Energy Conversion and Management 156 (2018) 34–44

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimal scheduling of heating and power hubs under economic and environment issues in the presence of peak load management

Sayyad Nojavan*, Majid Majidi, Kazem Zare

Faculty of Electrical and Computer Engineering, University of Tabriz, P.O. Box: 51666-15813, Tabriz, Iran

ARTICLE INFO

Keywords:
Hub energy system
Multi-objective model
Emission
ε-constraint approach
Max-min fuzzy satisfying method
Demand response program

ABSTRACT

Financial issues have been always one of major priorities in scheduling of energy systems. Although these systems are able to serve several types of energy demands but generated emission by these systems is a challenging problem. Since improvement of each one of mentioned issues has negative effects on the other issue therefore a trade-off solution is necessary to be obtained between these issues. In this paper, a multi-objective model has been presented to satisfy both economic and environmental objectives of a hub energy system in the presence of demand response program. In the proposed paper, ε-constraint and max–min fuzzy satisfying methods have been employed to solve and select the trade-off solution. The main reason of implementation of demand response program is to reduce operation cost and improve environmental performance of hub energy system. In fact, demand response program transfers some percentage of load from peak periods to off-peak periods to flatten load curve which leads to reduction of cost and emission. A mixed-integer linear programming has been used to simulate the proposed model and general algebraic modeling system software has been utilized to solve it. A sample hub energy system containing renewable and non-renewable energy resources has been studied and comparison results are presented to validate efficiency of proposed techniques.

1. Introduction

Recently, optimal operation of energy systems capable of supplying different energy demands called multi-carrier energy systems or hub energy systems has been one of major topics in the scheduling of power systems [1]. Various energy resources like combined heat and power systems (CHP) can be employed to enhance efficiency of operating systems [2]. Moreover, heat energy resources like boiler can be exploited to supply thermal demand [3]. In addition to mentioned non-renewable energy resources, renewable generation units can be integrated in hub energy systems to meet several types of loads [4]. It should be noted that utilization of resources burning fossil fuels in hub energy systems has made emission problem of these systems a big challenge for system operators [5].

Operation of hub energy systems with different purposes and applications has been studied within various researches which are summarized in the following: Economic dispatch problem of multiple energy hub system has been investigated through Self-Adoptive Learning with Time Varying Acceleration Coefficient-Gravitational Search Algorithm in [6]. With the aim of gaining maximum profit, hub energy system has been optimally designed in [7]. Influence of optimizing transmission networks on performance of hub energy system has been evaluated in [8]. Using a new approach, optimal power flow problem of hub energy systems has been investigated and the results have been compared with the ones obtained through other approaches in [9]. New formulations have been presented for accurate modeling of hub energy system with taking technical constraints into account in [10]. In order to improve performance of a residential hub energy system in the smart grid, a real-time based model has been presented in [11]. Employing controlling structure called hierarchical control structure, economic operation of a multi-carrier energy system has been evaluated in [12]. Optimal performance of multi-carrier energy system and optimal sizing of resources in this system have been investigated in [13]. Economic performance of multi-carrier energy system subject to uncertain behavior of renewable sources has been studied in [14]. Using evolutionary algorithm in [15], optimal operation of multi-carrier energy system has been investigated. Optimal operation of an on-grid multi-carrier energy system including different types of renewable energy sources has been evaluated in [16]. Using Monte Carlo simulation technique in [17], economic performance of hub energy system has been investigated. Optimal operation of hub energy system has been studied through two types of pricing namely dynamic pricing and time-of-use pricing in [18]. Using dispatch strategy, performance of hub energy system subject to curtailment in grid integration and real time pricing has been

---

* Corresponding author.
E-mail addresses: sayyad.nojavan@tabrizu.ac.ir (S. Nojavan), majidmajidi95@ms.tabrizu.ac.ir (M. Majidi), kazem.zare@tabrizu.ac.ir (K. Zare).

https://doi.org/10.1016/j.enconman.2017.11.007
Received 29 July 2017; Received in revised form 20 September 2017; Accepted 2 November 2017
0196-8904/ © 2017 Elsevier Ltd. All rights reserved.

Nomenclature

Indices

t	time index

Parameters

η_{ee}^{T}	transformer efficiency
η_{ge}^{CHP}	gas to electricity efficiency of CHP
η_{gh}^{B}	gas to heat efficiency of boiler
η_{ee}^{CON}	converter efficiency
η_{ch}^{e}	electrical storage charging efficiency
η_{dis}^{e}	electrical storage discharging efficiency
η_{ch}^{h}	heat storage charging efficiency
η_{dis}^{h}	heat storage discharging efficiency
$\alpha_{\min}^{e}$	coefficient for minimum capacity modeling of electrical storage
$\alpha_{\max}^{e}$	coefficient for maximum capacity modeling of electrical storage
α_{loss}^{e}	coefficient for loss of power modeling in electrical storage
$\alpha_{\min}^{h}$	coefficient for minimum capacity modeling of heat storage
$\alpha_{\max}^{h}$	coefficient for maximum capacity modeling of heat storage
α_{loss}^{h}	coefficient for loss of power modeling in heat storage
A^{NET}	upstream network availability
A^{CHP}	CHP availability
A^{WIND}	wind turbine availability
$C_{c}^{st,e}$	nominal capacity of electrical storage
$C_{c}^{st,h}$	nominal capacity of heat storage
EF_{CO}^{CHP}	CO_2 emission factor for CHP unit
EF_{SO}^{CHP}	SO_2 emission factor for CHP unit
EF_{NO}^{CHP}	NO_2 emission factor for CHP unit
EF_{CO}^{B}	CO_2 emission factor for boiler
EF_{SO}^{B}	SO_2 emission factor for boiler
EF_{NO}^{B}	NO_2 emission factor for boiler
EF_{CO}^{L}	CO_2 emission factor for gas consumption in residential section
EF_{SO}^{L}	SO_2 emission factor for gas consumption in residential section
EF_{NO}^{L}	NO_2 emission factor for gas consumption in residential section
EF_{CO}^{Net}	CO_2 emission factor for upstream network power
EF_{SO}^{Net}	SO_2 emission factor for upstream network power
EF_{NO}^{Net}	NO_2 emission factor for upstream network power
$g_{\min}^{net}$	gas network minimum capacity
$g_{\max}^{net}$	gas network maximum capacity
g_{t}^{l}	gas demand in residential section
$LPF^{shup,e}$	coefficient for increased electrical load
$LPF^{shdo,e}$	coefficient for decreased electrical load
$p_{\min}^{e}$	upstream network minimum capacity
$p_{\max}^{e}$	upstream network maximum capacity
p_{c}^{T}	transformer rated capacity
p_{c}^{CHP}	nominal capacity of CHP
p_{c}^{B}	nominal capacity of CHP
P_r	wind turbine rated power
p_{t}^{el}	electrical load
p_{t}^{h}	heating load
wa_{t}^{l}	water demand
$wa_{\min}$	minimum limitation of water network
$wa_{\max}$	maximum limitation of water network
w_{co},w_{ci},w_{r}	cut-out, cut-in and rated speeds of wind turbine
$w(t)$	wind speed
$x,\ y,\ z$	coefficients for modeling generation of wind turbine
λ_{t}^{e}	price of purchased power from upstream network
λ^{wi}	generation cost of wind turbine
λ^{g}	gas price
λ^{wa}	water price
λ_{s}^{e}	operation cost of electrical storage
λ_{s}^{h}	operation cost of heat storage
λ^{DR}	cost of demand response

Variables

$Cost$	total operation cost of hub energy system
$C_{t}^{st,e}$	available energy of electrical storage
$C_{t}^{st,h}$	available energy of heat storage
Em	total emission generated in hub energy system
g_{t}^{CHP}	gas consumption of CHP
g_{t}^{B}	gas consumption of boiler
g_{t}^{net}	total purchased gas from gas network
$I_{t}^{ch,e}$	binary variable, 1 if electrical storage is in charging mode; otherwise 0
$I_{t}^{dis,e}$	binary variable, 1 if electrical storage is in discharging mode; otherwise 0
$I_{t}^{ch,h}$	binary variable, 1 if heat storage is in charging mode; otherwise 0
$I_{t}^{dis,h}$	binary variable, 1 if heat storage is in discharging mode; otherwise 0
$I_{t}^{shup,e}$	binary variable, 1 if electrical load is increased; otherwise 0
$I_{t}^{shdo,e}$	binary variable, 1 if electrical load is decreased; otherwise 0
p_{t}^{e}	purchased power form upstream network
$p_{t}^{ch,e}$,$p_{t}^{dis,e}$	charge/discharge power of electrical storage
$p_{t}^{ch,h}$,$p_{t}^{dis,h}$	charge/discharge heat of thermal storage
$p_{t}^{loss,e}$	loss of power in electrical storage
$p_{t}^{loss,h}$	loss of heat in heat storage
$p_{t}^{el,DRP}$	electrical load in the presence of DRP
$p_{t}^{shup,e}$	increased electrical load
$p_{t}^{shdo,e}$	decreased electrical load
p_{t}^{wi}	produced power by wind turbine
wa_{t}^{net}	purchased water from water network

