} - \frac{P^{HS,dch}_{t}}{\eta^{HS,dch} H_s}\right) \tag{27}$$

$$0 \le P^{HS,ch}_{t} \le z^{HS,ch}_{t} P^{HS,ch}_{max} \tag{28}$$

$$0 \le P^{HS,dch}_{t} \le z^{HS,dch}_{t} P^{HS,dch}_{max} \tag{29}$$

$$H^{HS,min} \le H^{HS}_{t} \le H^{HS,max} \tag{30}$$

$$z^{HS,ch}_{t} + z^{HS,dch}_{t} \le 1 \tag{31}$$

$$H^{HS}_{t1} = H^{HS}_{t24} \tag{32}$$

Eq. (27) shows the energy content dynamic model of the heat storage unit. The maximum and minimum bounds of charging and discharging heat storage are presented in (28) and (29). The acceptable bounds of stored heat energy are presented in (30). Eq. (31) guarantees that the heat storage unit cannot be charged and discharged simultaneously. Similar to (26), Eq. (32) shows stored heat energy at the beginning and the end of the day should be equal.

2.5. Electrical DR program

The EH can participate in electrical and thermal DR to manage the operating conditions and eventually to reduce the cost. The constraints (33)-(36) are considered for the electrical DR program [21].

$$\sum_{t} P^{E,up}_{t} = \sum_{t} P^{E,down}_{t} \tag{33}$$

$$0 \le P^{E,up}_{t} \le MR^{E}_{up} P^{EL}_{t} I^{E,up}_{t} \tag{34}$$

$$0 \le P^{E,down}_{t} \le MR^{E}_{down} P^{EL}_{t} I^{E,dow}_{t} \tag{35}$$

$$I^{E,up}_{t} + I^{E,down}_{t} \le 1 \tag{36}$$

The electricity demand of the EH in the scheduling cycle should be kept constant, which is modeled by (33). The minimum and maximum bounds of shifted-up and shifted-down of electric load are considered by (34) and (35), respectively. Finally, Eq. (36) ensures that the EH cannot increase and decrease the load simultaneously.

2.6. Thermal DR program

The constraints (37)-(40) describe the thermal DR for the EH [21].

$$\sum_{t} P^{H,up}_{t} = \sum_{t} P^{H,down}_{t} \tag{37}$$

$$0 \le P^{H,up}_{t} \le MR^{H}_{up} P^{HL}_{t} I^{H,up}_{t} \tag{38}$$

$$0 \le P^{H,down}_{t} \le MR^{H}_{down} P^{HL}_{t} I^{H,dow}_{t} \tag{39}$$

$$I^{H,up}_{t} + I^{H,down}_{t} \le 1 \tag{40}$$

Eq. (37) keeps the thermal demand of the EH unchanged. The minimum and maximum bounds for thermal load shifting are shown in (38) and (39), respectively. Similar to (36), Eq. (40) shows that the EH must either increase or decrease the thermal load at each time step.

2.7. Electrical and thermal balance

The electrical balance of the EH is described in (41)-(44). Eq. (41) defines that the electrical load of the EH should be equal to generating power at each time slot. In this paper, we apply the Direct Current Load Flow (DCLF) in the optimization problem. The DCLF is a non-iterative approach and guarantees convergence. Eq. (42) indicates the power flow limit of each line. The voltage angle of each bus (except for Slack bus) should remain according to (43), while Eq. (44) fixes voltage angle Slack bus equal to zero [17].

$$\begin{gathered}\mathit{Minimize}\ \left\{Cost_{Grid}+Cost_{PV}+Cost_{WT}+Cost_{CHP}+Cost_{Boiler}+Cost_{EDR}+Cost_{HDR}++Cost_{Storage}+Cost_{Emission}\right\}\\ \mathit{subject\ \ to}:\mathit{Equations}\ \ (2)-(10)\ \ \mathit{and}\ \ (14)-(52)\end{gathered} \tag{53}$$

$$P_t^{Grid}+\sum_s\rho_s\left(P_{s,t}^{PV}+P_{s,t}^{WT}\right)+P_t^{ECHP}+P_t^{E,down}+P_t^{ES,dch} = P_t^{E,up}+P_t^{ES,ch}+\sum_s\rho_sP_{s,t}^{EL}+\sum_{p,q\in Ap}B_{p,q}\left(\delta_{p,t}-\delta_{q,t}\right) \tag{41}$$

$$-F_{p,q}^{max}\le B_{p,q}\left(\delta_{p,t}-\delta_{q,t}\right)\le F_{p,q}^{max} \tag{42}$$

$$-\pi\le\delta_{p,t}\le\pi \tag{43}$$

$$\delta_{slack,t}=0 \tag{44}$$

The thermal balance of the EH is defined in (45) [21].

