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Energy xxx (2015) 1–14

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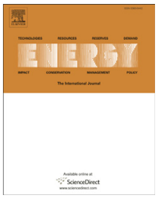

A comprehensive model for self-scheduling an energy hub to supply cooling, heating and electrical demands of a building Q5

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ARTICLE INFO

Article history:
Received 6 March 2015
Received in revised form
27 October 2015
Accepted 28 October 2015
Available online xxx

Keywords:
Energy hub
Combined heat and power
Feasible operation region
Electric heat pump
Energy storage systems

ABSTRACT

This paper presents an innovative method for modeling energy hubs based on energy flow between its constituent elements. Using this method, modeling of energy hubs with different elements and connections is facilitated. Also, an appropriate mixed integer nonlinear programming model is presented for short term 24-hour scheduling an energy hub, in which, the objective is to fulfill daily cooling, heating and electric demands of a hypothetical building with the maximum profit. Furthermore, in the energy flow based modeling method presented in this paper, energy storage elements are not only used at the output of the hub; but also, are capable of being used as inputs for other elements inside the energy hub. In order to evaluate the performance of the model, simulations have been accomplished for one hot and one cold typical day. Presented energy hub includes various elements such as combined heat and power, electric heat pump, boiler, absorption chiller and electrical and thermal energy storages. Moreover, in the modeling of the proposed energy hub, feasible operation region for combined heat and power system together with technical constraints of energy hub equipment is considered. Analyzing numerical results, flexibility of the energy hub for feeding the required loads of the building, operation of combined heat and power and the effect of electrical heat pumps in meeting cooling and heating loads of the building are evaluated. The numerical results show that combined heat and power operation points and its average electrical and thermal efficiency in hot and cold days are totally different and electric heat pump, regarding its high efficiency, is the main supplier of cooling and heating loads of the building in the studied energy hub.

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1. Introduction

Achieving ambitious goals of reducing greenhouse gas (GHG) emissions and optimizing energy consumption, needs specific strategies, not only in electric energy sector; but also, in all other energy sectors as well. A considerable amount of consumed energy in the world is used in domestic and commercial sectors. Namely, in United States in 2013, nearly 40 percent of total consumed energy is used in domestic and commercial sectors; the same amount has been used in the mentioned sectors in Iran too [1,2]. Based on the report of energy information administration in 2011, nearly 30 percent of consumed energy in the world has been consumed in domestic and commercial sectors. On the other hand, cooling and heating demands of domestic sector is almost 65 percent of energy consumption in this sector [3].

1.1. *Energy hub*

Nowadays, owing to distribution networks for energy such as natural gas and electricity in different urban areas, together with technology developments such as CHP (combined heat and power systems), EHP (electric heat pump), Ab.Chiller (absorption chiller), TES (thermal energy storage) and EES (electrical energy storage) in conjunction with smart control and measurement equipment, integrated operation for energy management is feasible. Concept of energy hub which is firstly introduced by Anderson et al. in 2007 is a functional unit capable of transforming, conditioning and storing of several kinds of energy [4,5]. In fact, using mentioned technologies, the energy hub represents an interface between different energy infrastructures at its input ports, such as EDS (electrical distribution system) and GDS (natural gas distribution system) and

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http://dx.doi.org/10.1016/j.energy.2015.10.137
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Please cite this article in press as: Moghaddam IG, et al., A comprehensive model for self-scheduling an energy hub to supply cooling, heating and electrical demands of a building, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.10.137

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Acronyms

EHP	electric heat pump
EES	electrical energy storage
TES	thermal energy storage
A.B	auxiliary boiler
Ab.Chiller	absorption chiller
CHP	combined heat and power
EDS	electricity distributed system
GDS	gas distributed system

Variables

$E\,(t)$	electricity dispatching at each time period t (kWh)
$H\,(t)$	heat dispatching at each time period t (kWh)
$C\,(t)$	cooling dispatching at each time period t (kWh)
$F_{CHP}\,(t)$	fuel consumed by CHP at each time period t (kWh)
$F_{A.B}\,(t)$	fuel consumed by A.B at each time period t (kWh)
$F\,(t)$	total fuel consumed by energy hub at each time period t (kWh)
Income (t)	income of energy hub at each time period t (Mu)
Cost (t)	cost of energy hub at each time period t (Mu)
Profit	profit of energy hub (Mu)
$Cost^{st}_{CHP}(t)$	startup cost of CHP at each time period t (Mu)
$Cost^{shd}_{CHP}(t)$	shut down cost of CHP at each time period t (Mu)
$Eng^{EES}\,(t)$	Energy stored level in EES at each time period t (kWh)
$Eng^{TES}\,(t)$	energy stored level in TES at each time period t (kWh)
s (t)	binary variable equals to 1 if CHP is on and 0 otherwise
x (t)	binary variable equals to 1 if EES is charging and 0 otherwise
y (t)	binary variable equals to 1 if EES is discharging and 0 otherwise
u (t)	binary variable equals to 1 if TES is charging and 0 otherwise
v (t)	binary variable equals to 1 if TES is discharging and 0 otherwise
m (t)	binary variable equals to 1 if transmitting energy from EDS and 0 otherwise
n (t)	binary variable equals to 1 if receiving energy from EDS and 0 otherwise
l (t)	binary variable equals to 1 if EHP operates in cooling mode
b (t)	binary variable equals to 1 if EHP operates in Heating mode
f	fuel consumption function of CHP