Abbreviations

CHP	combined heat and power system
DRP	demand response program
GAMS	general algebraic modeling system
MILP	mixed-integer linear programming
TOU	time-of-use rates of demand response program

investigated in [19]. Considering uncertainty modeling of wind, price and load, optimal operation of hub energy system has been investigated in [20]. Using a heuristic technique called Time Varying Acceleration Coefficient Gravitational Search algorithm, optimal performance of hub energy system has been evaluated in [21]. With the aim of minimizing total cost, optimal operation of hub energy system considering uncertainty of renewable sources has been studied using stochastic programming in [22]. A paradigm has been presented to optimize operation of interconnected multi-carrier energy systems in [23]. Employing teaching–learning based optimization algorithm, energy flow problem of multi-carrier energy system has been evaluated in [24]. Optimal dispatch strategies and coordinated operation of a hub energy system have been investigated in [25]. Using multi-agent systems approach, optimal operation of hub energy system has been evaluated

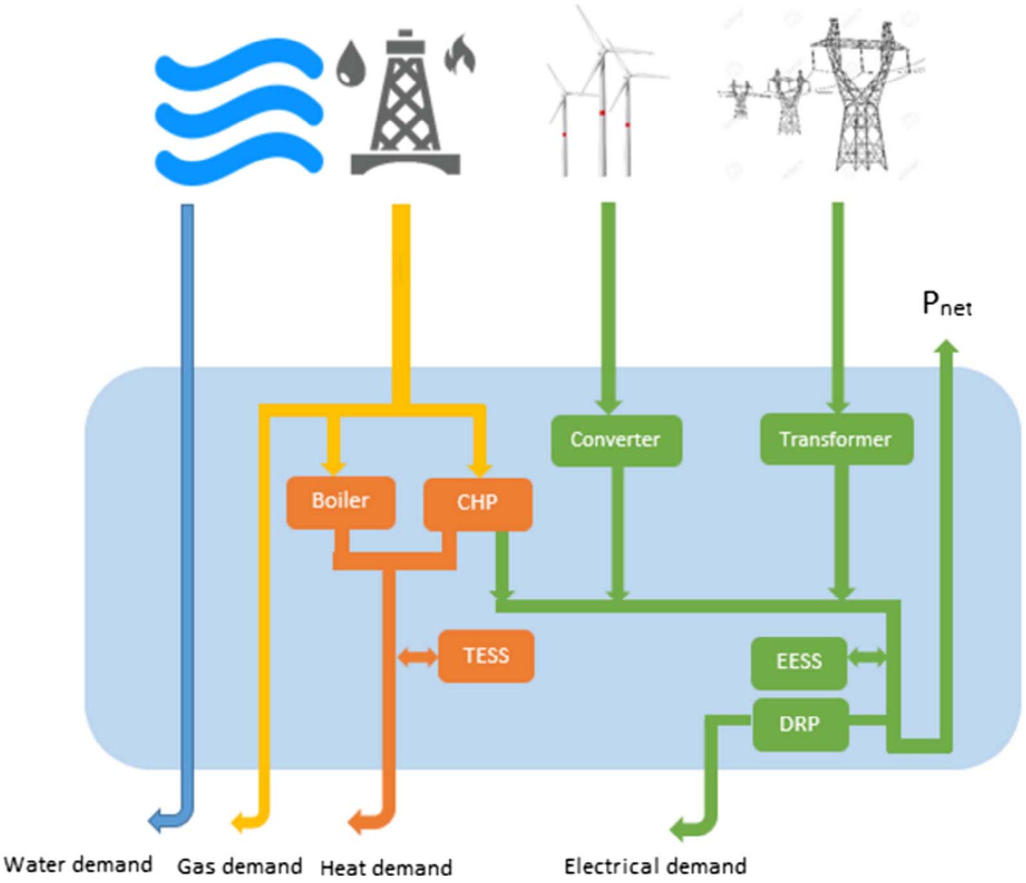

Fig. 1. Hub energy system.

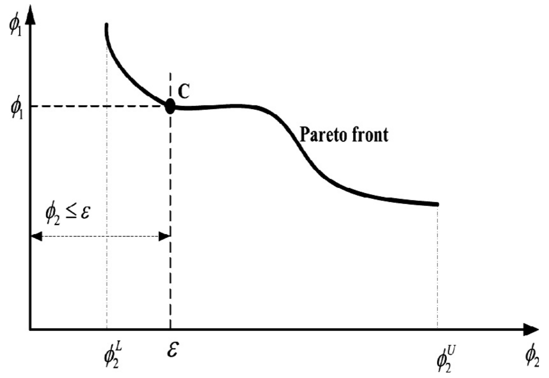

Fig. 2. Pareto front set.

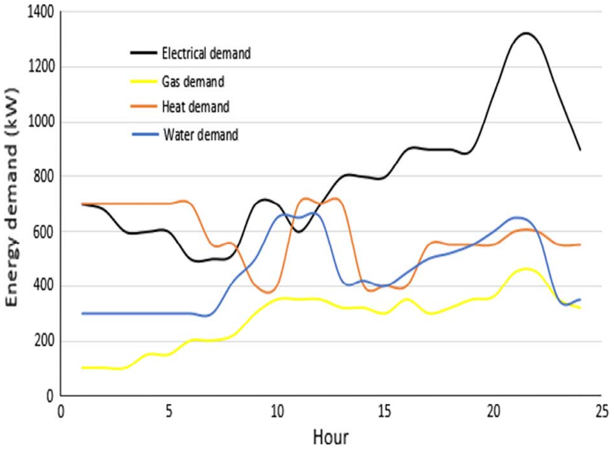

Fig. 3. Energy demand [20].

subject to commercial and technical limitations in [26].

Optimal sizing as well as planning problem of multi-carrier energy system has been studied with taking reliability issues into account in [27]. Scenario based optimal design problem of multi-carrier energy system has been studied through Monte Carlo approach under stochastic programming in [28]. Similar risk-based problem has been studied under demand response through stochastic programming in [29] in which conditional value-at-risk technique is employed to reduced risk of expected cost of hub system owing to volatility of load and market price forecasts. Optimal performance of hub energy system has been obtained through a multi-objective model in [30] in which genetic algorithm and adaptive neuro-fuzzy inference systems have been employed to predict energy demand and model energy curves of system. A new algorithm called distributed energy resources optimization has been developed to optimize operation of small-scale energy hub systems in [31]. Optimal power flow problem of hub energy system has been studied through a mixed-integer linear programming in [32]. Stochastic programming has been employed to model uncertainty based optimal operation problem of hub energy system under demand response and thermal energy market in [33]. Optimal operation of several interconnected multi-carrier energy systems has been studied under reliability issues in [34]. Finally, energy hub systems have been comprehensively reviewed in [35].

Due to higher efficiency and less waste of energy, hub energy systems are extensively expanded in power systems. These systems benefiting from various types of energy resources should be optimally scheduled to expose their maximum capacity. So, optimization of these systems is an essential issue. On the other hand, in addition to optimization, expected objectives are necessary to be determined since these objectives can lead to single objective problems or multi-objective

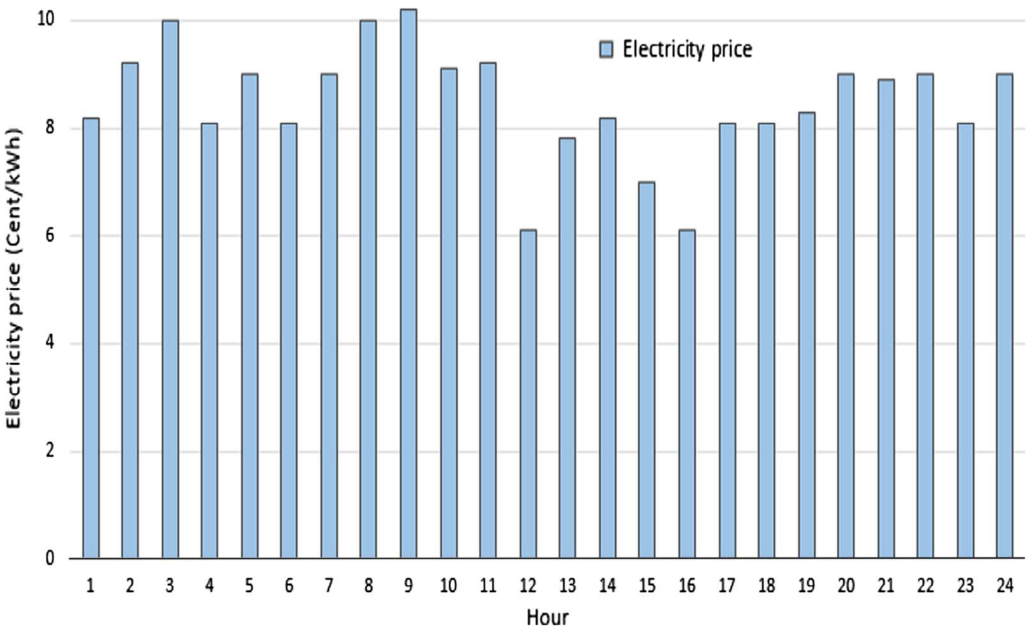

Fig. 4. price of imported electric power [20].