$$P_t^{HCHP}+P_t^{Hboiler}+P_t^{H,down}+P_t^{HS,dch}=P_t^{H,up}+P_t^{HS,ch}+\sum_s\rho_sP_{s,t}^{HL} \tag{45}$$

Eqs. (46) and (47) define the heat generation of the boiler and CHP, which is based on the gas-to-heat conversion efficiency and the input natural gas. Also, Eq. (48) model the electricity generation of CHP [18].

$$P_t^{Hboiler}=G_t^{Boiler}LHV\eta^{boiler}/\Delta T \tag{46}$$

$$P_t^{HCHP}=G_t^{CHP}LHV\eta_h^{CHP}/\Delta T \tag{47}$$

$$P_t^{ECHP}=G_t^{CHP}LHV\eta_e^{CHP}/\Delta T \tag{48}$$

2.8. Input bounds of natural gas

The maximum and minimum bounds of input natural gas for the boiler and CHP have been demonstrated as (49) and (50) [18]:

$$0\le G_t^{Boiler}\le G_{max}^{Boiler} \tag{49}$$

$$0\le G_t^{CHP}\le G_{max}^{CHP} \tag{50}$$

These limits show that the boiler and CHP should meet the maximum and minimum natural input limit.

2.9. Other related constraints

The heat pipe should meet the maximum and minimum thermal power transmission bounds that are presented by (51) [18].

$$0\le P_t^{HCHP}+P_t^{Hboiler}+P_t^{HS,dch}-P_t^{HS,ch}\le P_{max}^{H} \tag{51}$$

The bounds of exchanged power with the main grid is shown in (52) [25].

$$P_{max}^{Grid}\le P_t^{Grid}\le P_{max}^{Grid} \tag{52}$$

3. Multi-objective optimization

Multi-objective optimization is a category of decision-making involving two or more objectives to be optimized simultaneously [29, 30]. The proposed model considers the cost, emissions, average reserve, and power losses. The total cost of EH has been considered as the main objective because of its high importance. The others have the same importance in the EH's perspective and are considered as secondary objectives. Considering various objectives with different priorities, a combined LFA is applied to the model. The proposed LFA has implemented in two-steps as follows:

i) **Step1:** The EH only considers its total cost to determine the best plan of action. The total cost of EH includes the cost of imported power from the main grid, operation and maintenance (O&M) cost of local units, cost of energy storage systems, cost of the electrical and thermal DR programs, and cost of the pollutant emission. Therefore, in step 1, a stochastic single-objective optimization is performed considering the following constraint:

The $Cost^*$ is determined as the optimal cost of EH, and it is used in step 2.

i) **Step2:** In this step, we optimize the emission, ARI, and LII simultaneously. We utilize the Fuzzy approach to combine the non-homogenous objectives. The mathematical formulation of the Fuzzy approach is presented in (54):

$$\begin{gathered}\mathit{Max\ Min}\ \{\mu_k,\mu_s\}\\ \mathit{subject\ to}:\\ \mu_k=\frac{F_k-F_k^{Nadir}}{F_k^{Ideal}-F_k^{Nadir}}\quad\forall k\in\{1,\ldots,l\}\\ \mu_s=\frac{F_s^{Nadir}-F_s}{F_s^{Nadir}-F_s^{Ideal}}\quad\forall s\in\{l+1,\ldots,l+r\}\end{gathered} \tag{54}$$

where μ_k and μ_s are the membership functions of objective functions that should be maximized and minimized, respectively [31]. Also, F_s^{Nadir} and F_s^{Ideal} are the worst and the best response for objective F_s, respectively. The value of F_s^{Nadir} and F_s^{Ideal} have been used for the normalization of the non-homogeneous objectives which are obtained by solving the single-objective problems. It should be noted that the original Fuzzy approach (54) only considers the worst-case and has a non-compensatory approach [31]. To prevent this problem, we modify the original problem Eq. (54) and convert it to Eq. (55):

$$\begin{gathered}\mathit{Maximize}\ \left\{\frac{1}{l+r}\left[\sum_{k=1}^{l}\mu_k+\sum_{s=l+1}^{l+r}\mu_s\right]\right\}\\ \mathit{subject\ to}:\\ \mu_k=\frac{F_k-F_k^{Nadir}}{F_k^{Ideal}-F_k^{Nadir}}\quad\forall k\in\{1,\ldots,l\}\\ \mu_s=\frac{F_s^{Nadir}-F_s}{F_s^{Nadir}-F_s^{Ideal}}\quad\forall s\in\{l+1,\ldots,l+r\}\end{gathered} \tag{55}$$