Parameters

EL (t)	forecasted electrical load of the building at each time period t (kWh)
TL (t)	forecasted thermal load of the building at each time period t (kWh)
CL (t)	forecasted cooling load of the building at each time period t (kWh)
SC	startup cost of CHP (Mu)
SHC	shut down cost of CHP (Mu)
MUT	minimum up time of CHP (h)
MDT	minimum down time of CHP (h)
$H^{max,\ A.B}$, $H^{min,\ A.B}$	minimum/maximum heating capacity of auxiliary boiler (kW)
$\eta^{A.B}$	auxiliary boiler efficiency
$P^{max,EES}$	power capacity of EES (kW)
$P^{max,TES}$	power capacity of TES (kW)
$SOC^{max,\ EES}$	maximum state of charge of EES (kWh)
$SOC^{min,\ EES}$	minimum state of charge of EES (kWh)
$SOC^{max,\ TES}$	maximum state of charge of TES (kWh)
$SOC^{min,\ TES}$	minimum state of charge of TES (kWh)
η^{EES}	charging and discharging efficiency of EES
η^{TES}	charging and discharging efficiency of TES
$H^{min,\ EHP}$, $H^{max,\ EHP}$	minimum/maximum heating capacity of EHP in heating mode (kWh)
$C^{min,\ EHP}$,$C^{max,\ EHP}$	minimum/maximum cooling capacity of EHP in cooling mode (kWh)
$C^{min,\ Ab.Chiller}$, $C^{max,\ Ab.Chiller}$	minimum/maximum cooling capacity of Ab.Chiller in cooling mode (kWh)
$COP^{EHP\ cooling/heating}$	coefficient of performance of EHP in cooling/heating mode
$COP^{Ab.Chiller}$	coefficient of performance of Ab.Chiller
CLC	cable line capacity (kW)
GLC	gas line capacity (kW)
EPr (t)	electricity price at each time period t (Mu/kWh)
NGpr	natural gas price for heat generation (Mu/kWh)
NGpre	natural gas price for electricity generation (Mu/kWh)
Mu	monetary unit
a,b,c,d,e,g	coefficients of fuel consumption function of CHP

end user's demands, such as electrical, heating and cooling demands at its output ports. In order to have integrated energy operation, concepts such as MES (Multi Energy System) [6], MEC (Multi Energy Carrier) [7] and DMG (Distributed Multi Generation) [8] are used in relation with energy hub. In fact, energy hub structure is based on modeling and analysis using Multi Energy Carrier and Multi Energy System. Convertors inside energy hub not only integrate energy carriers, but also, cause these energy carriers being converted to required energy for consumers from diverse alternative paths [9].

1.2. Literature review

After introducing the energy hub concept by Anderson and colleagues [4], diverse studies have been accomplished in this regard. Operation and planning studies and design of energy hubs and MESs are carried out in different scales. Short term scheduling of residential and commercial energy hubs which is noticed in this paper, has been analyzed from various points of view in recent studies. Diversity of constituent equipment of energy hubs and their technical and economic constraints, diversity of services of these hubs in meeting different loads, environmental effects, reliability and DR (demand response) (DR) are the subjects under study regarding short term scheduling of energy hubs. Some papers have assessed these systems in small scales like a building [10–13] and some others in bigger scales like regions and cities [14,15].

Ref. [11], has focused on the modeling of a home as an energy hub, considering different electrical and thermal appliance. Short term scheduling of energy hub in this paper which is equipped with CHP and plug-in hybrid vehicle (PHEV) is accomplished with the objective of minimization of customer payment. Numerical results of this paper show that home load management in energy hub framework leads to lower customer payment costs. Ottesen et al. [12], has developed a 24-h scheduling model of energy flexibility in buildings. They have utilized this model of energy hub for a Norwegian university college building to minimize the operational cost. Their study shows that the model is able to reduce costs by reducing peak loads and utilizing price differences between periods

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and between energy carriers. Ref. [14] has presented a method for optimal electric distribution system expansion planning for an urban electric distribution system which the use of MEC sources and other sources of distribution networks are optimized; meanwhile, utility costs are minimized and reliability is maximized. Orehounig et al. [16], optimized the daily energy consumption in some neighbor buildings using the energy hub concept. The energy hub concept in this paper includes district heating, biomass and small hydro power plants. This paper has surveyed the effect of using the energy hub in energy, economic and environmental cases. La Scala et al. [17], have evaluated optimal energy flow in multicarrier networks on 30 bus IEEE test network. They have presented a multi objective model for reliable operation of the energy system. Also, they have analyzed the effect of using interconnected energy hubs in power networks. Shabanpour et al. [18], have presented a precise MILP (mixed integer programming) model of energy hub for scheduling of weekly generation of a residential energy hub in Zurich. Limiting the number of start-shutdown of equipment, considering partial load efficiency and increasing the accuracy of energy loss calculation of energy storage facilities are the important innovations in this paper. They have investigated the effect of increasing the accuracy of their model for an energy hub consisting CHP, PV (photovoltaic), Boiler and hot water tank. Shabanpour et al. [19], have solved the 24-h optimal power flow problem of multi-career energy networks using evolutionary algorithm, modified teaching–learning based optimization. The energy hubs considered in this paper, have three inputs of electricity, natural gas and district heating and two outputs of electricity and heat. Shahmohammadi et al. [20], have presented a linear model for planning of generation and operation of energy hubs considering reliability boundaries. They have concluded that using this model, they can economically calculate the energy hub equipment sizes in order to meet electrical and thermal loads in a way that operational costs are minimized and reliability boundaries are met. Pazouki et al. [21] have presented short term scheduling of an energy hub consisting DER (distributed energy resources) such as wind power, CHP and DR for a commercial building. Minimization of operational costs considering reliability and emission constraints is the main innovations of this paper. Sheikhi et al. [22], have presented daily scheduling of a smart grid using smart energy hubs framework. The focus in this paper is on the use of IDR (integrated demand response) for modifying of electricity and gas consumptions. This paper has formulated the interaction between smart energy hubs in IDR program as a non-cooperative game. The purpose of presented IDR game in the paper is maximization of electric and natural gas utilities' profit and minimization of customer's consumption cost. Moeini et al. [23], have modeled an online economic dispatch for a wind-based energy hub. In this article, the interactions between energy carriers with the presence of renewable energy have been scrutinized. The presented model in this article applied to an 11-hub test system in a 24-h period. Parisio et al. [24], have presented a robust schedule for operating an energy hub. Its solution to energy hub operation problem determines the energy carriers to be purchased and stored in order to satisfy energy requests while minimizing a cost function.

