A Multi-objective Framework for Optimal Energy Management of an Energy Hub: A Mixed-integer Linear Programming based on Augmented ε-Constraint Method

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Manuscript received 31 January, 2023; revised 29 April, 2023; accepted 13 July, 2023. Paper no. JEMT-2301-1429.

Energy hubs (EHs) by considering the interaction between various energy careers are known as promising tools to increase the efficiency of energy networks and pave the way for making the most of resources' advantages. In addition, EHs due to their ability for converting different types of energies provide the appropriate conditions for increasing green energies such as renewable energy resources and electric vehicles which propels energy networks towards net-zero networks. However, combining a wide range of resources in addition to increasing the complexity of the optimization problem raises the need to model different objectives in the formulation. In this regard, in this paper, a multi-objective mixed integer linear programming is proposed for optimal management of an EH. Three goals are taken into account in this study: minimizing total operation cost, minimizing the emission of fossil-fueled based units, and minimizing interruption in demand. The augmented -constraint method is utilized to solve the multi-objective problem.

keywords: *Energy hub, Multi-objective, Hydrogen storage, renewable energy sources, Combined heat and power unit.*

http://dx.doi.org/10.22109/JEMT.2023.384067.1429

NOMENCLATURE

Sets

s Index for scenarios

i Index for conventional distributed generations (CDGs)

t Index for time

$c \subset i$ Index for combined heat and power units (CHPs)

e Index for electric storage (ESs)

w Index for wind turbines (WTs)

h Index for hydrogen-based system (HBS)

k Index for emission type (NO_x, CO_2, and SO_2)

Parameters

$a_i^{CDG}, b_i^{CDG}, c_i^{CDG}$ Cost co-efficient of CDGs

p_i^{CDG-L}, p_i^{CDG-H} Maximum and minimum output power of CDGs

RU_i, RD_i Ramp-up and ramp-down rate of CDGs

p_c^{CDG-A},p_c^{CDG-B}, p_c^{CDG-C},p_c^{CDG-D} Power coefficient of CHP units

T_c^{CDG-A},T_c^{CDG-B}, T_c^{CDG-C},T_c^{CDG-D} Thermal coefficient of CHPs

M Big value

$D_{s,t}^{Heat}$ Total heat demand

$P_e^{CH,MAX}$,$P_e^{DC,MAX}$ Maximum charging and discharging rate of ESs

$\eta_e^{S,CH}$,$\eta_e^{S,DC}$ Charging and discharging efficiency of ESs

$SOC_e^{S,MIN}$,$SOC_e^{S,MAX}$ Minimum and maximum SOC of ESs

CCO_e^S Cost factor of ESs

DRP Percentage of interruptible loads in demand response program

D_e^{ELEC} Total electric demand

$\theta_{s,t}$ Wind speed

θ_W^{CUTIN},θ_W^{CUTOUT},θ_W^{RATED} Cut-in, cut-out, and rated speed of WTs

Pwt_W^{MAX} Maximum output power of WTs

$\eta_h^{HS,CH}$,$\eta_h^{HS,DC}$ Charging and discharging efficiency of hydrogen storages

$H_h^{HS,MIN}$,$H_h^{HS,MAX}$ Maximum capacity of stored hydrogen in the hydrogen storages

η_h^{PH} Efficiency of producing hydrogen by hydrogen system

η_h^{TH} Efficiency of producing power by hydrogen system

D_t^{HV} Total hydrogen vehicles demand

a_h^{PH},b_h^{PH} Cost coefficients of producing hydrogen by HS

a_h^{BH},b_h^{BH},c_h^{BH} Cost coefficients of producing power by HS

CCO_h^{HS} Cost factor of hydrogen storages

$D_{s,t}^{ELEC}$ Total residential electric demand

$P_{s,t}^{EV}$ Total electric vehicles demand

$EP_{s,t}$ Electricity price

$EF_{i,k}^{CDG}$ Emission factor of CDGs for each emission type

T_i^{CDG-ON},$T_i^{CDG-OFF}$ On-time and off-time constraints of CDGs

Variables

$CCDG_{s,i,t}$ Cost of CDGs

$u_{s,i,t}$ Binary variable for commitment state of CDGs

$P_{S,i,t}^{CDG}$ Generated power by CDGs

$X_{s,i,t}^{CDG-ON}$,$X_{s,i,t}^{CDG-OFF}$ On-time and off-time limits of CDGs

$T_{s,c,t}^{CDG}$ Total generated heat by CHPs

$u_{s,e,t}^{S,CH}$,$u_{s,e,t}^{S,DC}$ Binary variables for charging and discharging state of ESs

$P_{s,e,t}^{S,CH}$,$P_{s,e,t}^{S,DC}$ Amount of stored or released power by ESs

$SOC_{s,e,t}^S$ SOC od ESs

$CES_{s,e,t}$ Cost of ESs

$DR_{s,t}^I NU$ Amount of interruptible load in the DR program

$D_{s,t}^{ELEC,DR}$ Load after implementing the DR program

$P_{s,w,t}^{WT}$ Generated power by WTs

$H_{s,h,t}^{HS}$ Level of stored hydrogen in hydrogen storages

$H_{s,h,t}^{HS,CH}$,$H_{s,h,t}^{HS,DC}$ Amount of stored or released hydrogen by hydrogen storages