Unlike Eq. (54), the modified Fuzzy approach Eq. (55) considers all of the secondary objectives and enjoys the compensatory approach to improve the performance of the optimization problem. Since the cost of EH is the main objective function, we import the main objective function in Eq. (55) to the second step keeps the cost of EH in an acceptable range. Therefore, the final optimization problem is formulated as Eq. (56):

$$\begin{aligned}
&Maximize\ \left\{\frac{1}{l+r}\left[\sum_{k=1}^{l}\mu_k+\sum_{s=l+1}^{l+r}\mu_s\right]\right\}\\
&\mu_k=\frac{F_k-F_k^{Nadir}}{F_k^{Ideal}-F_k^{Nadir}}\quad \forall k\in\{1,\ldots,l\}\\
&\mu_s=\frac{F_s^{Nadir}-F_s}{F_s^{Nadir}-F_s^{Ideal}}\quad \forall s\in\{l+1,\ldots,l+r\}\\
&\qquad subject\ to: Cost\le\alpha\times Cost^{*}\\
&\qquad\quad Equations\ \ (1)-(52)
\end{aligned}\tag{56}$$

where parameter α is the safe margin for the main objective function. If $\alpha = 1$, step 2 remains the cost of EH at its optimum and searches to improve the secondary objectives. If $\alpha > 1$, the searching area in step 2 will be increased. Therefore, the secondary objectives will be improved by more than $\alpha = 1$. Also, it should be noted that if $\alpha > 1$, the cost of EH has been increased from its optimum. The optimal value of α is depended on the operator preferences, and can be different for the systems. Given that ARI, LII, and emission are the secondary objectives, the extended optimization problem Eq. (56) is shown in Eq. (57):

$$\begin{aligned}
&Maximize\ \left\{\frac{1}{3}\left[\frac{F_{LII}-F_{LII}^{Nadir}}{F_{LII}^{Ideal}-F_{LII}^{Nadir}}+\frac{F_{ARI}-F_{ARI}^{Nadir}}{F_{ARI}^{Ideal}-F_{ARI}^{Nadir}}+\frac{F_{Emission}^{Nadir}-F_{Emission}}{F_{Emission}^{Nadir}-F_{Emission}^{Ideal}}\right]\right\}\\
&\qquad subject\ \ to: Cost\le\alpha\times Cost^{*}\\
&\qquad\quad Equations\ (1)-(52)
\end{aligned}\tag{57}$$

The proposed model is able to consider various weights based on operator preferences. The paired comparison matrix can be employed to define the weight of the objectives [32, 33]. In this paper, we assume that the weights of the secondary objectives are the same ($w_{LII} = w_{ARI} = w_{Emission} = 0.33$).

The flowchart of the proposed model is shown in Fig. 1. At first, the scenarios of uncertain inputs are generated using the appreciated PDFs. The generated scenarios and other input data have been imported to the two-steps. The total daily cost of EH is minimized at the first step, where the optimal cost and primary scheduling of EH are determined. In step 2, the secondary objectives have been optimized, provided that the cost of EH remains in the acceptable range. Actually, the second step of optimization modifies the primary scheduling of EH to improve the emission, ARI, and LII. Finally, the results of the second step have been considered as the final results. If the second step of optimization cannot improve the secondary objectives, the primary scheduling of EH has been considered as the final result. It should be noted that the proposed model does not need any iteration between two-steps because the optimal value of objectives has been determined in the first iteration.

The proposed model can be easily applied in the current distribution system because it does not need significant changes in the distribution systems. Future distribution systems include several microgrids that are known as multi-microgrid systems. In the multi-microgrid systems (single or multi-carrier), each microgrid has an operator that they have various objectives. Besides, the safe margin of each operator can be different. The proposed model is able to consider various objectives and different safe margin. Also, the proposed model is suitable for private microgrids or energy hubs because it considers a safe margin for the cost of the system.

4. Input data and simulation results

The proposed model is applied to the standard IEEE 5-bus test system. The proposed model is able to apply on the small-scale and large-scale systems because it ensures the stability for the optimization problem. In this paper, we consider α=1.05. We consider a general structure of the EH considering photovoltaic panel, wind turbine, boiler, CHP unit, electrical, and thermal energy storage systems. The characteristics of energy storage systems, CHP, and boiler, are presented in Table 2 and Table 3 [18].