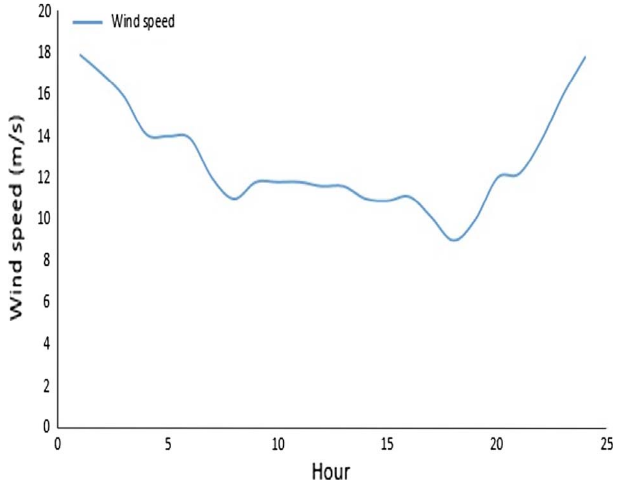

Fig. 5. Wind turbine speed [20].

Table 1
Prices and relevant costs of hub energy system.

Parameter [20]	Value	Unit
λ^{g}	6	Cent/kWh
λ^{wa}	4	Cent/kWh
λ^{wi}	0	Cent/kWh
λ_{s}^{e}	2	Cent/kWh
λ_{s}^{h}	2	Cent/kWh
λ^{DR}	2	Cent/kWh

problems with several objective functions to be minimized. One of these objectives is environmental goals which consideration necessitates a multi-objective model. Economic operation and environmental performance of hub energy system in the presence of DRP has been investigated in this paper. Since optimization results of each mentioned objective functions are in conflict with the optimization results of other one, then a multi-objective model has been proposed for economic-environmental operation of hub energy system under DRP. Studied hub energy systems includes electrical as well as thermal storage systems and renewable as well as non-renewable energy resources like wind turbine, CHP system and boiler. ε-constraint approach has been used to solve the proposed multi-objective model. Solving the proposed model within different iterations, Pareto front is obtained in with and without DRP. So, in order to find and select the trade-off solution providing a win-win strategy for both conflicting objective functions, max-min fuzzy satisfying technique is utilized. Obtained numerical results revealed that total operation cost and emission of hub energy system have been reduced up to 0.64 % and 0.97%, respectively. It should be noted that simulation results will be comprehensively discussed in the following sections. So, the contributions of proposed paper can be expressed as follows:

- Multi-objective model for optimal economic operation and environmental performance of hub energy system including electrical and thermal storage systems.
- Implementation of ε-constraint technique to solve the proposed multi-objective model.
- Implementation of max-min fuzzy satisfying method to select the trade-off solution.
- Employment of DRP to reduce operation cost and emission of hub energy system.
- Utilization of electrical and thermal storage systems to avoid waste of energy.
- Employing mixed-integer linear programming to guarantee optimal solution.

The other sections of proposed paper are classified as follows: Optimal economic-environmental performance of hub energy system under DRP is mathematically modeled in Section 2. A sample hub energy system is evaluated in Section 3 and comparison results are presented in the same Section. Finally, the conclusions and findings are presented in Section 4.

2. Mathematical formulation

A multi-carrier energy system containing various types of energy resources with different types of loads to be supplied is illustrated in Fig. 1 [20].

According to this Figure, generation of renewable units as well as electrical generation of CHP unit plus the purchased power from upstream network are due to supply electoral demand under DRP. Imported gas from gas network is used for three different applications.

Table 2
Date related to various units in the energy hub system.

Electrical storage parameter [20]			Thermal storage parameter [20]			Wind turbine parameter [20]		
#	Unit	Value	#	Unit	Value	#	Unit	Value
$\alpha^e_{\min}$	–	0.05	$\alpha^h_{\min}$	–	0.05	A^{WIND}	–	0.96
$\alpha^e_{\max}$	–	0.9	$\alpha^h_{\max}$	–	0.9	x, y, z	–	0.07, 0.01, 0.03
α^e_{loss}	–	0.2	α^h_{loss}	–	0.2	w_r	m/s	10
η^e_{ch}	%	90	η^h_{ch}	%	90	w_{ci}	m/s	4
η^e_{dis}	%	90	η^h_{dis}	%	90	w_{co}	m/s	22
$C^{st,e}_c$	kW	300	$C^{st,h}_c$	kW	200	p_r	kW	400
CHP parameter [20]			Upstream network parameter [20]			Boiler, gas and water network parameters [20]		
#	Unit	Value	#	Unit	Value	#	Unit	Value
η^{CHP}_{ge}	%	40	A^{NET}	–	0.99	η^B_{gh}	%	85
η^{CHP}_{gh}	%	35	$P^e_{\max}$	kW	1000	P^B_c	kW	800
A^{CHP}	–	0.96	$P^e_{\min}$	kW	0	$g^{net}_{\max}$	kW	1800
P^{CHP}_c	kW	800	P^T_c	kW	800	$wa_{\max}$	kW	1000
Boiler emission [47]			Upstream network emission [46]			CHP emission [47]		
#	Unit	Value	#	Unit	Value	#	Unit	Value
EF^B_{CO}	kg/kWh	0.37	EF^{Net}_{CO}	kg/kWh	0.368	EF^{CHP}_{CO}	kg/kWh	0.37
EF^B_{SO}	kg/kWh	0.000003	EF^{Net}_{SO}	kg/kWh	0.0002	EF^{CHP}_{SO}	kg/kWh	0.000003
EF^B_{NO}	kg/kWh	0.00009	EF^{Net}_{NO}	kg/kWh	0.0008	EF^{CHP}_{NO}	kg/kWh	0.00009

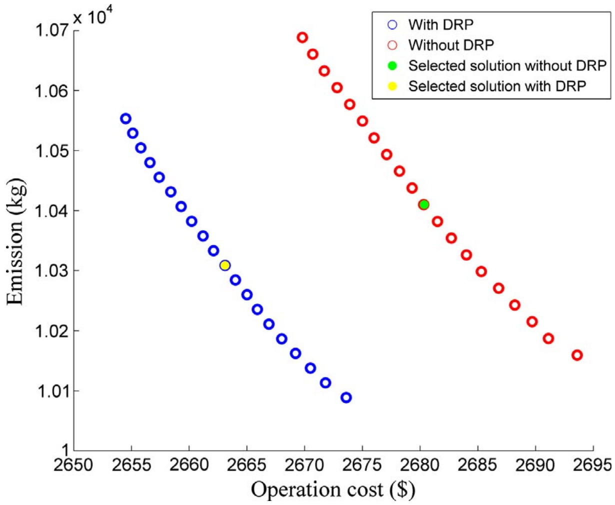

Fig. 6. Pareto front and selected solutions in cases 1 & 2.

Some percentage of purchased gas is dedicated for supplying residential gas demand. Imported gas is also used to supply CHP unit and boiler to generate heat and electricity. As expressed in Fig. 2, water is transmitted to residential section to supply water demand. In addition to energy resources mentioned above, electrical and thermal energy storage systems have been also used in the hub system to save energy at the times of excess production and supply thermal and electrical loads in peak time periods. Also, DRP has been implemented to flatten load curve and reduce total cost and emission of hub energy system. As mentioned before, main goal of proposed multi-objective model is to improve economic operation as well as environmental performance of hub energy system. Mathematical formulation related to optimal economic-environmental performance problem of hub energy system considering DRP is presented in the following:

2.1. Objective function 1

Operation cost of hub energy system is the first objective function of proposed multi-objective optimization model which should be minimized (1a) [20].

$$\text{Min } \Phi_1 = Cost = \sum_{t}^{H} (B + C + D + E + F + G + H + I + J) \tag{1a}$$

$$B = \lambda_t^e \times p_t^e \tag{1b}$$

$$C = \lambda^{wi} \times p_t^{wi} \tag{1c}$$

$$D = \lambda_s^e \times (p_t^{ch,e} + p_t^{dis,e}) \tag{1d}$$

$$E = \lambda^{DR} \times (p_t^{e,shdo} + p_t^{e,shup}) \tag{1e}$$

$$F = \lambda_t^e \times (p_t^{ch,e} - p_t^{dis,e}) \tag{1f}$$

$$G = \lambda^g \times g_t^{CHP} \tag{1g}$$

$$H = \lambda^g \times g_t^B \tag{1h}$$

$$I = \lambda_s^h \times (p_t^{ch,h} + p_t^{dis,h}) \tag{1i}$$

$$J = \lambda^{wa} \times wa_t \tag{1j}$$

where $Cost$ is total operation cost of hub energy system, p_t^e is purchased power form upstream network, p_t^{wi} is produced power by wind turbine, $p_t^{ch,e}$ is charging power of electrical storage, $p_t^{dis,e}$ is discharging power of electrical storage, $p_t^{e,shdo}$ is decreased electrical load, $p_t^{e,shup}$ is increased electrical load, g_t^{CHP} is gas consumption of CHP, g_t^B is gas consumption of boiler, $p_t^{ch,h}$ is charging heat of thermal storage, $p_t^{dis,h}$ is discharging heat of thermal storage and wa_t is purchased water from water network.