1.3. Contributions

The aim of this paper is presenting a comprehensive model for scheduling a residential energy hub in which, not only cooling, heating and electrical demands of the building are met, but also, electricity can be sold to the distribution network maximizing the profit. In this paper, a comprehensive energy hub including CHP system, EHP, EES, TES, Ab.Chiller and A.B is designed and presented. Consideration of potential routes between constituent elements of this energy hub is one of the major innovations in proposed model. To the best of our knowledge, apart from Ref. [25], in which, using storage facility at both sides of converters is considered, in all studies, storage facilities are at the outlets of energy hub which cause the hub performance to decrease. Energy storage systems in this paper are not necessarily installed at the outlet in order to overcome the mentioned drawback of the current energy hubs. Due to the above mentioned feature, the normal matrix-based methods that are widely used for modeling of energy hubs are less effective here, considering the complexity of modeling. This paper presents an innovative method for modeling of energy hub based on energy flow between the constituent elements of the energy hub. Using this method, each multi input-multi output energy hub which has different energy storing elements and diverse internal connections will be easily modeled.

Another contribution of this paper is that, it considers all technical potential interconnections between different constituent parts of the proposed energy hub which have had lower attentions in the previous works. Considering feasible paths between different constituting parts of the hub is among the innovations introduced by the proposed energy hub which increases its performance despite making system more complicated. Using these paths augments flexibility and variety of the output services paths. Supplying the required demands, the modeled energy hub can also exchange energy with EDS. Various energy paths considered among system parts inside the proposed energy hub not only increase flexibility of the hub to meet different demands, but also enhance its reliability and continued service provision under critical situations. The central core of the proposed energy hub, CHP system, is modeled regarding FOR (feasible operation region) introduced in Refs. [26,27]. The mentioned feasible operation region is considered as MILP formulas in generation planning. Considering this area, operation strategy of co-generation system will be different with normal linear case; since, in this case, electrical and thermal efficiencies of the system are not constant and vary with the operation points. In the proposed model also technical constraints of the CHP system, including minimum working time, minimum shutdown time and startup and shutdown costs are considered. The model is developed in a way that the lack of any of the elements or paths will not affect the optimization process. The ultimate model is a MINLP (mixed integer non-linear programming) model based on the 24 h generation schedule of the proposed energy hub with electrical energy and natural gas as inputs to meet cooling, heating and electrical demands of a building. The modeled energy hub fulfills the above demands and is able to exchange energy with the EDS.

2. Energy hub model

As it can be seen in Fig. 1, the proposed model for energy hub is fed by GDS and EDS.

The output services of the hub include meeting the cooling, heating and electrical loads of a hypothetical building. Fig. 2 shows the proposed energy hub arrangement, including units and interconnections between these units as the following:

1. CHP generation system: This system is fed by natural gas and is able to generate electricity and heat;
2. EHP: This device uses electric energy to transfer heat from a cold medium to a hot medium;
3. Ab.Chiller: Heat energy is fed to this system and the output is cooling energy;
4. EES: Electrical energy is stored by this equipment at a particular time to be used later;
5. TES: Heat energy is stored by this equipment at a given time to be used later;

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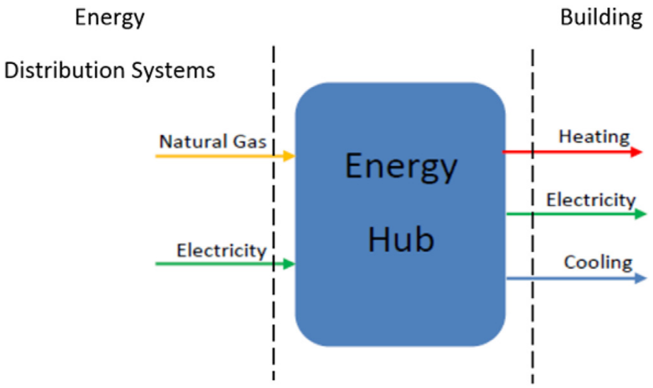

Fig. 1. Schematic representation of proposed energy hub and energy flow.

6. A.B: Natural gas is used as input to this equipment and it generates heat energy as its output.

In the proposed energy hub, electrical, cooling and heating demands of a hypothetical building are fulfilled through different techniques. Table 1, shows the potential capability of the elements of the energy hub in meeting the electrical, thermal and cooling demands of the building. While some of these paths may not be cost-effective under normal conditions, they may be used in emergency conditions such as deficit of natural gas and electricity and congestion of electrical and natural gas connection lines.

2.1. Electrical demand

Fig. 3 illustrates how electrical demands of the building are fulfilled. These demands are fulfilled by CHP system, EDS and EES element.

Table 1
Potential capabilities of the energy hub components in fulfilling building demands.

Demand	TES	EDS	EHP	A.B	Ab.Chiller	EES	CHP
Electrical Demand	–	✓	–	–	–	✓	✓
Heat Demand	✓	✓	✓	✓	–	✓	✓
Cool Demand	–	✓	✓	✓	✓	✓	✓

2.2. Thermal and cooling demands

Generation of cooling energy and meeting the cooling loads are depicted in Fig. 4. As it can be seen, both the Ab.Chiller and the EHP can fulfill cooling demands of the building. Such demands also can be fulfilled by EDS and GDS and energy converters in the energy hub.