$u_{s,h,t}^{HS,CH}$,$u_{s,h,t}^{HS,DC}$ Binary variables for charging and discharging state of hydrogen storages

$H_{s,h,t}^{TH}$ Amount of consumed hydrogen by HS to produce electricity

$P_{s,h,t}^{P2H}$ Amount of power to hydrogen in HS

$H_{s,h,t}^{PH}$ Amount of produced hydrogen by HS

$P_{s,h,t}^{H2P}$ Amount of hydrogen to power in HS

$CHS_{s,h,t}$ Cost of HS

$P_{s,t}^{UN}$ Amount of exchanged power with up-stream network

Abbreviations

CHP Combined heat and power unit

CDG Conventional Distributed generation

DR Demand response

EH Energy hubs

ES Electric storage

EV Electric vehicle

HBS Hydrogen-based system

HS Hydrogen storage

HV Hydrogen vehicle

MC Monte Carlo

$MILP$ Mixed integer linear programming model

$MINLP$ Mixed integer nonlinear programming model

RES Renewable energy resource

SOC State of charge

UN Upstream network

1. INTRODUCTION

In recent years, to decrease the dependency on fossil fuels and to conquer global warming challenges new technologies and concepts are developed in power systems. An increase in the population of cities, besides creating systems to satisfy the demand of consumers in various aspects such as electric, water, and heat demands creates a need of optimizing all of these energy careers together in order to increase the efficiency of energy networks. The concept of energy hubs (EHs) is created to optimize several energy careers together [1]. Toward more realistic EHs two aspects should be implemented. First, consider important resources i.e., renewable energy resources (RESs), electric vehicles (EVs), and combined heat and power units (CHPs). It is crystal clear that in the near future, the penetration of these resources has been increased dramatically owing to their enormous advantages. Thus, these resources are an inseparable part of EHs. In addition, EHs are introduced to consider the interaction among different energy careers. In this regard, considering different goals in the optimal energy management of an EH plays a decisive role. Furthermore, nowadays, hydrogen is known as a reliable and useful energy source that can be used by hydrogen vehicles (HVs) to raise the efficiency of EHs [2].

Quite a few works have been published in the field of energy management of an EH. In these papers, authors concentrate on providing appropriate approaches for modeling the interaction between different energy careers. However, their methods only consider one aspect by modeling a single objective problem. In addition, their methods suffer a lack of modeling all essential resources and constraints. A basic method without modeling the well-known resources such as EVs, HVs, and RESs is implemented in [3]; furthermore, this work is not investigated demand response (DR) and degradation cost of storages. Voropai et al. [4] has offered a simple model for an EH with the aim of peak load shaving. In this model RESs, EVs, and HVs are not modeled. In addition, DR as a key concept in recent energy networks is not investigated. A model for planning an EH in a short-term horizon is done in [5], but this work does not investigate any of the EVs or HVs. In [6], an EH is implemented by considering water and electricity networks interactions. However, this work does not consider all the important constraints such as the emission of fossil-fueled based units, and degradation cost of storages, and the DR program. Ma et al. [7], have proposed a method based on a mixed integer linear programming model (MILP) with the aim of minimizing cost; however, the uncertainty of RESs is not investigated in this method in addition to not considering EVs, HVs, and CHPs. A single objective problem to minimize the costs of an EH is studied in [8], this work is a mixed integer nonlinear programming model (MINLP) problem that is not suitable for large-scale problems due to high computational cost. A metaheuristic method based on a quantum particle swarm algorithm for optimal scheduling of an EH is presented in [9]. Metaheuristic-based methods need a large number of iterations to search the space answer and cannot guarantee the global optimal solution. A scenario-based method is presented in [10] for minimizing cost; the scenarios are generated based on the Monte Carlo (MC) method. Moreover, this method is not modeled HVs and EVs. An optimization problem is done for the energy management of an EH in [11]. However, uncertainty modeling, emission effects, and HVs are not investigated. In addition to the above-mentioned limitations of the previous works none of the references [3]-[11] does not present a multi-objective model for considering different aspects and goals in their formulation.

Recently, some papers implemented multi-objective optimizations to move toward a more realistic approach. However, there are some deficiencies in these models too. Reference [12] presented a multi-objective non-linear method for optimal bidding and scheduling of an EH by considering compressed air energy storages. This paper aims to decrease the total daily operation cost and determine the electricity price. However, this work, first, does not implement EVs, HVs, DR, emission, and storages cost, second, non-linear formulation brings a high computational cost and cannot guarantee the global optimal solution. In [13], a coastal EH is considered to reduce total operating and environmental costs. These two objectives of the nature of costs cannot be considered as two separate objective functions. Moreover, EVs and HVs are not taken into account. A method based on dynamic stochastic programming has been carried out in [14]. However, this simple formulation does not consider RESs, EVs, HVs, DR, and emissions.