Total operation cost of hub energy system consists of several individual costs including cost of import of electric power from upstream network (1b), cost of electricity generation by wind turbine (1c), operation cost of electrical storage (1d), cost of DRP implementation (1e),

Table 3
Pareto front solutions for cases 1 and 2 (without and with DRP).

#	Without DRP					#	With DRP				
	Cost ($)	Emission (kg)	Φ_1 (p.u.)	Φ_2 (p.u.)	min(Φ_1,Φ_2)		Cost ($)	Emission (kg)	Φ_1 (p.u.)	Φ_2 (p.u.)	min(Φ_1,Φ_2)
1	2669.77	10688.50	1	0	0	1	2654.47	10553.53	1.000	0.000	0.000
2	2670.66	10660.65	0.963	0.053	0.053	2	2655.05	10529.08	0.969	0.053	0.053
3	2671.72	10632.81	0.918	0.105	0.105	3	2655.84	10504.62	0.928	0.105	0.105
4	2672.80	10604.96	0.873	0.158	0.158	4	2656.62	10480.17	0.888	0.158	0.158
5	2673.88	10577.12	0.827	0.211	0.211	5	2657.41	10455.71	0.846	0.211	0.211
6	2674.95	10549.27	0.782	0.263	0.263	6	2658.35	10431.26	0.797	0.263	0.263
7	2676.03	10521.43	0.737	0.316	0.316	7	2659.30	10406.80	0.748	0.316	0.316
8	2677.11	10493.58	0.692	0.368	0.368	8	2660.25	10382.35	0.698	0.368	0.368
9	2678.19	10465.74	0.646	0.421	0.421	9	2661.19	10357.89	0.649	0.421	0.421
10	2679.26	10437.89	0.601	0.474	0.474	10	2662.14	10333.44	0.599	0.474	0.474
11	**2680.34**	**10410.05**	**0.556**	**0.526**	**0.526**	**11**	**2663.08**	**10308.98**	**0.550**	**0.526**	**0.526**
12	2681.49	10382.20	0.507	0.579	0.579	12	2664.03	10284.53	0.501	0.579	0.501
13	2682.74	10354.36	0.455	0.632	0.632	13	2664.98	10260.07	0.451	0.632	0.451
14	2684.00	10326.51	0.402	0.684	0.684	14	2665.92	10235.62	0.402	0.684	0.402
15	2685.33	10298.67	0.346	0.737	0.737	15	2666.89	10211.16	0.351	0.737	0.351
16	2686.77	10270.82	0.285	0.789	0.789	16	2668.00	10186.71	0.293	0.789	0.293
17	2688.22	10242.98	0.225	0.842	0.842	17	2669.22	10162.25	0.230	0.842	0.230
18	2689.67	10215.13	0.164	0.895	0.895	18	2670.49	10137.80	0.163	0.895	0.163
19	2691.12	10187.29	0.103	0.947	0.947	19	2671.76	10113.34	0.097	0.947	0.097
20	2693.56	10159.45	0.000	1.000	1.000	20	2673.62	10088.89	0.000	1.000	0.000

Bold values are the best compromise solution which are selected by fuzzy satisfying technique.

Table 4
Comparison results of cases 1 and 2.

Parameters	Case 1	Case 2
Total cost ($)	2680.34	2663.08
Total emission (kg)	10410.05	10308.98
Cost reduction (%)	0	0.64
Emission reduction (%)	0	0.97

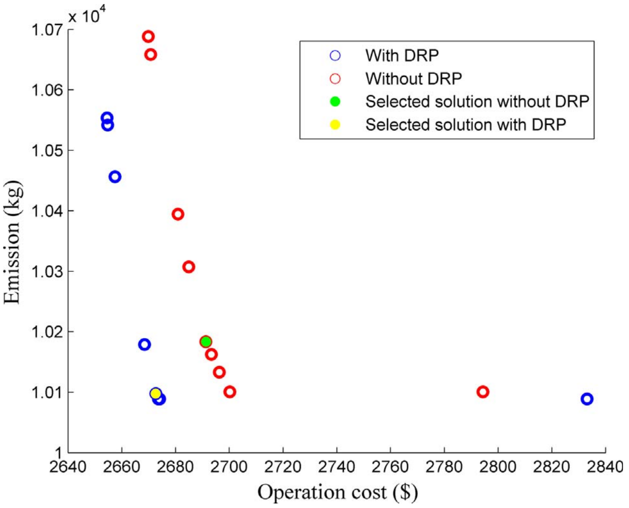

Fig. 7. Pareto front obtained through weighted sum method.

cost/revenue of exchanged power (1f), cost of gas procurement for operation of CHP unit (1g) and boiler (1h), operation cost of thermal storage (1i) and cost of purchased water for supplying water demand (1j).

2.2. *Objective function 2*

Total emission produced by hub energy system including CO_2, SO_2 and NO_2 emissions is the second objective function of proposed multi-objective optimization model which should be minimized (2a).

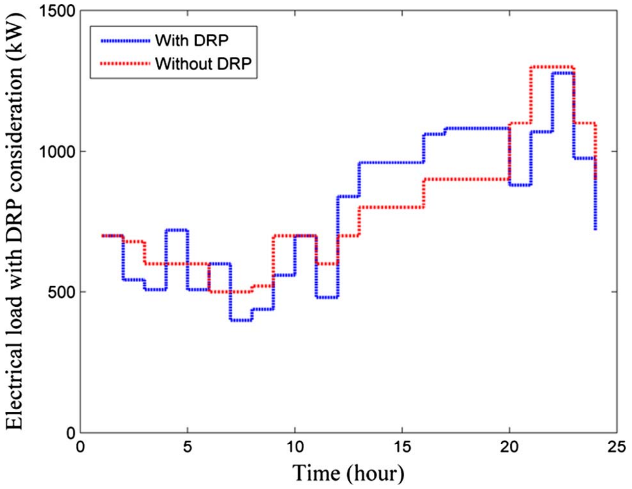

Fig. 8. Electrical load in the presence of DRP.

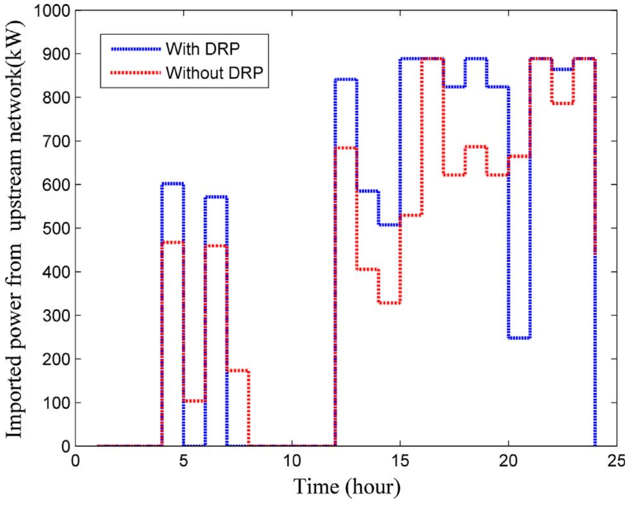

Fig. 9. Imported power form upstream network.

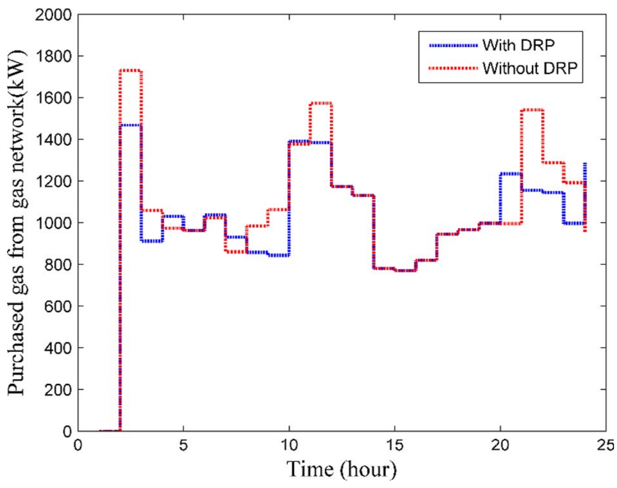

Fig. 10. Total procured gas.