Thermal demands, as in Fig. 5, are fulfilled by CHP, EHP, A.B and TES, which is made possible by both electrical and gas distribution grids.

3. Mathematical model of energy hub

Modeling of the proposed energy hub using normal matrix based methods, considering interconnections between its constituent elements and existence of energy storage elements in it, will be a very complicated task. In proposed energy hub, storing elements are not necessarily installed at the outlet. This feature aggrandizes the complexity of the modeling. For this reason, an innovative method for energy hub modeling based on energy flow between the constituent elements of the hub is presented. In this paper, a general rule is used for indicating dispatched energy flow values in equations. For each of dispatched energy flows such as electricity, heat and cold, source of energy flow is shown as superscript and destination is shown as subscript of the energy flow. For example, the electrical energy flowing from EDS to EHP is

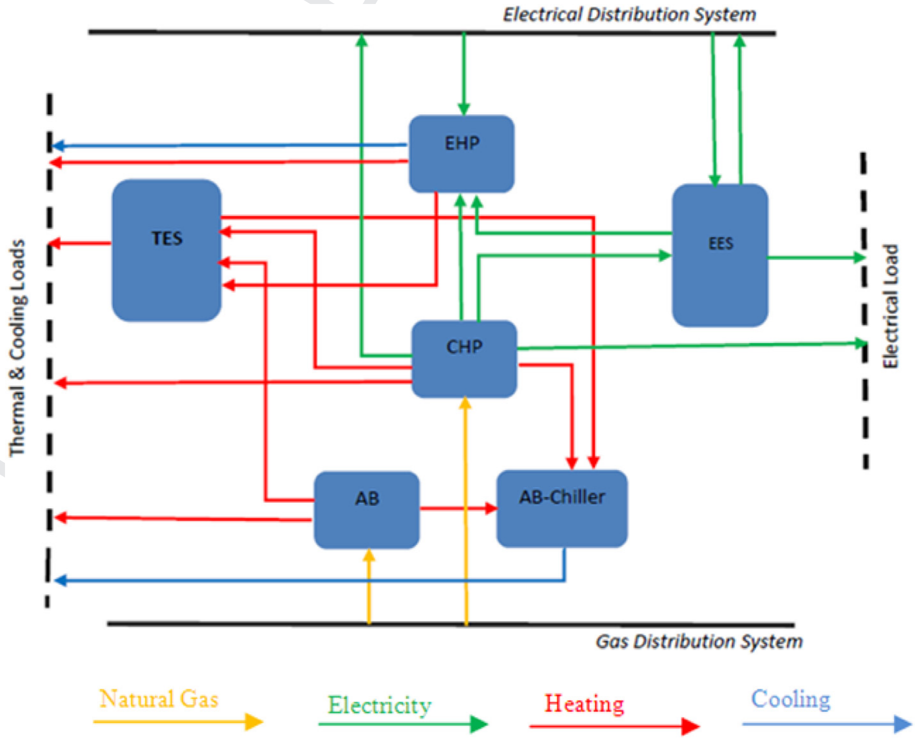

Fig. 2. Schematic representation of proposed energy hub and energy flow.

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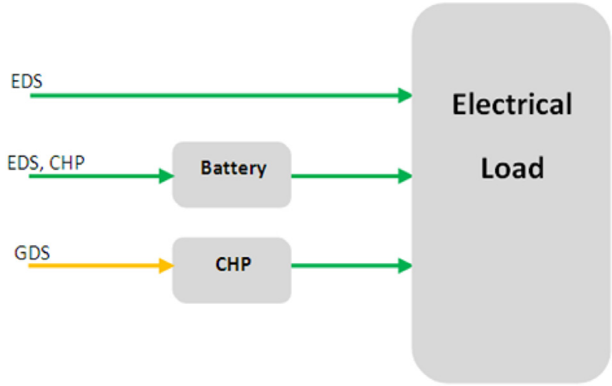

Fig. 3. Options of meeting the electrical load.

written as $E_{EHP}^{EDS}(t)$, while $E_{EHP}(t)$ denotes the total input electric energy of EHP and $E^{EDS}(t)$ indicates total dispatched energy from EDS. Heat energy transmitted from A.B to heat demand is written as $H_{TL}^{A.B}$, while the cooling energy generated by the Ab.Chiller and consumed by the building is shown as $C_{CL}^{Ab.Chiller}$.

Fig. 6 shows general schematic of optimization procedure of this paper. The details of the presented model are described in the Sections 3.1–3.9.

3.1. Objective function

The profit of the energy hub (Eq. (1)), is maximized considering some constraints including different building demands, energy prices and operational and technical constraints:

$$\textbf{Max} \quad profit = \sum_{t=1}^{t=24} Income(t) - Cost(t) \tag{1}$$

$$Income(t) = \left(E_{EDS}^{CHP}(t) + E_{EDS}^{EES}(t)\right).\mathrm{EPr}(t) \tag{2}$$

$$\begin{aligned} Cost(t) = {} & f\left(E^{CHP},\ H^{CHP}, t\right).\mathrm{NGPre} + F^{boil}(t).\mathrm{NGPr}(t) + \left(E_{EL}^{EDS}(\mathrm{t})\right. \\ & \left. + E_{EES}^{EDS}(\mathrm{t}) + E_{EHP}^{EDS}(t)\right).\mathrm{EPr}(t) + Cost_{CHP}^{st}(t) + Cost_{CHP}^{shd}(t) \end{aligned} \tag{3}$$

The first term of Eq. (1) represents the total income made by selling electricity to EDS, detailed in Eq. (2). The second term of this equation is the total operational and technical costs of energy hub units, detailed in Eq. (3). Fuel costs of the CHP and the A.B, costs of purchasing energy from EDS and the CHP system startup cost and shutdown cost are considered in Eq. (3). It should be noted that fuel costs can be different for single heat generation and CHP generation. In fact, in order to encourage the use of CHP system, input fuel is subsidized by governments in some countries, like Iran [28].