According to the previous works in this field, this paper aims to cover the limitation of the former works and present an efficient multi-objective approach for optimal management of an EH. The advantage of this method is considering the most common and important sources in the EH body. EVs and HVs are modeled as the new demands in EHs. A hydrogen-based system (HBS) is also investigated to meet the demand for HVs and used the advantages of this energy. Furthermore, WTs and CHPs are modeled to increase efficiency and reduce the cost of the EH to satisfy both the heat and electric demands. Electric storages (ESs) are investigated to overcome the stochastic behavior of RESs. In addition, a wide range of constraints is taken into account to present a more realistic scheme. This type of modeling is developed based on future needs in the energy sector and paves the way to achieve net-zero networks. In fact, this paper follows three goals. First, minimizing the total cost of the EH to consider the economic aspect. Second, minimizing the total emission of fossil fuels to overcome global warming and move

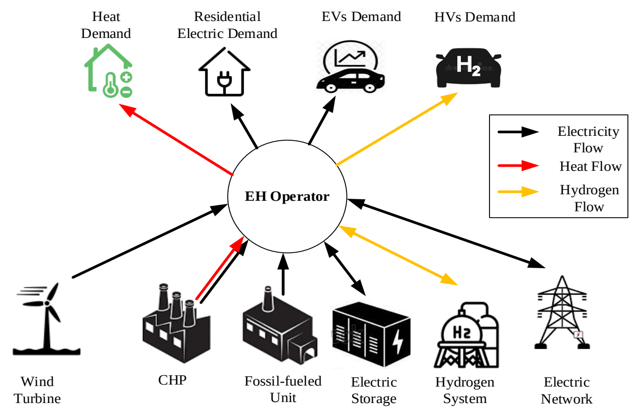

Fig. 1. Structure of the EH

towards net-zero networks. Third, minimizing interruptions in load demand to maximize the welfare of consumers. The whole optimization problem in this paper is a MILP problem which is suitable for large-scale problems and can guarantee the global optimal solution. A comparison between the existing papers in the field of EHs' optimal management is done in Table 1 to better illustrate the novelties of the proposed method in this paper. The rest of the paper is organized as follows: Section 2 provides the problem formulation. Section 3 The numerical implements numerical results of the paper. Section 4 describes the conclusions.

2. PROBLEM FORMULATION

EHs that contain different sources should solve the problem from different points of view by considering various goals. In this regard, an EH as depicted in Fig. 1 is considered. The purpose of this EH is to satisfy electric and heat demands by minimizing three goals: minimizing the total cost, minimizing emission cost, and minimizing total load interruption to increase the social welfare of consumers. The EH in this paper contains RESs, CHP, electric, and hydrogen storages. In the following, the mathematical modeling of the problem is presented.

For the conventional distributed generation units (CDGs)—fossil-fueled based units—equation (1) is used for calculating their operation cost – note that in this paper the start-up and shut-down costs are neglected. Equation (2) is used to maintain the CDGs power in the reliable range. (3) and (4) are considered to model the ramp rate constraints of CDGs. Finally, (5) and (6) demonstrate off-time and on-time limitations [15]. All of the non-linear equations are linearized based on the appropriate methods as described in [16].

$$CCDG_{s,i,t} = (a_i^{CDG} P_{(s,i,t)}^{CDG^2} + b_i^{CDG} P_{(s,i,t)}^{CDG} + c_i^{CDG}) u_{(s,i,t)} \quad (1)$$

$$P_i^{(CDG-L)} u_{(s,i,t)} \le P_{(s,i,t)}^{CDG} \le P_i^{(CDG-H)} u_{(s,i,t)} \quad (2)$$

$$P_{(s,i,t)}^{CDG} - P_{(s,i,(t-1))}^{CDG} \le [1 - u_{(s,i,t)}(1 - u_{s,i,(t-1)})]RU_i + u_{(s,i,t)}(1 - u_{(s,i,(t-1))})P_i^{(CDG-L)} \quad (3)$$

$$P_{(s,i,(t-1))}^{CDG} - P_{(s,i,t-1)}^{CDG} \le (1 - u_{s,i,(t-1)})(1 - u_{s,i,t})]RD_i + u_{s,i,(t-1)}(1 - u_{s,i,t})P_i^{(CDG-L)} \quad (4)$$

Table 1. comparison between existing work in the field of EHs' optimal energy management