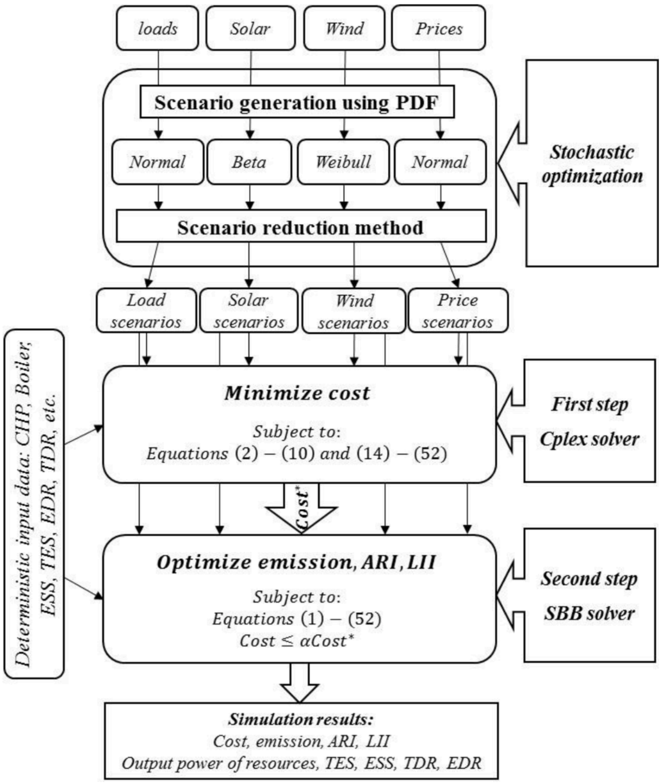


Fig. 1. The flowchart of the proposed model.

The scenarios of electrical and thermal loads are shown in Figs. 2 and 3, respectively. The maximum DR participation of both electrical and thermal loads is set to 10 percent. The maximum exchanged power with the main grid is 500 kW for each time slot. The ASWT.12.0-50 kW wind turbine (rated power 50 kW) is utilized in the EH. The rated, cut-in, and cut-out speeds of ASWT.12.0-50 are 11 m/s, 2.5 m/s, and 25 m/s, respectively. The values of u^{Grid}, u^{CHP}, and u^{Boiler} are 0.187 kg/kWh, 0.177 kg/kWh, and 0.177 kg/kWh, respectively [18]. Also, T^{c} and N^{MPT} for PV modules are considered 25°C and 0.005, respectively.

The scenarios of renewable generation are provided in Figs. 4 and 5 [25]. Finally, the price scenarios are demonstrated in Fig. 6 [34].

Two case studies are investigated to evaluate the performance of the proposed model:

- Case study I: A general energy scheduling has been performed to minimize the operation cost of EH. This energy scheduling is commonly used in previous researches as [18] and [19].
- Case study II: the performance of the proposed model is investigated in this case study. The daily total cost of EH is the main objective

Table 2
The characteristic of energy storage systems.

Energy storage	$E^{ES,min}$ (kWh)	$E^{ES,max}$ (kWh)	$P^{ES,ch}_{min}$ (kW)	$P^{ES,dch}_{max}$ (kW)	Efficiency (%)
Electrical storage	10	100	20	20	96
Thermal storage	10	100	20	20	98

Table 3
The characteristic of CHP and boiler.

$C_{O\&M}^{CHP}$ (cents/kWh)	η_e^{CHP} (%)	η_h^{CHP} (%)	LHV (kWh/m^3)	G_{max}^{CHP} (m^3/h)
2	35	45	9.7	100
$C_{O\&M}^{boiler}$ (cents/kWh)	η^{boiler} (%)		LHV (kWh/m^3)	G_{max}^{Boiler} (m^3/h)
2.7	80		9.7	100

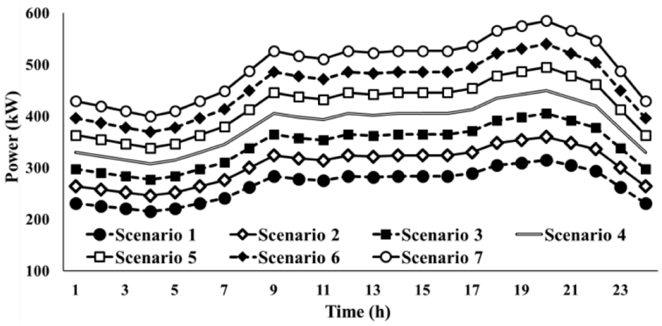


Fig. 2. Scenarios of electrical loads.

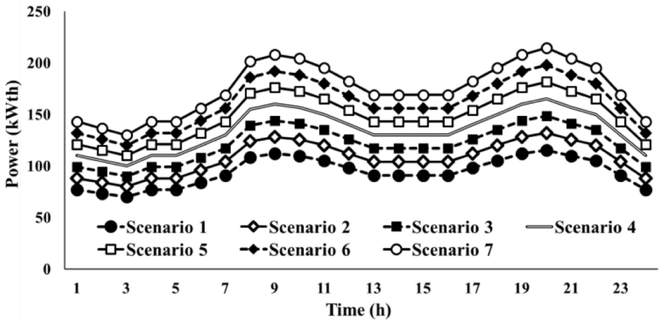


Fig. 3. Scenarios of thermal loads.