3.2. Demand constraints

The most important constraint in the operation of energy hub is meeting electrical, cooling and heating demands considered in Eqs. (4)–(6).

$$EL(t) = E_{EL}^{EDS}(t) + E_{EL}^{CHP}(t) + E_{EL}^{EES}(t) \tag{4}$$

$$TL(t) = H_{TL}^{A.B}(t) + H_{TL}^{CHP}(t) + H_{TL}^{TES}(t) + H_{TL}^{EHP}(t) \tag{5}$$

$$CL(t) = C_{CL}^{Ab.Chiller}(t) + C_{CL}^{EHP}(t) \tag{6}$$

3.3. CHP system constraints

Central core of the proposed energy hub is a CHP system. Eq. (7) and Eq. (8) show the dispatching paths of electrical and thermal energy by CHP system, respectively.

$$E^{CHP}(t) = E_{EL}^{CHP}(t) + E_{EDS}^{CHP}(t) + E_{EES}^{CHP}(t) + E_{EHP}^{CHP}(t) \tag{7}$$

$$H^{CHP}(t) = H_{EL}^{CHP}(t) + H_{TES}^{CHP}(t) + H_{air}^{CHP}(t) \tag{8}$$

It should be noted that in the CHP system, the electricity and heat are not generated independently, but, the generation of any of them affects the other. This dependency is represented by using a feasible region for each CHP. In fact, the CHP system can control the generation of electricity and heat in this area. Fig. 7 shows the heat-power feasible operation region (FOR) of a cogeneration unit used in the proposed energy hub. A-F points are the corners of the operational area where working points of the CHP system occur. Since this area has an angle of more than 180°, FOR in Fig. 7 is regarded as non-convex. Hence, it cannot be described by normal linear constraint. Partitioning methods are used to model non-convex areas including, ear clipping method [26], in which the non-convex area is divided into several convex areas. The method has also been used by Ref. [29].

Specific linear equations have been proposed by Ref. [29] to describe such area, which are used in this paper. The non-convex

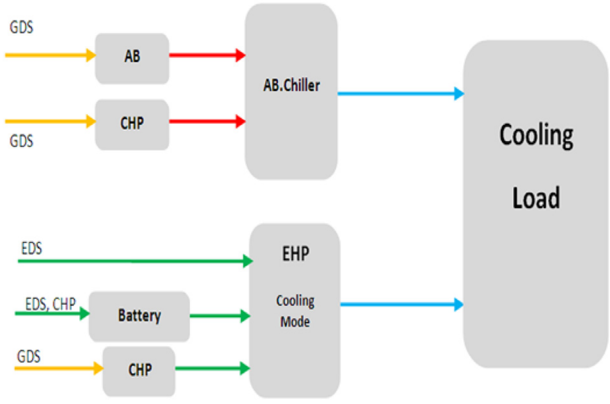

Fig. 4. Options of meeting the cooling load.

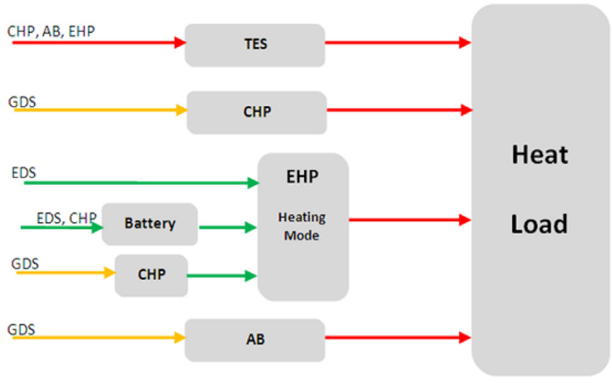

Fig. 5. Options of meeting the heating load.

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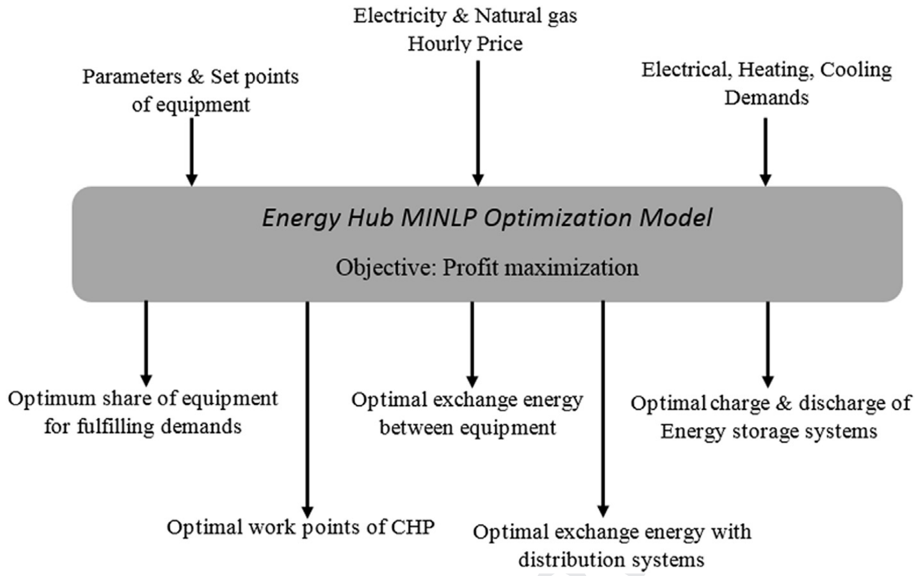

Fig. 6. Optimization procedure.