Ref.	EH components							Emission cost	DR	Optimization problem	Multi-objective
	RES	CDG	ES	CHP	HBS	HV	EV				
[3]	×	✓	✓	✓	×	×	×	✓	×	MILP	×
[4]	×	✓	✓	✓	×	×	×	×	×	MATLAB Simulink	×
[5]	✓	✓	✓	✓	×	×	×	×	×	MINLP	×
[6]	✓	✓	✓	✓	×	×	✓	×	×	MILP	×
[7]	✓	✓	✓	×	×	×	×	✓	✓	MILP	×
[8]	✓	✓	✓	✓	×	×	×	×	✓	MINLP	×
[9]	✓	✓	✓	✓	×	×	×	✓	×	MILP	×
[10]	✓	✓	✓	✓	×	×	×	✓	✓	MILP	×
[11]	✓	✓	✓	✓	×	×	✓	×	×	MINLP	×
[12]	×	✓	✓	✓	×	×	×	×	×	MINLP	✓
[13]	✓	✓	✓	✓	×	×	×	✓	✓	MINLP	✓
[14]	×	✓	✓	✓	×	×	×	×	×	MILP	✓
This paper	✓	✓	✓	✓	✓	✓	✓	✓	✓	MILP	✓

$$[X_{(s,i,(t-1))}^{(CDG-ON)} - T_i^{(CDG-ON)}] * [u_{(s,i,(t-1))} - u_{(s,i,t)}] \geq 0 \quad (5)$$

$$[X_{(s,i,(t-1))}^{(CDG-OFF)} - T_i^{(CDG-OFF)}] * [u_{(s,,i,t)} - u_{(s,i,(t-1))}] \geq 0 \quad (6)$$

In addition to equations (1)-(6) for CHP units which are responsible for satisfying heat demand equations (7)-(11) are also taken into account. (7)-(10) are used to calculate heat based on generated power [17]. Heat balance is checked by (11).

$$[X_{(s,i,(t-1))}^{(CDG-OFF)} - T_i^{(CDG-OFF)}] * [u_{(s,,i,t)} - u_{(s,i,(t-1))}] \geq 0 \quad (7)$$

$$P_{(s,c,t)}^{CDG} - P_c^{CDG,B} - \frac{P_c^{CDG,B} - P_c^{CDG,C}}{T_c^{CDG,B} - T_c^{CDG,C}} (T_{(s,c,t)}^{CDG} - T_c^{CDG,B}) \geq -(1 - u_{s,c,t})M \quad (8)$$

$$P_{(s,c,t)}^{CDG} - P_c^{CDG,C} - \frac{P_c^{CDG,C} - P_c^{CDG,D}}{T_c^{CDG,C} - T_c^{CDG,D}} (T_{(s,c,t)}^{CDG} - T_c^{CDG,C}) \geq -(1 - u_{s,c,t})M \quad (9)$$

$$0 \leq T_{s,c,t}^{CDG} \leq T_c^{CDG,A} u_{s,c,t} \quad (10)$$

$$\sum_C T_{(s,c,t)}^{CDG} = D_{(s,t)}^{Heat} \quad (11)$$

Equations (12)-(16) are used to model ESs. The amount of ES charging and discharging are calculated based on (12)-(14). In addition, the state of charge (SOC) of ESs which is depend on ES charging and discharging, and their efficiency is obtained by (15) and limited by (16), (17) is the degradation cost of ES [18].

$$0 \leq P_{(s,e,t)}^{(S,CH)} \leq P_e^{(CH,MAX)} u_{(s,e,t)}^{(S,CH)} \quad (12)$$

$$0 \leq P_{(s,e,t)}^{(S,DC)} \leq P_e^{(DC,MAX)} u_{(s,e,t)}^{(S,DC)} \quad (13)$$

$$u_{(s,e,t)}^{(S,CH)} + u_{(s,e,t)}^{(S,DC)} \leq 1 \quad (14)$$

$$SOC_{(s,e,t)}^{S,MIN} = SOC_{(s,e,(t-1))}^{S} + P_{(s,e,t)}^{(S,CH)} \eta_e^{(S,CH)} - P_{(s,e,t)}^{(S,DC)} \eta_e^{(S,DC)} \quad (15)$$

$$SOC_e^{(S,MIN)} \leq SOC_{(s,e,t)}^{S} \leq SOC_e^{(S,MAX)} \quad (16)$$

$$CES_{s,e,t} = CCO_e^S (P_{s,e,t}^{S,CH} + P_{s,e,t}^{S,DC}) \quad (17)$$

The contribution of consumers in the DR in this paper is modeled as interruptible loads. The maximum limit of decreasing in load demand should be lower than DRP% of the load at that bus which is calculated based on (18). Equation (19) displays the amount of load after implementing the DR program

$$0 \leq DR_{s,t}^{INU} \leq DRP\ D_{s,t}^{ELEC} \quad (18)$$

$$D_{s,t}^{ELEC,DR} = D_{s,t}^{ELEC} - DR_{s,t}^{INU} \quad (19)$$

The output power of WT depends on wind speed which is obtained based on (20) [19].

$$P_{(s,w,t)}^{W} T = \left\{ \begin{array}{ll} 0 & \theta_{s,t} < \theta_{s,t}{}^{CUTIN}, \theta_{s,t} > \theta_W{}^{CUTOUT} \\ \frac{Pwt_w^{\max}(\theta_{s,t} - \theta_w{}^{CUTIN})}{\theta_w{}^{RATED} - \theta_w{}^{CUTIN}} & \theta_w{}^{CUTIN} < \theta_{s,t} < \theta_w{}^{RATED} \\ Pwt_w^{\max} & \theta_w{}^{RATED} < \theta_{s,t} < \theta_W{}^{CUTOUT} \end{array} \right\} \quad (20)$$