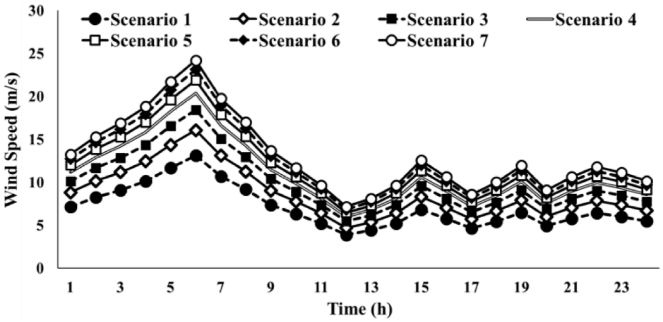


Fig. 4. Scenarios of wind speed.

function, while the emission, loss improvement index, and average system reserve are the secondary objective functions. The results of the case studies are shown in Table 4.

The results demonstrate that the proposed model significantly improves the emission of greenhouse gases, IPI, and LII of EH. The proposed model reduces the emission of greenhouse gases from 7986.99 Kg to 7227.24 Kg. Besides, the ARI of EH is increased by 79.25 kWh. Actually, the proposed model improves the greenhouse gas emission, ARI, about 9.51 and 74.87 percent, respectively. As we mentioned, the LII is one of the objectives. In order to improve the LII, the operator imports less energy from the upstream network. As a result, the power passes from shorter lines, and the power losses have improved by 24.56 percent. The hourly loss of the EH is presented in Fig. 7.

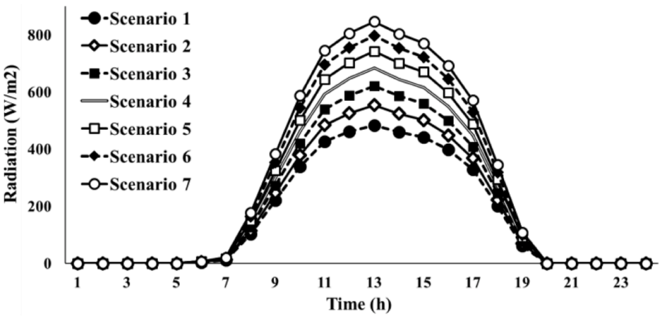


Fig. 5. Scenarios of solar radiation.

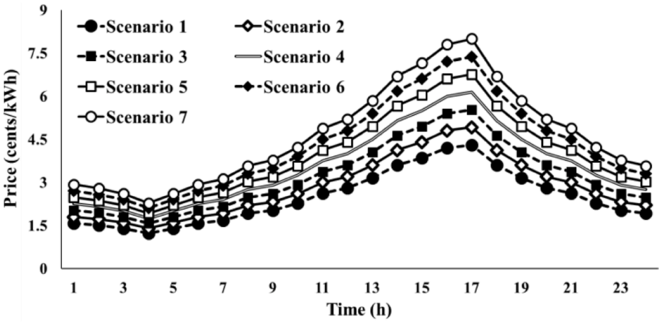


Fig. 6. Scenarios of prices.

Table 4
The results of case studies.

Case studies	*Cost (cents)*	*Emission (Kg)*	*ARI (kWh)*	*IPI (%) [25]*	*LII (%)*
Case I	51972.11	7986.66	105.85	24.97	-
Case II	54570.71	7227.24	185.10	40.52	24.56
Improvement (%)	-5	+9.51	+74.87	+62.24	+24.56

According to Fig. 7, the hourly loss of EH the most of the time is improved because the importing power from the upstream network has been reduced. The importing power from the upstream network is shown in Fig. 8.

Fig. 8 shows that importing power from the upstream network in case II is less than the case I. In the proposed model, the operator of the EH supplies most of the required energy from the local resources. Therefore, the independence of the EH is improved and reaches from 24.97 percent to 40.52 percent. The output electrical and thermal power of the CHP unit is presented in Figs. 9 and 10.

Figs. 9 and 10 show that local resources, as well as the CHP unit, generates more energy in the proposed model. There are several reasons for this. At first, the operator wants to reduce importing power from the upstream network to improve the loss of the system. So, the required energy should be supplied by local resources. Second, the emission of greenhouse gases is considered as the objective function of the proposed model. Due to the local resources have a low emission coefficient, they generate more power in case II. In case I, the CHP only is utilized at the peak periods, while in the proposed model, most of the thermal and electrical load is supplied by CHP. The output energy of the boiler is shown in Fig. 11.

According to Fig. 11, the boiler is only used in case I because in case II, all of the required thermal energy is provided by CHP. In case II, the operator utilized CHP to import less electrical energy from the upstream network. Therefore, thermal energy is supplied by CHP, and the EH does not need the boiler. The performance of the electrical and thermal

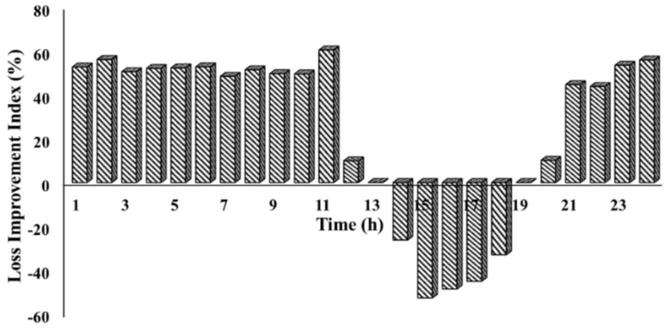


Fig. 7. The hourly loss of EH.