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operational area of the CHP system is divided into two convex areas, section I and section II. The operational area is modeled using Eqs. (9)–(17).

$$E^{CHP}(t) - E_B^{CHP} - \frac{E_B^{CHP} - E_C^{CHP}}{H_B^{CHP} - E_C^{CHP}}\left(H^{CHP}(t) - H_B^{CHP}\right) \le 0 \tag{9}$$

$$E^{CHP}(t) - E_C^{CHP} - \frac{E_C^{CHP} - E_D^{CHP}}{H_C^{CHP} - E_D^{CHP}}\left(H^{CHP}(t) - H_C^{CHP}\right) \ge 0 \tag{10}$$

$$E^{CHP}(t) - E_E^{CHP} - \frac{E_E^{CHP} - E_F^{CHP}}{H_E^{CHP} - E_F^{CHP}}\left(H^{CHP}(t) - H_E^{CHP}\right) \ge -(1 - x_1(t)) \times M \tag{11}$$

$$E^{CHP}(t) - E_D^{CHP} - \frac{E_D^{CHP} - E_E^{CHP}}{H_D^{CHP} - E_E^{CHP}}\left(H^{CHP}(t) - H_D^{CHP}\right) \ge -(1 - x_2(t)) \times M \tag{12}$$

$$H^{CHP}(t) - H_E^{CHP} \ge -(1 - x_2(t)) \times M \tag{13}$$

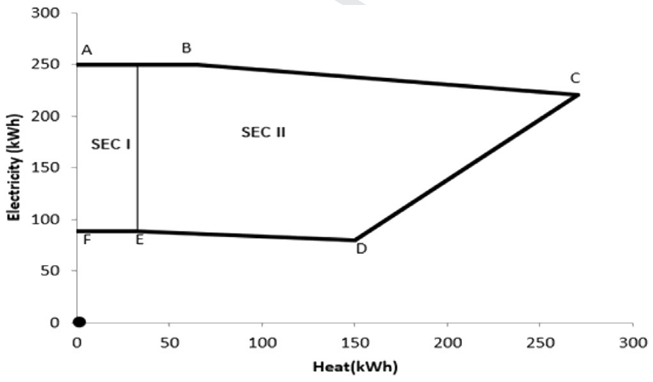

Fig. 7. Heat – power feasible region of CHP.

$$H^{CHP}(t) - H_E^{CHP} \le (1 - x_1(t)) \times M \tag{14}$$

$$x1(t) + x2(t) = s(t) \tag{15}$$

$$0 \le H^{CHP}(t) \le H_C^{CHP}.s(t) \tag{16}$$

$$0 \le P^{CHP}(t) \le P_A^{CHP}.s(t) \tag{17}$$

In Eqs. (11)–(14), $X_1(t) = 1$ ($X_2(t) = 1$) means that the CHP operates in the first (second) convex section of FOR and M denotes a very large number. According to Eq. (15), the operation region would be either I or II when CHP unit is ON and be none of them when CHP unit is OFF. Eq. (16) and Eq. (17) set the produced heat and power to zero for an OFF unit. Eqs. (18)–(21) show the costs of system start-up and shutdown.

$$Cost_{CHP}^{st}(t) \ge 0 \tag{18}$$

$$Cost_{CHP}^{sh}(t) \ge 0 \tag{19}$$

$$Cost_{CHP}^{st}(t) = SC.(s(t) - s(t-1)) \tag{20}$$

$$Cost_{CHP}^{sh}(t) = SHC.(s(t-1) - s(t))\Big) \tag{21}$$

Also, the minimum times for the CHP system to be on or off are determined by the Eqs. (22)–(23):

$$s(t) - s(t-1) - s(k) \le 0 \quad \forall t,\ \forall k \in \{t, t+1, \ldots, MUT + t - 1\} \tag{22}$$

$$s(t-1) - s(t) + s(k) \le 1 \quad \forall t\ ,\ \forall k \in \{t, t+1, \ldots, MDT + t - 1\} \tag{23}$$

The fuel consumption function of CHP system for electricity and heat generation based on the [30] is considered as Eq. (24).

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$$f\left(E^{CHP},H^{CHP},t\right) = a.\left(E^{CHP}(t)\right)^2 + b.E^{CHP}(t) + c.\left(H^{CHP}(t)\right)^2 + \mathrm{d}.H^{CHP}(t) + e.E^{CHP}(t).H^{CHP}(t) + g \tag{24}$$

3.4. A.B constraints

Eq. (25) shows upper and lower capacity limits of the boiler where binary variable k(t) is equal to 1, if the auxiliary boiler produces heat in time period t. Eqs. (26), (27) calculate the amount of fuel used by boiler with respect to its heat generation at each time step.

$$H^{min.A.B}.k(t) \le H^{A.B}(t) \le H^{max,\ A.B}.k(t) \tag{25}$$

$$H^{A.B}(t) = H^{A.B}_{TES}(t) + H^{A.B}_{Ab.Chiller}(t) + H^{A.B}_{TL} \tag{26}$$

$$H^{A.B}(t) = \eta^{A.B}.F^{A.B}(t) \tag{27}$$

3.5. EES constraints

Charging and discharging rates of the EES are determined in Eq. (28) and Eq. (29) and charging and discharging paths of EES in the proposed hub are stated in Eq. (31) and Eq. (32). Binary variables x(t) and y(t), in Eq. (30), are considered to ensure that charging and discharging of EES do not happen at the same time.

$$0 \le E_{EES}(t) \le P^{max}_{EES}(t).x(t) \tag{28}$$

$$0 \le E^{EES}(t) \le P^{max}_{EES}.y(t) \tag{29}$$

$$x(t) + y(t) \le 1 \tag{30}$$

$$E_{EES}(t) = \left(E^{CHP}_{EES}(t) + E^{EDS}_{EES}(t)\right)\Big/\eta^{ch}_{EES} \tag{31}$$

$$E^{EES}(t) = \left(E^{EES}_{EDS}(t) + E^{EES}_{EL}(t) + E^{EES}_{EHP}(t)\right).\eta^{Dch}_{EES} \tag{32}$$