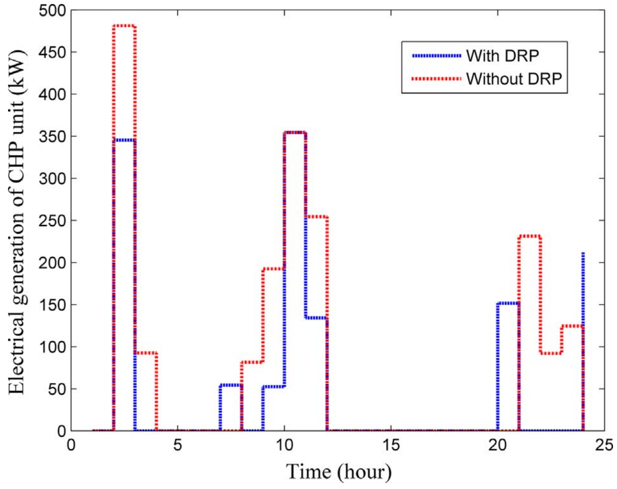

Fig. 11. Electrical generation of CHP unit.

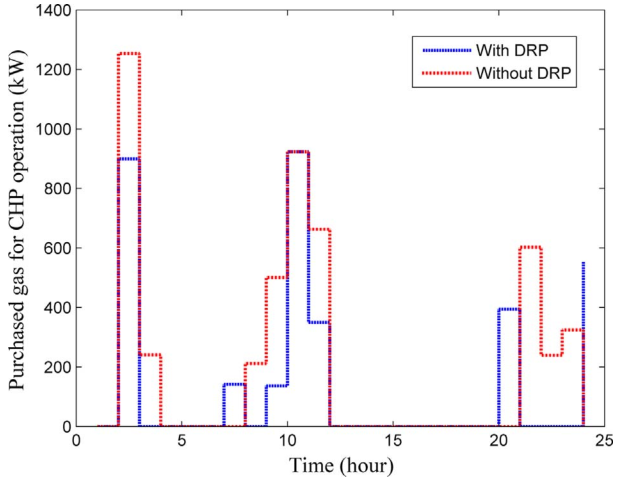

Fig. 12. Imported gas for CHP unit.

$$Min\ \Phi_2 = Em = (Em^{CHP} + Em^{B} + Em^{L} + Em^{NET}) \tag{2a}$$

$$Em^{CHP} = (EF_{CO}^{CHP} \times g_t^{CHP}) + (EF_{SO}^{CHP} \times g_t^{CHP}) + (EF_{NO}^{CHP} \times g_t^{CHP}) \tag{2b}$$

$$Em^{B} = (EF_{CO}^{B} \times g_t^{B}) + (EF_{SO}^{B} \times g_t^{B}) + (EF_{NO}^{B} \times g_t^{B}) \tag{2c}$$

$$Em^{L} = (EF_{CO}^{L} \times g_t^{L}) + (EF_{SO}^{L} \times g_t^{L}) + (EF_{NO}^{L} \times g_t^{L}) \tag{2d}$$

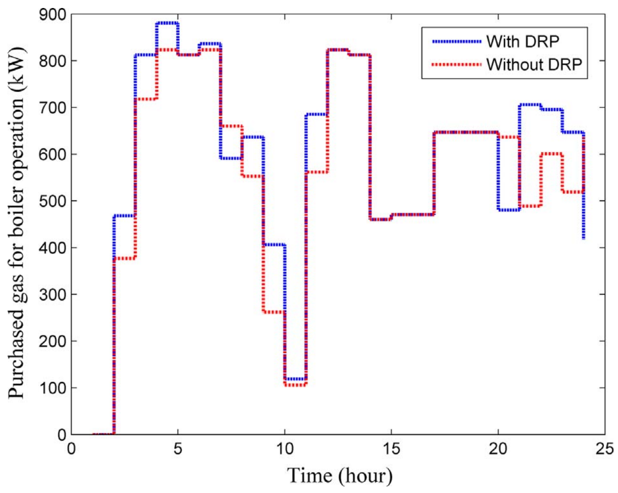

Fig. 13. Imported gas for boiler.

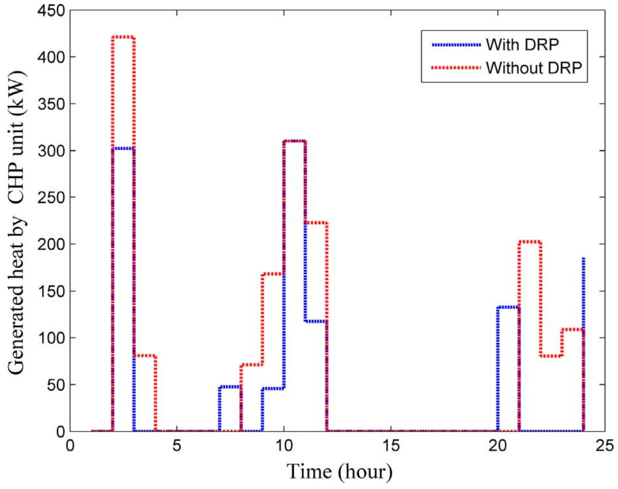

Fig. 14. Heat generation of CHP unit.

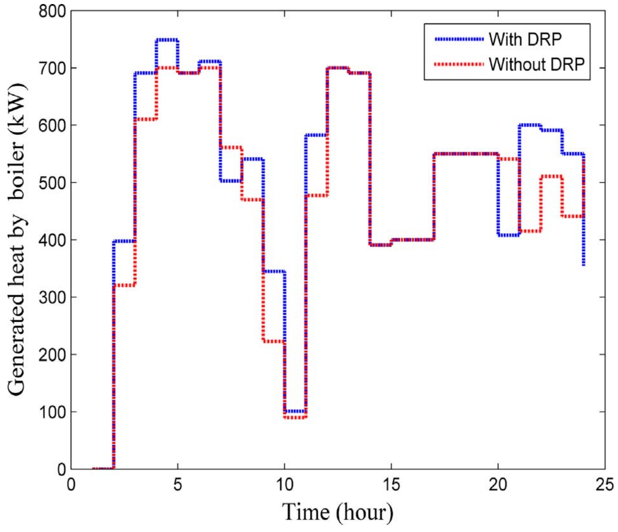

Fig. 15. Heat generation of boiler.

$$Em^{NET} = (EF_{CO}^{NET} \times p_t^{e}) + (EF_{SO}^{NET} \times p_t^{e}) + (EF_{NO}^{NET} \times p_t^{e}) \tag{2e}$$

where Em is total emission of hub energy system, Em^{CHP} is emission of CHP unit, Em^{B} is emission of boiler, Em^{L} is emission of consumed residential gas and Em^{NET} is emission of imported power from upstream

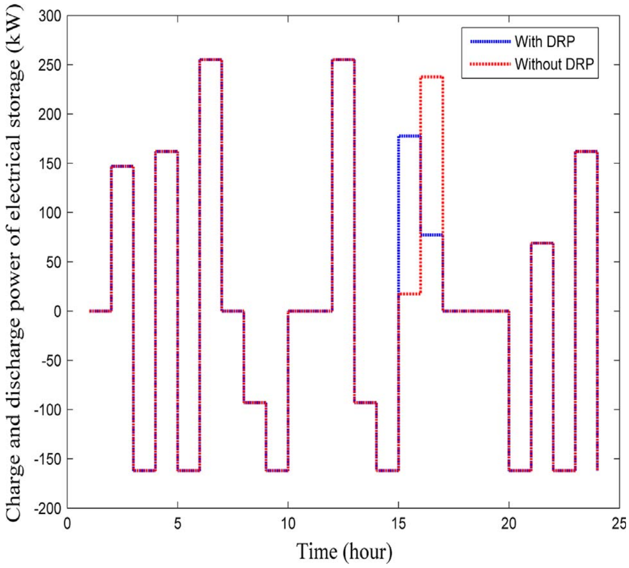

Fig. 16. Charge and discharge of electrical storage.

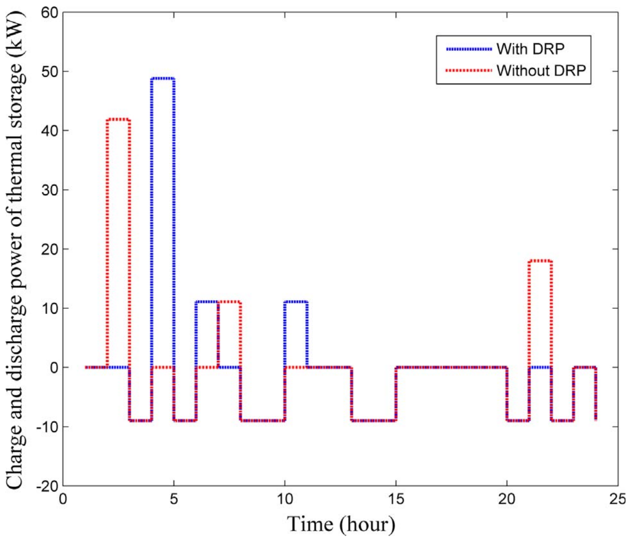

Fig. 17. Charge and discharge of heat storage.

network.