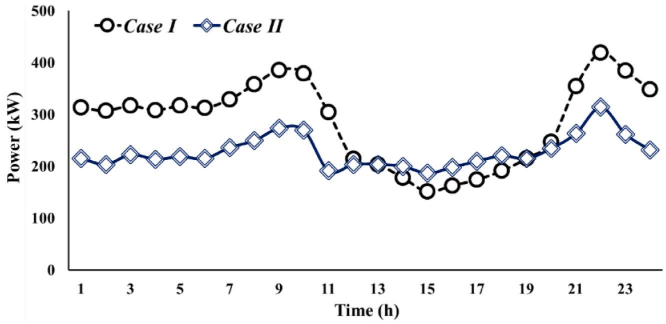


Fig. 8. Purchasing power from the upstream network

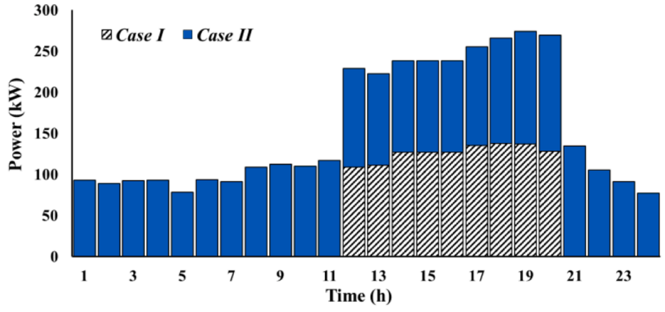


Fig. 9. The electrical output power of CHP.

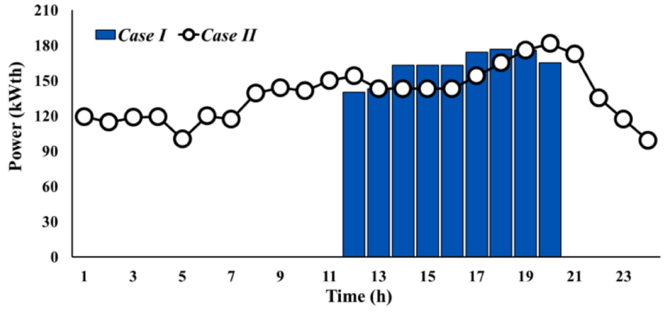


Fig. 10. The thermal output power of CHP.

storages for two case study is shown in Fig. 12.

Fig. 12 demonstrates that in case I, the electrical and thermal storages are charged at the off-peak periods when the wholesale market price is low, and the stored energy has been discharged at the peak period to reduce the daily cost of the EH. Unlike case I, in case II the storage systems have been fully charged at off-peak periods to maximize the reserve capacity of the EH. In the proposed model, the operator only charges storage systems to create a safe margin for itself. The ARI of EH in case I is 105.85 kWh, which is improved by 74.87 percent in case II. The effect of the electrical DR programs on the operation of the EH is presented in Figs. 13 and 14, respectively.

Figures show that a part of loads has been shifted from the peak period to the off-peak times, so the cost of EH has been reduced. Actually, the operator uses the potential controllable loads to re-shape the load profile according to the wholesale market price. A sensitivity analysis is performed about the parameter α to investigate the efficiency of the prioritized model. The parameter α has been increased from 1.00 to 1.05, and the simulation results are presented in Table 5.

Given that the total daily cost of EH is the main objective, we consider $1 \leq \alpha \leq 1.05$. Based on the preference of the operator, the parameter α can be chosen more than these values, where the operator should trade-off between the objectives. The simulation results show that by increasing α, the secondary objectives are improved significantly. This sensitivity analysis ensures the efficiency of the proposed model and shows that its efficiency is not dependent on the specific α. It should be noted that if the cost margin is set 1, the proposed two-step framework keeps the cost of the EH in its optimum, while the greenhouse gas emissions, ARI, IPI, and LII are improved as 2.83 percent, 47.46 percent, 16.06 percent, and 4.49 percent, respectively.

A sensitivity analysis has been performed in Figs.15 and 16 to show the efficiency of the proposed model in different conditions. The $\alpha = 1.05$ and Ideal and Nadir solutions are set according to the base case. Fig. 15 evaluates the performance of the proposed model in the different DR levels.