Eq. (33) corresponds to the energy balance in the EES at each time step and the upper and lower limits of the stored energy are given by Eq. (34).

$$Eng^{EES}(t) = Eng^{EES}(t-1) + E_{EES}(t) - E^{EES}(t) \quad for\ t \ge 1 \tag{33}$$

$$SOC^{min}_{EES} \le Eng^{EES}(t) \le SOC^{max}_{EES} \tag{34}$$

Since energy generation schedule of the energy hub has been considered for 24 h, Eq. (35) states that the primary stored energy level at the time interval 1 is taken equal to the stored energy level at the time interval 24:

$$\sum_{t=1}^{t=24}\left(E_{EES}(t) - E^{EES}(t)\right) = 0 \tag{35}$$

3.6. TES constraints

Like the EES, the constraints of this system are stated in Eqs. (36)–(43). u(t) and v(t) are binary variables that are utilized to prevent the TES from charging and discharging at the same time:

$$0 \le H_{TES}(t) \le P^{max}_{TES}(t).u(t) \tag{36}$$

$$0 \le H^{TES}(t) \le P^{max}_{TES}(t).v(t) \tag{37}$$

$$H_{TES}(t) = \left(H^{CHP}_{TES}(t) + H^{A.B}_{TES}(t) + H^{EHP}_{TES}\right)\Big/\eta^{ch}_{TES} \tag{38}$$

$$H^{TES}(t) = \left(H^{TES}_{TL}(t) + H^{TES}_{Ab.Chiller}(t)\right).\eta^{Dch}_{TES} \tag{39}$$

$$Eng^{TES}(t) = Eng^{TES}(t-1) + H_{TES}(t) - H^{TES}(t) \quad for\ t \ge 1 \tag{40}$$

$$\sum_{t=0}^{t=24}\left(H_{TES}(t) - H^{TES}(t)\right) = 0 \tag{41}$$

$$SOC^{min}_{TES} \le Eng^{TES}(t) \le SOC^{max}_{TES} \tag{42}$$

$$u(t) + v(t) \le 1 \tag{43}$$

3.7. Ab.Chiller constraints

Eqs. (44)–(45) determine the constraints of the cooling energy dispatching paths and cooling capacity of the Ab.Chiller, respectively.

$$C^{Ab.Chiller}_{CL}(t) = \left(H^{A.B}_{Ab.Chiller}(t) + H^{CHP}_{Ab.Chiller}(t) + H^{TES}_{Ab.Chiller}(t)\right).COP^{Ab.Chiller} \tag{44}$$

$$C^{min,Ab.Chiller} \le C^{Ab.Chiller}_{CL}(t) \le C^{max,Ab.Chiller} \tag{45}$$

3.8. Electricity and natural gas connection lines constraints

Eqs. (46)–(49) indicate the path and the capacity of the line, through which, electrical energy is exchanged with the grid at any time interval t.

$$E^{EDS}(\mathrm{t}) = E^{EDS}_{EL}(\mathrm{t}) + E^{EDS}_{EES}(\mathrm{t}) + E^{EDS}_{EHP}(t) \tag{46}$$

$$E_{EDS}(\mathrm{t}) = E^{EES}_{EDS}(\mathrm{t}) + E^{CHP}_{EDS}(\mathrm{t}) \tag{47}$$

$$0 \le E^{EDS}(t) \le CLC.m(t) \tag{48}$$

$$0 \le E_{EDS}(t) \le CLC.n(t) \tag{49}$$

$$m(t) + n(t) \le 1 \tag{50}$$

Binary variables m(t) and n(t) together with Eq. (50) prohibit electric energy being sent to and received from EDS simultaneously.

$$fuel_{A.B}(t) + fuel_{CHP}(t) \le GLC \tag{51}$$

The constraint on gas consumption by two gas consumers in the energy hub is defined by Eq. (51).

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3.9. EHP constraints

The constraints of the EHP are shown in Eqs. (53)–(56). l (t) and b (t) are binary variables that are utilized to prevent heating mode and cooling mode of the EHP from happening at the same time:

$$C^{min,EHP}.l(t) \le C^{EHP}_{CL}(t) \le C^{max,EHP}.l(t) \tag{52}$$

$$C^{EHP}_{CL}(t) = \left(E^{CHP}_{EHP}(t) + E^{EDS}_{EHP}(t) + E^{EES}_{EHP}(t)\right).COP^{cooling}_{EHP} \quad \text{Cooling mode} \tag{53}$$

$$H^{EHP} = H^{EHP}_{TL} + H^{EHP}_{Ab.Chiller} + H^{EHP}_{TES} \tag{54}$$

$$H^{EHP}(t) = \left(E^{CHP}_{EHP}(t) + E^{EDS}_{EHP}(t) + E^{EES}_{EHP}(t)\right).COP^{heating}_{EHP} \quad \text{Heating mode} \tag{55}$$

$$H^{min,\ EHP}.b(t) \le H^{EHP}(t) \le H^{max,\ EHP}.b(t) \tag{56}$$

$$l(t) + b(t) \le 1 \tag{57}$$

3.10. Energy hub flexibility

One of the most important advantages of the proposed energy hub is its flexibility in meeting loads of the building in emergency conditions like deficit of natural gas and electricity or participating energy hub in a demand response program. In fact, in order to investigate performance of the proposed energy hub when it encounters the reduction of each input energy source regardless of energy prices and energy hub operation costs, objective function of the proposed model (Eq. (1)) is changed to Eq. (58).

$$\text{Min}\ \ W.f_1(t) + (1 - W).f_2(t) \tag{58}$$

$$0 \le W \le 1 \tag{59}$$

In which, f_1(t) is the consumption of natural gas and f_2(t) is the input electrical energy from EDS. As shown in Eq. (59), W is a weighting factor whose value varies between [0, 1]. It is clear that in Eq. (58), w = 0 is in a situation, in which, optimal minimum electric energy should be received from the network and w = 1 is in a situation in which optimal input natural gas should be minimized.