HVs are known as effective resources to decrease pollution. In this vein, it is crucial to consider a reliable source to supply their demand. Thus, this paper considers a HBS to satisfy the demand for HVs. This system as described in equations (21)-(29) has the ability to store, produce, and consume hydrogen by utilizing hydrogen storages (HSs), water electrolyzers, and fuel cells. Equation (21) is used to calculate the amount of hydrogen stored in the HS which is restricted by (22). The amount of produced or consumed hydrogen by HS is calculated based on (23)-(25). The produced hydrogen or power by the HS is obtained based on (26) and (27). Hydrogen balance is shown in (28). Finally, equation (29) shows the total cost of HS.

$$H_{s,h,t}^{HS} = H_{s,h,(t-1)}^{HS} + H_{s,h,t}^{HS,CH}\eta_h^{HS,CH} - H_{s,h,t}^{HS,DC}\eta_h^{HS,DC} \quad (21)$$

$$H_h^{HS,MIN} \leq H_{s,h,t}^{HS} \leq H_h^{HS,MAX} \quad (22)$$

$$0 \leq H_{s,h,t}^{HS,CH} \leq H_h^{CH,MAX} u_{s,h,t}^{HS,CH} \quad (23)$$

$$0 \leq H_{s,h,t}^{HS,DC} \leq H_h^{DC,MAX} u_{s,h,t}^{HS,DC} \quad (24)$$

$$u_{s,h,t}^{HS,CH} + u_{s,h,t}^{HS,DC} \leq 1 \quad (25)$$

$$H_{s,h,t}^{PH} = P_{s,h,t}^{P2H}\eta_h^{PH} \quad (26)$$

$$P_{s,h,t}^{H2P} = H_{s,h,t}^{TH}\eta_h^{TH} \quad (27)$$

$$\sum_h H_{s,h,t}^{HS,DC} + H_{s,h,t}^{PH} - H_{s,h,t}^{HS,CH} - H_{s,h,t}^{TH} - D_t^{HV} = 0 \quad (28)$$

$$CHS_{s,h,t} = (a_h^{PH} H_{s,h,t}^{PH} + b_h^{PH}) + (a_h^{BH} P_{s,h,t}^{H2P^2} + b_h^{BH} P_{s,h,t}^{H2P} + c_h^{BH}) + CCO_h^{HS}(H_{s,h,t}^{HS,CH} + H_{s,h,t}^{HS,DC}) \quad (29)$$

$$P_{s,t}^{UN} + \sum_C P_{s,c,t}^{CDG} + \sum_w P_{s,w,t}^{WT} + \sum_h (P_{s,h,t}^{H2P} - P_{s,h,t}^{P2H}) + \sum_e (P_{s,e,t}^{S,DC} - P_{s,e,t}^{S,CH}) - D_{s,t}^{ELEC,DR} - P_{s,t}^{EV} = 0 \quad (30)$$

The EH operator aims to minimize three goals in this paper: first, minimizing total cost to consider economic aspects of the problem (equation (31))—note that the first term in this equation is the cost of exchanging power with the upstream network (UN)—; second, minimizing total emission to pave the way for increasing RES's penetration and reduce dependency to fossil fuels (equation (32)); third, minimizing the total amount of interruption in consumers demands in order to maximize their welfare (equation (33)).

$$Objecive1 = minimizing \sum_s \sum_t (EP_{s,t}\ P_{s,t}^{UN} + \sum_e CCDG_{s,i,t} + \sum_e CES_{s,e,t} + \sum_h CHS_{s,h,t}) \quad (31)$$

$$Objecive2 = minimizing \sum_s \sum_k \sum_i \sum_t EF_{i,k}^{CDG}\ P_{s,i,t}^{CDG} \quad (32)$$

$$Objecive3 = minimizing \sum_s \sum_t DR_{s,t}^{INU} \quad (33)$$

3. CASE DESCRIPTION AND RESULTS

A. Software and Method Description

The optimization part is done in GAMS software using the CPLEX solver. For modeling uncertainties, the MC method is implemented in MATLAB version 2019b. All the simulation parts have been done on a PC with an Intel Core i7, 3.4 GHz CPU, and 16 GB of RAM. MC method needs a high number of scenarios for modeling stochastic parameters with good accuracy. In this regard 200 scenarios are generated for each parameter; however, this high number of scenarios leads to a high computational cost. Consequently, a method known as Kantorovich Distance is utilized to reduce scenarios to the five most probable scenarios. In addition, the multi-objective problem is implemented by using an augmented ε-constraint method. This method is based on lexicographic optimization which constructs the payoff table to find the secure Pareto optimal solutions and avoids weakly optimal solutions [20].