According to Eq. (2a), total emission produced by hub energy system consists of four terms.

The first term is generated emission due to gas consumption of CHP unit (2b). The second term is the emission related to gas consumption of boiler (2c). The third term is produced emission due gas consumption in residential section (2d) and finally the last term is emission due to electrical power generation in power plants using fossil fuels which is later transmitted to supply hub energy system (2e).

2.3. Technical constraints of thermal section

Heating demand is one of various loads due to be supplied by different resources in the hub energy system. The resources supplying thermal demand are boiler, CHP unit and thermal storage system (3a).

$$p_t^h = [\eta_{gh}^B \times g_t^B] + [A^{CHP} \times \eta_{gh}^{CHP} \times g_t^{CHP}] + (p_t^{dis,h} - p_t^{ch,h}) \tag{3a}$$

In order to avoid waste of excess generated heat, thermal storage system has been employed. Available heat inside the thermal storage at each time is expressed by Eq. (3b).

$$C_t^{st,h} = C_{t-1}^{st,h} + p_t^{ch,h} \times \eta_{ch}^h - p_t^{dis,h}/\eta_{dis}^h - p_t^{loss,h} \tag{3b}$$

where $C_t^{st,h}$ is state of charge of heat storage and $p_t^{loss,h}$ is loss of heat inside heat storage.

Loss of heat in the storage is expressed as function of available energy in the storage system (3c).

$$p_t^{loss,h} = \alpha_{loss}^h \times C_t^{st,h} \tag{3c}$$

Stored heat inside the storage is limited through Eq. (3d).

$$\alpha_{\min}^h \times C_c^{st,h} \leqslant C_t^{st,h} \leqslant \alpha_{\max}^h \times C_c^{st,h} \tag{3d}$$

Eqs. (3e) and (3f) have been used to limit charging and discharging heat of storage system.

$$\frac{\alpha_{\min}^h \times C_c^{st,h} \times I_t^{ch,h}}{\eta_{ch}^h} \leqslant p_t^{ch,h} \leqslant \frac{\alpha_{\max}^h \times C_c^{st,h} \times I_t^{ch,h}}{\eta_{ch}^h} \tag{3e}$$

$$\alpha_{\min}^h \times C_c^{st,h} \times I_t^{dis,h} \times \eta_{dis}^h \leqslant p_t^{dis,h} \leqslant \alpha_{\max}^h \times C_c^{st,h} \times I_t^{dis,h} \times \eta_{dis}^h \tag{3f}$$

where $I_t^{ch,h}$ is binary variable for charging state of thermal storage and $I_t^{dis,h}$ is binary variable for discharging state of thermal storage.

Simultaneous charge and discharge of thermal storage is constrained by Eq. (3g).

$$I_t^{ch,h} + I_t^{dis,h} \leqslant 1 \tag{3g}$$

2.4. Technical constraints of electrical section

Electrical demand with considering DRP is due to be met by purchased power from upstream network and the electric power produced by wind turbine, CHP unit as well as discharge power of electrical storage system (4a).

$$\begin{aligned} p_t^l + p_t^{shup} - p_t^{shdo} = {} & [A^{NET} \times \eta_{ee}^T \times p_t^e] + [A^{WIND} \times \eta_{ee}^{CON} \times p_t^{wi}] \\ & + [A^{CHP} \times \eta_{ge}^{CHP} \times g_t^{CHP}] + [p_t^{dis,e} - p_t^{ch,e}] \end{aligned} \tag{4a}$$

Eq. (4b) is employed to limit purchased power from upstream network which should not exceed predefined limitations.

$$\eta_{ee}^T \times p_t^e \leqslant p_c^T \tag{4b}$$

It should be noted that purchased power from upstream network should not exceed the rated capacity of transformer used in transmission line (4c).

$$\eta_{ee}^T \times p_t^e \leqslant p_c^T \tag{4c}$$

As the only renewable unit utilized in the hub energy system, wind turbine generates electricity which mathematical formulation is provided in (4d).

$$p_t^{wi} = \begin{cases} 0 & w < w_{ci} \\ p_r(z - y.\ w(t) + x.\ w^2(t)) & w_{ci} \leqslant w < w_r \\ p_r & w_r \leqslant w < w_{co} \\ 0 & w \geqslant w_{co} \end{cases} \tag{4d}$$

Saving electricity at the times of excess generation, electrical storage system helps other units to supply electrical demand in peak time periods. Available electric power inside the storage system at each time is expressed by Eq. (4e).

$$C_t^{st,e} = C_{t-1}^{st,e} + p_t^{ch,e} \times \eta_{ch}^e - p_t^{dis,e}/\eta_{dis}^e - p_t^{loss,e} \tag{4e}$$

where $C_t^{st,e}$ is available energy of electrical storage and $p_t^{loss,e}$ is loss of energy in electrical storage.

Stored energy inside the storage is limited through Eq. (4f).

$$\alpha_{\min}^e \times C_c^{st,e} \leqslant C_t^{st,e} \leqslant \alpha_{\max}^e \times C_c^{st,e} \tag{4f}$$

Loss of electricity in the storage is expressed as function of available energy in the storage system (4g).

$$p_t^{loss,e} = \alpha_{loss}^{e} \times C_t^{st,e} \tag{4g}$$

Eqs. (4h) and (4i) have been used to limit charging/discharging power of storage system.

$$\frac{\alpha_{\min}^{e} \times C_c^{st,e} \times I_t^{ch,e}}{\eta_{ch}^{e}} \leqslant p_t^{ch,e} \leqslant \frac{\alpha_{\max}^{e} \times C_c^{st,e} \times I_t^{ch,e}}{\eta_{ch}^{e}} \tag{4h}$$

$$\alpha_{\min}^{e} \times C_c^{st,e} \times I_t^{dis,e} \times \eta_{dis}^{e} \leqslant p_t^{dis,e} \leqslant \alpha_{\max}^{e} \times C_c^{st,e} \times I_t^{dis,e} \times \eta_{dis}^{e} \tag{4i}$$

where $I_t^{ch,e}$ is binary variable for charging state of electrical storage and $I_t^{dis,e}$ is binary variable for discharging state of electrical storage.

Simultaneous charge and discharge of electrical storage is constrained by Eq. (4j).

$$I_t^{ch,e} + I_t^{dis,e} \leqslant 1 \tag{4j}$$

2.5. Demand response program (DRP)

Many efforts have been already done to handle peak load issues in peak time periods [36]. Since installation of new power plants for a specific period is not economically a good idea, demand response programs have been appeared as a good option for peak load management issues [37]. DRP consists of several load management programs [38]. In this paper, time-of-use (TOU) rates of DRP has been implemented to help operator of hub energy system to improve both economic and environmental performances of hub energy system [39,40]. Using TOU program, some percentage of load is transferred from peak time (expensive) periods to other (cheaper) periods which leads to reduction of operation cost as well as emission of hub energy system. Mathematical form of this sentence is expressed by (5a).

$$p_t^{el,DRP} = p_t^{el} + p_t^{shup,e} - p_t^{shdo,e} \tag{5a}$$

where $p_t^{el,DRP}$ is electrical load in the presence of DRP.

Increase and decrease of load in DRP are limited through Eqs. (5b) and (5c), respectively.

$$0 \leqslant p_t^{shup,e} \leqslant LPF^{shup,e} \times p_t^{l} \times I_t^{shup,e} \tag{5b}$$

$$0 \leqslant p_t^{shdo,e} \leqslant LPF^{shdo,e} \times p_t^{l} \times I_t^{shdo,e} \tag{5c}$$

where $I_t^{shup,e}$ is binary variable for increase of load and $I_t^{shdo,e}$ is binary variable for decrease of load.

Simultaneous increase or decrease of load in DRP is limited by (5d).

$$I_t^{shup,e} + I_t^{shdo,e} \leqslant 1 \tag{5d}$$

It should be noted that at the end of each day, increased and decreased loads should be equal which is expressed by (5e).

$$\sum_{t}^{H} p_t^{shup,e} = \sum_{t}^{H} p_t^{shdo,e} \tag{5e}$$

2.6. Other technical constraints

Energy balance limitation related to water demand is provided by (6a).

$$wa_t^{l} = wa_t^{net} \tag{6a}$$

Sum of the gases used in CHP unit, boiler and residential section should be equal to the imported gas from gas network (6b).

$$g_t^{net} = g_t^{B} + g_t^{CHP} + g_t^{l} \tag{6b}$$

where g_t^{net} is total purchased gas from gas network.