We can observe that the proposed model significantly improves the IPI and ARI in different DR levels. The improvements for ARI and IPI are always more than 68% and 51%, respectively. Also, the emission of greenhouse gases has been improved between 8-9 % in different conditions. By increasing the DR level, the operator shifts most of its load to the off-peak period. Therefore, at the peak-period, the energy exchange with the main grid has been reduced. As a result, the power losses decreased, and LII reduced. Nevertheless, the proposed model improves the ARI, LII, IPI, and emission in different DR levels. The performance of the proposed model in different scales of battery energy resources is shown in Fig. 16. The Parameter BESSF (Battery Energy Storage Scaling Factor) is a scaling factor to scale the base-case battery energy storage capacity.

The results of Fig. 16 demonstrate that the improvements in the proposed model in terms of ARI, IPI, and emissions are always more than 63%, 58%, and 9%, respectively. Also, the LII has positive values. It shows that the proposed model improves the power losses in different BESSFs. According to the Figs. 15 and 16, the proposed model does not depend on the specific working conditions and has this capability to improve the secondary objectives. The proposed model is solved under GAMS software on a core i7, 2.2 GHz processor with 4 GB of RAM. The first step is solved by Mixed-Integer Linear Programming (MILP) solver Cplex and its run time is 0.078 second. The second step is modeled by Mixed-Integer non-Linear Programming (MINLP) solver SBB and its run time is 27.89 seconds. The optimal solutions of the two steps are

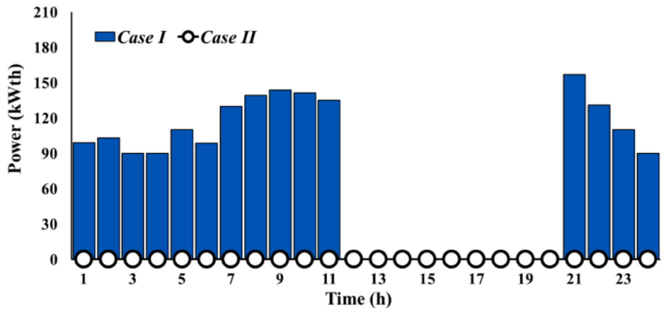
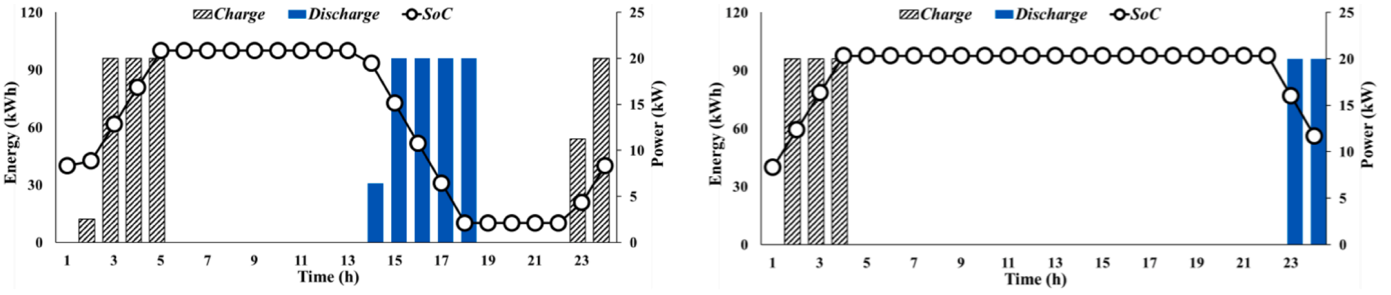
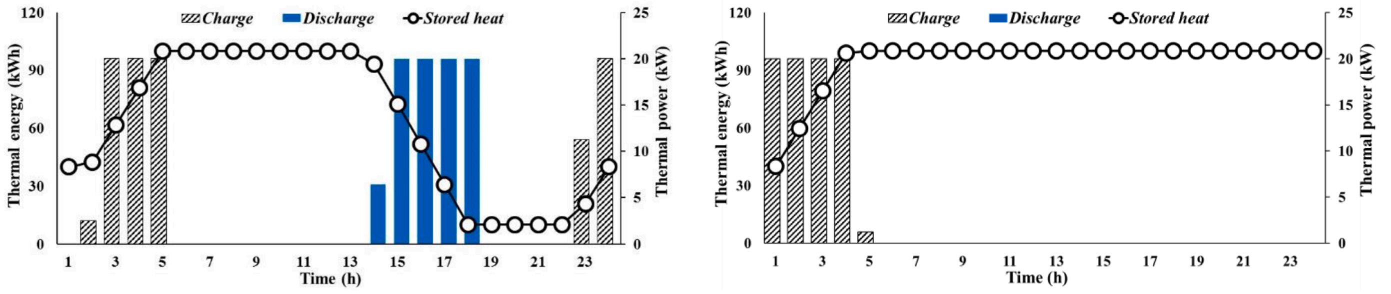


Fig. 11. The performance of the boiler in case studies.



a. Performance of electrical energy storages in case I

b. Performance of electrical energy storages in case II



c. Performance of thermal energy storages in case I

d. Performance of thermal energy storages in case II

Fig. 12. The performance of electrical and thermal storages.