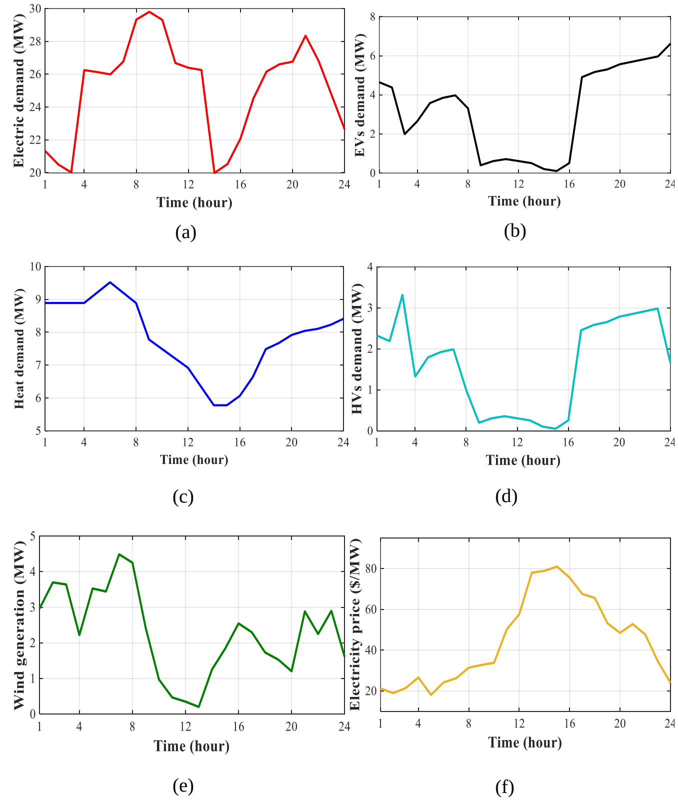

Fig. 2. Forecasted values for different parameters. (a) electric demand; (b) electric vehicles demand; (c) heat demand; (d) hydrogen vehicles demand; (e) wind turbines' generated power; (f) electricity price.

B. Input Data

The overall structure of the EH is shown in Fig. 1. Data for three years from 2019 to 2022 are used as the dataset [21–23]. The load profile is selected based on reference [23]. Also, the weather data of Iran is used to calculate the WTs' output power [22]. For the electricity price, the data from IESO for Ontario province are selected [24]. The National Household Travel Survey (NHTS) data [25] is used to model a residential load profile for EVs and HVs. The stochastic input parameters for the average MC scenarios are depicted in Fig. 2. Tables 2-5 are shown the input data for various sources. DDGs data is presented in Table 2. DDG1 is a CHP unit, extra information for this unit is presented in Table 3. HS data is presented in Table 4. Tables 5 and 6 show the ES data and emission data, respectively [26]. The ES cost factor (CCO_e^S) is 0.27\$/MW and for HS (CCO_h^{HS}) is 0.1\$/MW. WD Cost Factor (DES_{CF}) is 0.02\$/MW, WD unit data is presented in [18].

C. Numerical Results

The optimization problem is run for the proposed EH as illustrated in Fig. 1 and based on data in tables 2-6. The results of this study are presented in figures 3-7 and tables 7 and 8. In Table 7, the payoff matrix for three objective functions is given. In addition, after implementing the ε-constraint method fifteen Pareto optimal solutions are obtained for this problem. These

Table 2. DDGs data

Parameter	DDG1	DDG2
$a_i^{CDG}(\frac{\$}{MW^2h})$	1.8	1.6
$b_i^{CDG}(\frac{\$}{MWh})$	14	15
$c_i^{CDG}(\frac{\$}{h})$	45	43
$RU_i(MW)$	5	3
$RD_i(MW)$	5	3
$T_i^{CDG-OFF}(h)$	4	3
$T_i^{CDG-ON}(h)$	4	3
$P_i^{CDG-L}(MW)$	1	1
$P_i^{CDG-H}(MW)$	17	8

Table 3. CHP data

Parameter (MW)	DDG1
$P_c^{CDG,A}$	18
$P_c^{CDG,B}$	15
$P_c^{CDG,C}$	8
$P_c^{CDG,D}$	9
$T_c^{CDG,A}$	17
$T_c^{CDG,B}$	18
$T_c^{CDG,C}$	12
$T_c^{CDG,D}$	0

Table 4. Hydrogen system data

Parameter	Value	Parameter	Value
$a_h^{BH}(\frac{\$}{MW^2h})$	0.0027	$H_h^{CH,MAX}(MW)$	3
$b_h^{BH}(\frac{\$}{MWh})$	5.06	η_h^{PH}	0.8
$c_h^{BH}(\frac{\$}{h})$	14.4	η_h^{TH}	0.7
$a_h^{PH}(\frac{\$}{MWh})$	1.41	$H_h^{HS,MAX}(MWh)$	17
$b_h^{PH}(\frac{\$}{h})$	0.125	$H_h^{HS,MIN}(MWh)$	4
$H_h^{DC,MAX}(MW)$	3	$\eta_h^{HS,CH}$,$\eta_h^{HS,DC}$	0.9