It should be noted that the imported water and gas should not exceed the water and gas networks rated capacities which are expressed by Eqs. (6c) and (6d), respectively.

$$wa_{\min} \leqslant wa_t^{net} \leqslant wa_{\max} \tag{6c}$$

$$g_{\min}^{net} \leqslant g_t^{net} \leqslant g_{\max}^{net} \tag{6d}$$

It should be noted that electrical generation of CHP unit as well as heat generation of boiler are limited by Eqs. (6e) and (6f), respectively.

$$\eta_{ge}^{CHP} \times g_t^{CHP} \leqslant p_c^{CHP} \tag{6e}$$

$$\eta_{gh}^{B} \times g_t^{B} \leqslant p_c^{B} \tag{6f}$$

2.7. Multi-objective model solving techniques

In this section, the methods employed for solving proposed multi-objective problem are briefly described [41–44].

Based on ε-constraint method, one of the objective functions is set to be the main objective function of multi-objective model and the other objective function is considered as a limitation for the main objective function. So, a single-objective problem should be minimized subject to related constraints (7a).

$$\begin{aligned} &\text{OF}=\min(\Phi_1)\\ &\text{s.t.}\\ &\begin{cases}\Phi_2 \leqslant \varepsilon\\ \text{Equal \& unequal equations}\end{cases}\end{aligned} \tag{7a}$$

Changing value of ε from $\phi_2^{\min}$ up to $\phi_2^{\max}$, main objective function of multi-objective model is changed and therefore Pareto front is obtained like the example shown in Fig. 2 [42].

Afterward, max-min fuzzy technique converts both of conflicting objective functions into their normalized forms (7b).

$$\mu_k^n = \begin{cases} 1 & f_k^n \leqslant f_k^{\min}\\ \dfrac{f_k^{\max} - f_k^n}{f_k^{\max} - f_k^{\min}} & f_k^{\min} \leqslant f_k^n \leqslant f_k^{\max}\\ 0 & f_k^n \geqslant f_k^{\max} \end{cases} \tag{7b}$$

It should be noted that optimality level of nth solution of objective function k is expressed by μ_k^n. Also, $f_k^{\min}$ and $f_k^{\max}$ are the minimum and maximum values of objective function k.

After normalization process, a comparison is done between per unit values of each objective function in each iteration and the minimum value between them is selected (7c).

$$\mu^n = \min(\mu_1^n,\dots,\mu_N^n)\ ;\ \forall\ \ n= 1,\dots,N_P \tag{7c}$$

The best compromise solution providing a trade-off between two conflicting objective functions is the maximum value of selected minimums (7d).

$$\mu^{\max} = \max(\mu^1,\dots,\mu^{N_P}) \tag{7d}$$

3. Numerical investigation

A sample hub energy system has been studied in this section and numerical results have been presented to validate effectiveness of proposed approaches.

3.1. Input data

As mentioned in former sections, several types of energy resources are integrated in hub energy system to supply different energy demands. Hub energy system is due to supply different types of loads which are illustrated in Fig. 3 [20]. Some percentage of electrical demand is supplied though the purchased power from upstream network which price is illustrated in Fig. 4 [20]. Also, using wind speed which profile is shown in Fig. 5 [20], wind turbine generates electric power to supply electrical demand. In order to supply heating, gas and water demands, hub energy system purchases gas and water from gas and water networks. The price of imported gas for operation of boiler and CHP unit as well as price of imported water are presented in Table 1. Also, operation costs of electrical and thermal storages as well as generation cost of wind turbine and operating cost of DRP are presented in Table 1. It should be noted that the necessary info about operation of each equipment in the hub energy system is provided in Table 2. The proposed multi-objective model for economic-environmental operation of hub energy system is solved using GAMS optimization package utilizing CPLEX 11.0 [45]. It is noteworthy that simulation time is 15.483 s.

3.2. Simulation results

In this section, the proposed model has been investigated within two case studies and the relevant results have been presented to validate effectiveness of employed techniques.

Case 1: economic-environmental operation of energy hub system without DRP

Case 2: economic-environmental operation of energy hub system with DRP

In the first case, economic-environmental operation of energy hub system has been studied without consideration of DRP. The proposed multi-objective model is solved by ε-constraint method for different iterations and then Pareto front is obtained which is illustrated in red color in Fig. 6. It should be noted that detailed results of obtained solutions for all the iterations in the first case are presented in Table 3. The best possible solution satisfying both conflicting objective functions is selected by max-min fuzzy satisfying technique which is solution #11. The selected solution is depicted in green color in Fig. 6. According to this solution, total operation cost and emission of hub energy system are equal to 2680.34 $ and 10410.05 kg, respectively.

In the second case, the same problem is solved in the presence of DRP. Utilizing ε-constraint method, the proposed model is solved for different iterations and then the Pareto front is obtained in the second case which is illustrated in blue color in Fig. 6. Detailed results of obtained solutions for all the iterations in the second case are presented in Table 3. By employing max-min fuzzy satisfying technique the best compromise solution satisfying both conflicting objective functions is selected which is solution #11. The selected solution is depicted in yellow color in Fig. 6. According to selected solution, total operation cost and emission of hub energy system in case 2 are 2663.08 $ and 10308.98 kg, respectively.

It can be understood form the obtained results that due to implementation of DRP, total operation cost of hub energy system in case 2 is reduced 0.64% which satisfies economic goals. Also total emission of hub system in case 2 is reduced 102 kg which satisfies environmental objectives. For more clarification, comparison results of cases 1 and 2 are presented in Table 4.

3.3. Comparison

In the section, simulation results obtained through ε-constraint approach have been compared with the results obtained through weighted sum method.

The same simulations have been done through weighted sum method and obtained Pareto front through this approach is illustrated in Fig. 7.

According to the obtained Pareto solutions in weighted sum method, selected solution in without DRP includes operation cost and emission of 2691.319 $ and 10183.409 kg, respectively. Also, selected solution under DRP contains operation cost and emission of 2672.573 $ and 10097.728 kg, respectively. Comparing these values with the ones obtained under ε-constraint approach, it can be understood that economic results obtained through ε-constraint method in with and without DRP are better than the ones obtained through weighted sum approach. On the other hand, in comparisons with ε-constraint method, environmental results of hub system under weighted sum approach are better since emission of hub energy system in this approach is less than the one obtained in ε-constraint method.

Furthermore, operation of different integrated equipment in the hub energy system is illustrated through Figs. 8–17. As mentioned before, DRP transfers some percentage of load form peak time periods to other periods which is illustrated in Fig. 8. In order to supply electrical load, hub energy system has attempted to import power from upstream network which is shown in Fig. 9. According to this Figure, imported power in peak periods has been reduced and instead increased in off-peak periods which has led to less operation cost of hub energy system.

Total procured gas from gas network is illustrated in Fig. 10. As shown in this Fig, due to positive effects of load management program, hub energy system has purchased less gas from gas network which has led to reduction of operation cost.

Due to implementation of DRP, hub energy system has mostly used upstream network power and generation of renewable unit to supply electrical demand which has led to reduction of electrical generation of CHP unit which is illustrated by Fig. 11. Due to less electricity generation of CHP unit, less gas is consumed by this unit and on the other hand procured gas for consumption of boiler has been increased to supply heating demand. Purchased gases for consumption of CHP unit and boiler are illustraed through Figs. 12 and 13, respectively. Also generated heats by CHP unit and boiler are illustraed by Figs. 14 and 15, respectively.

Charge and discharge profiles of electrical and heat storage systems are changed according to optimal operation of integrated sources in the presence of DRP. Profiles related to charge and discharge of electrical and thermal storages are illustrated through Figs. 16 and 17, respectively.

4. Conclusion

In this paper, economic operation as well as environmental performance of hub energy system has been investigated in the presence of DRP. A multi-objective model has been proposed to consider both conflicting objecting functions namely operation cost and emission of hub energy system. Using ε-constraint technique, the proposed model is solved for different iterations and then the trade-off solution satisfying both objective functions is selected by max-min fuzzy satisfying approach. According to the selected solution without considering DRP, total operation cost and emission of hub energy system are 2680.34 $ and 10410.05 kg, respectively. Also, based on the selected solution under positive effects of DRP, total operation cost and emission of hub energy system are 2663.08 $ and 10308.98 kg, respectively. Comparing the selected solutions with and without DRP, it can be understood that due to implementation of DRP, total operation cost of hub energy system has been decreased 0.64 % which satisfies economic goals. Also, total emission of hub energy system in the presence of DRP has been reduced 102 kg which provides satisfaction of authorities dealing with environmental issues. So, implementation of DRP enhanced not only economic operation but also environmental performance of multi-carrier energy system.

References

[1] Bogdanov D, Breyer C. North-East Asian super grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manage 2016;112:176–90.

[2] Karami H, Sanjari MJ, Gooi HB, Gharehpetian GB, Guerrero JM. Stochastic analysis of residential micro combined heat and power system. Energy Convers Manage 2017;138:190–8.