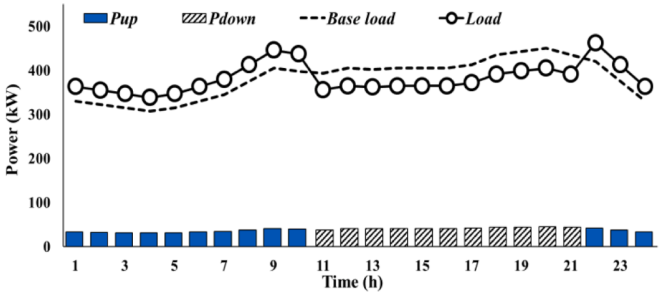


Fig. 13. The electrical load of EH in case I.

Table 5
The sensitivity analysis of parameter α.

Margin (%)	*Cost (cents)*	*Emission (Kg)*	*ARI (kWh)*	*IPI (%)*	*LII (%)*
Case I	51972.11	7986.66	105.85	24.97	-
α=**1.00**	51972.11	7759.58	156.09	28.98	4.49
α=**1.01**	52491.83	7530.29	166.19	33.47	10.53
α=**1.02**	53011.55	7366.13	169.38	36.69	16.68
α=**1.03**	53531.27	7226.94	171.13	39.48	22.54
α=**1.04**	54050.99	7214.38	182.50	40.26	23.90
α=**1.05**	54570.71	7227.24	185.10	40.52	24.56

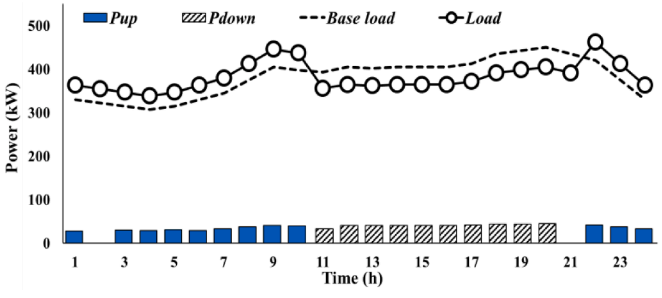


Fig. 14. The electrical load of EH in case II

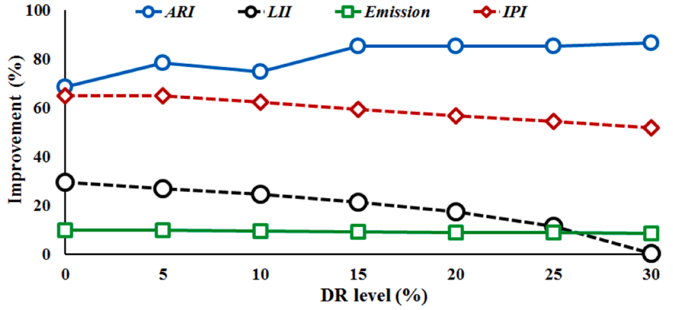


Fig. 15. The performance of the proposed model in different DR levels.

obtained with an optimality gap of 0.0001%.

5. Conclusion

This paper proposed multi-objective energy management of EH considering the economic, environmental, and security aspects. In this strategy, the cost of the EH was minimized at first to determine the optimal solution from an economic perspective. The secondary objectives, namely improvement of greenhouse gas emission, system reserve, and loss, were optimized provided that the cost of the EH remains within the allowable range. Besides, the thermal and electrical demand response programs could provide the opportunity for cost-saving to the EH. The uncertainty of renewable generation, and market prices, loads were applied to the model by probabilistic optimization to bring the model closer to reality. The proposed model is able to consider various safe margin. Therefore, it can be applied to different systems with various preferences. In future work, we will be modeled the multi-carrier multi-microgrid systems as the multi-energy hub to investigate the efficiency of the proposed model. The operators of energy hubs will

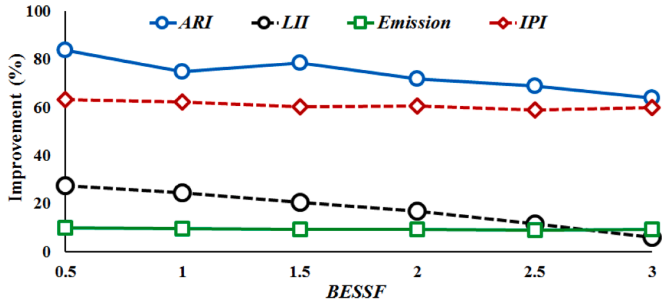


Fig. 16. The performance of the proposed model in different BESSFs.

be had different objectives that can be modeled as a mix of two-step and multi-step optimization.

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i) Discussion and analysis
ii) Editing the revise draft preparation

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We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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