Pareto optimal solutions are figured in Fig. 3 In order to show

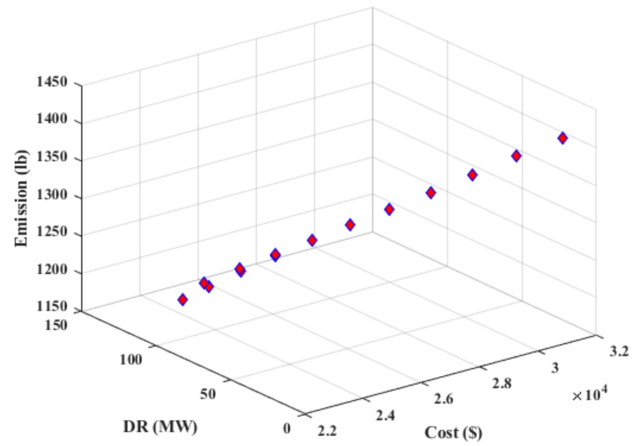

Fig. 3. Pareto optimal solutions

the numerical results of the study in the next figures and table (figures 4-7 and Table 8) the results are presented for one of these Pareto optimal solutions (i.e., Cost=23985.169, DR=120.798, and EM= 1170.544). Total residential electric demand before and after implementing the DR program (load interruption) is demonstrated in Fig. 4. In this paper, it is supposed that 20% of the load can be reduced during the DR program. As stated in this figure, the contribution of the DR program is low during the early hours of the day, and it increases from 12-24 when the electricity price is high (Fig. 2 (f)). In Fig. 5 the generated power by

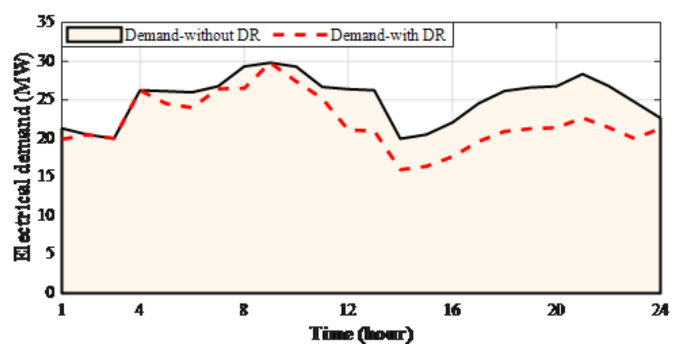

Fig. 4. Electric load demand before and after implementing the DR program.

two DDGs is presented. DDG1 which is responsible for meeting the heat demand of the EH adjusts its power according to both heat and electric demand. In addition, DDG2 which has a lesser operation cost than DDG2 is operated at its maximum power limit for 24 hours. Fig. 6 shows the amount of power exchanges between the UN and the EH. Positive values indicate purchasing power from the UN and negative values indicate selling power. As can be seen from this figure, in most hours the EH purchases power from the UN, especially during the early hours of the day in low price hours to decrease three objectives (cost emission, and interruption in demand). Moreover, the EH sells power to the UN in hours 13-16 when the electricity price is at its maximum amount (Fig. 2 (f)). The performance of HBS is shown in Fig. 7. Due to the fact that this system is responsible to satisfy

Table 5. ES data

Parameter	$SOC_e^{S,MIN}$ (MWh)	$SOC_e^{S,MAX}$ (MWh)	$P_e^{CH,MIN}$ (MW)	$P_e^{CH,MAX}$ (MW)	$\eta_e^{S,CH}$ $\eta_e^{S,DC}$
Value	1	5	1	1	0.75

Table 6. Emission data

Unit	Emission type	$EF_{i,k}^{CDG}(lb/MWh)$
CDG	NO_x	0.44
	SO_2	0.008
	CO_2	1.596

Table 7. Payoff matrix for different objectives.

Cost ($)	Obj1 (Cost)	Obj2 (DR)	Obj3 (Emission)
Obj1 (Cost)	23618.839	120.798	1179.144
Obj2 (DR)	30984.449	0	1431.915
Obj3 (Emission)	23985.169	120.798	1170.544

the hydrogen demand of HVs, this system consumed power to produce hydrogen. Its maximum generation is adjusted based on the HVs demand (Fig. 2 (d)) and the surplus of this hydrogen is stored in the HS. Finally, Table 8 presents the detail of the operation cost for this Pareto optimal point based on different components

4. CONCLUSIONS

In this paper, a model based on multi-objective optimization is proposed for satisfying the heat, electric, and hydrogen demand of an energy hub (EH). A wide range of important components and constraints are taken into account to present a more realistic solution based on the needs of the future energy networks such as renewable energy resources, combined heat and power units, electric and hydrogen storages, and electric and hydrogen vehicles. In addition, the emission cost of fossil-fueled-based units is taken into account to pave the way for increasing the penetration of renewable energy resources. Three goals are minimized in this formulation, first, minimizing cost, second, minimizing the emission of fossil fuels, and third, minimizing interruptions in load demand. The whole problem is formulated as a mixed integer linear programming model (MILP) which has the ability to solve large-scale problems and is solved by the augmented ε-constraint method to find the secure Pareto optimal solutions and avoids weakly optimal points.