[3] Li C, Gillum C, Toupin K, Park YH, Donaldson B. Environmental performance assessment of utility boiler energy conversion systems. Energy Convers Manage

2016;120:135–43.
[4] Aalami HA, Nojavan S. Energy storage system and demand response program effects on stochastic energy procurement of large consumers considering renewable generation. IET Gener Transm Distrib 2016;10(1):107–14.
[5] Al-Sharafi A, Yilbas BS, Sahin AZ, Ayar T. Performance assessment of hybrid power generation systems: economic and environmental impacts. Energy Convers Manage 2017;132:418–31.
[6] Beigvand SD, Abdi H, La Scala M. A general model for energy hub economic dispatch. Appl Energy 2017;190:1090–111.
[7] Moghaddam IG, Saniei M, Mashhour E. A comprehensive model for self-scheduling an energy hub to supply cooling, heating and electrical demands of a building. Energy 2016;94:157–70.
[8] Shabanpour-Haghighi A, Seifi AR. Effects of district heating networks on optimal energy flow of multi-carrier systems. Renew Sustain Energy Rev 2016;59:379–87.
[9] Geidl M, Andersson G. Optimal power flow of multiple energy carriers. IEEE Trans Power Syst 2007;22(1):145–55.
[10] Evins R, Orehounig K, Dorer V, Carmeliet J. New formulations of the 'energy hub'model to address operational constraints. Energy 2014;73:387–98.
[11] Bozchalui MC, Hashmi SA, Hassen H, Cañizares CA, Bhattacharya K. Optimal operation of residential energy hubs in smart grids. IEEE Trans Smart Grid 2012;3(4):1755–66.
[12] Xu X, Jia H, Wang D, David CY, Chiang HD. Hierarchical energy management system for multi-source multi-product microgrids. Renew Energy 2015;78:621–30.
[13] Sheikhi A, Ranjbar AM, Oraee H. Financial analysis and optimal size and operation for a multicarrier energy system. Energy Build 2012;48:71–8.
[14] Pazouki S, Haghifam M. Market based short term scheduling in energy hub in presence of responsive loads and renewable resources. 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013). 2013. p. 0191.
[15] Shabanpour-Haghighi A, Seifi AR. Multi-objective operation management of a multi-carrier energy system. Energy 2015;88:430–42.
[16] Pazouki S, Haghiafm MR. Market based operation of a hybrid system including wind turbine, solar cells, storage device and interruptable load. In: Electrical Power Distribution Networks (EPDC), 2013 18th Conference on 2013 Apr 30. IEEE. p. 1–7.
[17] Kienzle F, Ahcin P, Andersson G. Valuing investments in multi-energy conversion, storage, and demand-side management systems under uncertainty. IEEE Trans Sustain Energy 2011;2(2):194–202.
[18] Kamyab F, Bahrami S. Efficient operation of energy hubs in time-of-use and dynamic pricing electricity markets. Energy 2016;106:343–55.
[19] Perera AT, Nik VM, Mauree D, Scartezzini JL. Electrical hubs: an effective way to integrate non-dispatchable renewable energy sources with minimum impact to the grid. Appl Energy 2017;190:232–48.
[20] Pazouki S, Haghifam MR, Moser A. Uncertainty modeling in optimal operation of energy hub in presence of wind, storage and demand response. Int J Electr Power Energy Syst 2014;61:335–45.
[21] Beigvand SD, Abdi H, La Scala M. Optimal operation of multicarrier energy systems using time varying acceleration coefficient gravitational search algorithm. Energy 2016;114:253–65.
[22] Najafi A, Falaghi H, Contreras J, Ramezani M. Medium-term energy hub management subject to electricity price and wind uncertainty. Appl Energy 2016;168:418–33.
[23] Yang H, Xiong T, Qiu J, Qiu D, Dong ZY. Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response. Appl Energy 2016;167:353–65.
[24] Shabanpour-Haghighi A, Seifi AR. Simultaneous integrated optimal energy flow of electricity, gas, and heat. Energy Convers Manage 2015;101:579–91.
[25] Ma T, Wu J, Hao L. Energy flow modeling and optimal operation analysis of the micro energy grid based on energy hub. Energy Convers Manage 2017;133:292–306.
[26] Skarvelis-Kazakos S, Papadopoulos P, Unda IG, Gorman T, Belaidi A, Zigan S. Multiple energy carrier optimisation with intelligent agents. Appl Energy 2016;167:323–35.
[27] Moradi S, Ghaffarpour R, Ranjbar AM, Mozaffari B. Optimal integrated sizing and planning of hubs with midsize/large CHP units considering reliability of supply. Energy Convers Manage 2017;148:974–92.
[28] Dolatabadi A, Mohammadi-ivatloo B, Abapour M, Tohidi S. Optimal stochastic design of wind integrated energy hub. IEEE Trans Industr Inf 2017;13(5):2379–88.
[29] Dolatabadi A, Mohammadi-Ivatloo B. Stochastic risk-constrained scheduling of smart energy hub in the presence of wind power and demand response. Appl Therm Eng 2017;123:40–9.
[30] Kampouropoulos K, Andrade F, Sala E, Espinosa AG, Romeral JL. Multiobjective optimization of multi-carrier energy system using a combination of ANFIS and genetic algorithms. IEEE Trans Smart Grid 2016.
[31] Roldán-Blay C, Escrivá-Escrivá G, Roldán-Porta C, Álvarez-Bel C. An optimisation algorithm for distributed energy resources management in micro-scale energy hubs. Energy 2017;132:126–35.
[32] Shao C, Wang X, Shahidehpour M, Wang X, Wang B. An MILP-based optimal power flow in multicarrier energy systems. IEEE Trans Sustain Energy 2017;8(1):239–48.
[33] Vahid-Pakdel MJ, Nojavan S, Mohammadi-ivatloo B, Zare K. Stochastic optimization of energy hub operation with consideration of thermal energy market and demand response. Energy Convers Manage 2017;145:117–28.
[34] Zhang X, Che L, Shahidehpour M, Alabdulwahab AS, Abusorrah A. Reliability-based optimal planning of electricity and natural gas interconnections for multiple energy hubs. IEEE Trans Smart Grid 2017;8(4):1658–67.
[35] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Yousefi H. Energy hub: from a model to a concept – a review. Renew Sustain Energy Rev 2017;80:1512–27.
[36] Majidi M, Nojavan S, Zare K. Optimal stochastic short-term thermal and electrical operation of fuel cell/photovoltaic/battery/grid hybrid energy system in the presence of demand response program. Energy Convers Manage 2017;144:132–42.
[37] Nojavan S, Majidi M, Zare K. Risk-based optimal performance of a PV/fuel cell/battery/grid hybrid energy system using information gap decision theory in the presence of demand response program. Int J Hydrogen Energy 2017;42(16):11857–67.
[38] Ghalelou AN, Fakhri AP, Nojavan S, Majidi M, Hatami H. A stochastic self-scheduling program for compressed air energy storage (CAES) of renewable energy sources (RESs) based on a demand response mechanism. Energy Convers Manage 2016;120:388–96.
[39] Nojavan S, Qesmati H, Zare K, Seyyedi H. Large consumer electricity acquisition considering time-of-use rates demand response programs. Arab J Sci Eng 2014;39(12):8913–23.
[40] Nojavan S, Ghesmati H, Zare K. Robust optimal offering strategy of large consumer using IGDT considering demand response programs. Electric Power Syst Res 2016;130:46–58.
[41] Nojavan S, Majidi M, Esfetanaj NN. An efficient cost-reliability optimization model for optimal siting and sizing of energy storage system in a microgrid in the presence of responsible load management. Energy 2017;139:89–97.
[42] Nojavan S, Majidi M, Najafi-Ghalelou A, Ghahramani M, Zare K. A cost-emission model for fuel cell/PV/battery hybrid energy system in the presence of demand response program: ε-constraint method and fuzzy satisfying approach. Energy Convers Manage 2017;138:383–92.
[43] Majidi M, Nojavan S, Esfetanaj NN, Najafi-Ghalelou A, Zare K. A multi-objective model for optimal operation of a battery/PV/fuel cell/grid hybrid energy system using weighted sum technique and fuzzy satisfying approach considering responsible load management. Sol Energy 2017;144:79–89.
[44] Mohseni-Bonab SM, Rabiee A, Jalilzadeh S, Mohammadi-Ivatloo B, Nojavan S. Probabilistic multi objective optimal reactive power dispatch considering load uncertainties using Monte Carlo simulations. J Oper Autom Power Eng 2015;3(1):83–93.
[45] The GAMS Software Website, 2017 [Online]. Available: < http://www.gams.com/help/index.jsp?topic=%2Fgams.doc%2Fsolvers%2Findex.html > .
[46] Elsied M, Oukaour A, Gualous H, Brutto OA. Optimal economic and environment operation of micro-grid power systems. Energy Convers Manage 2016;122:182–94.
[47] Elsied M, Oukaour A, Gualous H, Hassan R. Energy management and optimization in microgrid system based on green energy. Energy 2015;84:139–51.