Table 8. Detail of total operation cost

Cost ($)	Value ($)
DDG	16535.962
HS	4148.825
UN	3300.381
Total cost	23985.169

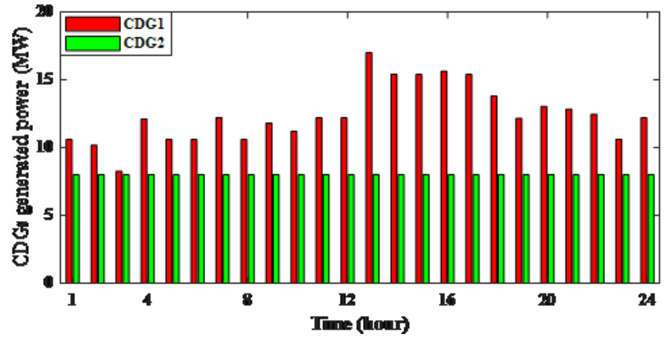

Fig. 5. DDGs output power

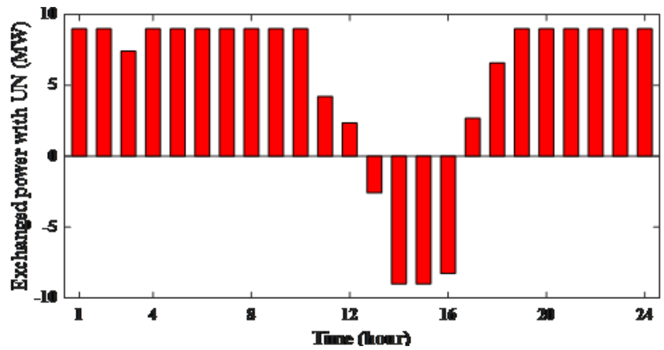

Fig. 6. Amount of exchanged power between the EH and UN

ACKNOWLEDGMENT

This work has been supported by the Center for international scientific studies & collaboration (CISSC), Ministry of Science, Research, and Technology, Islamic Republic of Iran.

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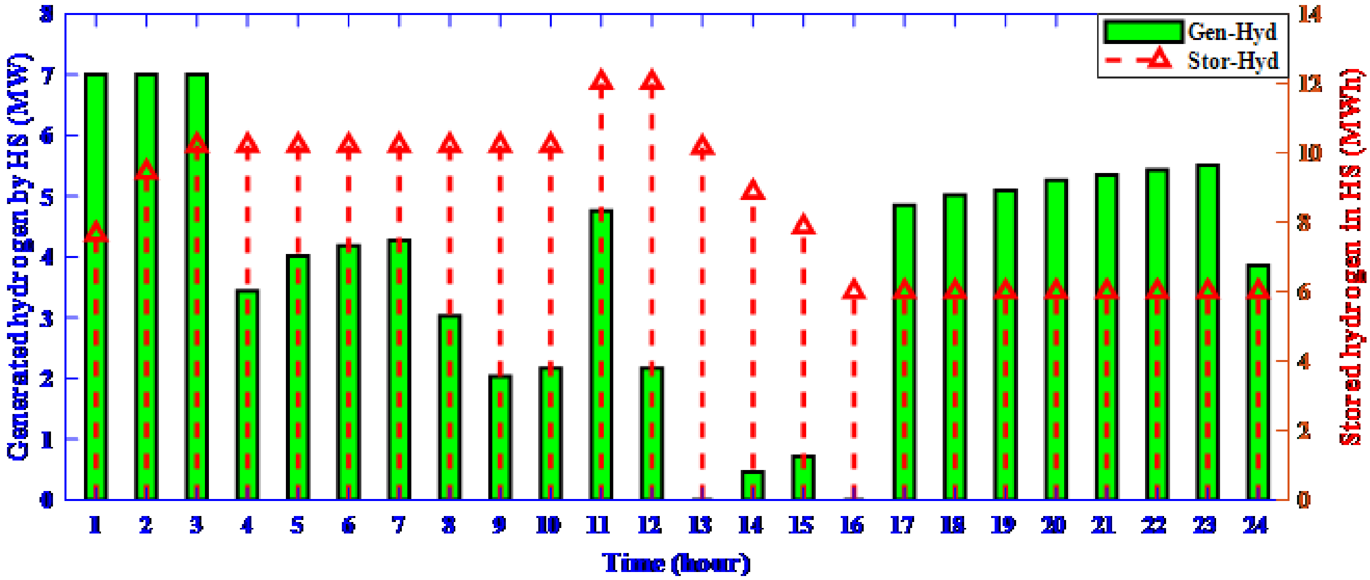

Fig. 7. Performance of hydrogen system.

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