Furthermore, if the aim of the optimization is minimization of electricity and natural gas consumption regardless of the costs, the Eq. (58) is changed to Eq. (60).

$$\text{Min}\ \ f_1(t) + f_2(t) \tag{60}$$

In this case, regardless of energy prices, the optimization model seeks for minimization of consumption of input energies altogether. This case could be considered as a special case for optimization based on Eq. (58) in which, coefficients of both functions f_1 (t) and f_2 (t) are considered the same.

4. Numerical results

In this section, the proposed model is implemented in optimal operational scheduling problem of energy hub over a 24-h time interval. In order to investigate the performance of the presented model efficiently, energy hub scheduling generation has been programmed for cold (case 1) and hot (case 2) typical days based on cost optimization. The Mixed Integer Non-Linear Programming model is implemented in GAMS optimization software [31] and solved using the DICOPT solver that is a program for solving MINLP problems which include linear binary or integer variables and linear and nonlinear continuous variables [32].

4.1. Input data

In Table 2, electrical, heating and cooling loads for a hypothetical building are shown. Electric loads for consumptions other than heating and cooling is supposed the same in the both cases.

In this article, electricity price is assumed to be based on TOU (time of use) method. Also, electricity buy and sale rate is the same and calculated as shown in Table 3. The gas price for heat generation NGPr and value for electricity generation NGPre are same in this paper and is 16Mu/kWh.

Parameter values which are used in this article are shown in Tables 4–7. Efficiency values for different units in presented energy hub are shown in Table 4.

It should be mentioned that the operation of Ab.chiller and EHP are somehow dependent on environmental conditions, based on the manufacture [33,34]. Also, the COP values of EHP and Ab.chiller Q2 decrease when operating at partial loads [18]. However, for the sake of simplicity and without losing the integrity of the subject, COP values of the heat pump and the Ab.chiller is supposed constant at different hours of the day and diverse loads as in Refs. [35–38]. However, the presented model can be easily extended to the case with variable COP.

The capacity of the units in energy hub and interconnection power lines with electricity and gas distribution networks are shown in Table 5. Also, coefficients of CHP fuel consumption function are shown in Table 6.

Moreover, maximum and minimum state of charge and initial levels of energy storages systems are shown in Table 7. In the

Table 2
Forecasting Cooling and heat load of building over 24 h.

Case	Load (kWh)	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
Case 1	Heating	192.2	207.6	239.3	253.2	383.4	253.2	336.8	398.5	504	523.2	492.7	520.6
	Cooling	23.2	24.1	23.8	24.4	25.2	27.5	40.5	45	49	54.4	67.5	62.5
Case 2	Heating	35.5	22.9	15.9	15.9	25.5	63.7	57.3	25.5	79.6	101.9	108.3	76.4
	Cooling	212.4	222	202.7	173.7	135.1	193.1	154.4	270.3	463.3	559.8	637.1	675.7
case 1,2	Electrical	58.5	70.2	81.9	105.3	117	140.4	198.9	245.7	257.4	245.7	163.8	152.1
Case	**Load (kWh)**	**t13**	**t14**	**t15**	**t16**	**t17**	**t18**	**t19**	**t20**	**t21**	**t22**	**t23**	**t24**
Case 1	Heating	613.6	540	582.2	444	360	300.5	286.4	270.6	242.4	227.9	163.2	208.2
	Cooling	70	65	55	43.5	35.5	26.5	24.1	23.8	24.3	25.2	21	21.5
Case 2	Heating	89.2	89.2	106.4	75.2	67.1	77.4	91.4	126.3	119.2	91.2	56.1	35.1
	Cooling	666	700.6	748.1	637.1	579.2	540.5	386.1	328.2	308.9	289.6	270.3	251
case 1,2	Electrical	140.4	152.1	163.8	187.2	198.9	234	256.5	222.3	187.2	140.4	105.3	58.5

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Table 3
Three – level TOU tariffs for a day.

Time (h)	1–5 24	6–10 15–18 22–23	11–14 19–21
Price (Mu/kWh)	40	60	80

Table 4
Efficiency of units.

Symbol	Value
η^{EES}	0.87
η^{TES}	0.9
$\eta^{A.B}$	0.95
COP^{EHP}	2.5
$COP^{Ab.Chiller}$	0.75

Table 6
CHP fuel function coefficients.

a	b	c	d	e	g
0.00216	0.90625	0.00188	0.26250	0.00188	16.56

following, simulation results are investigated thoroughly in order to evaluate the efficiency of the presented model.

The overall results of simulations are shown in Table 8. Also, Fig. 8 shows the operation of the main equipment.

4.2. Electrical load balancing

In Fig. 9, the optimal strategies for meeting the electricity loads are depicted. Although, electricity load and price are considered the same for both cases, load fulfilling methods are different due to inequality of heating and cooling loads in these cases.

Table 9a and b, show CHP, EDS and EES shares in fulfilling the electricity load of the building in cases 1 and 2 respectively. Most of the electrical load of the building is met by CHP in case 1 and by EDS in case 2.

4.3. Thermal and cooling load balancing

As it is apparent in Fig. 10a and b, methods of satisfying thermal demand are totally different in the two cases. Due to the high COP of EHP, maximum of heating energy in case 1 is supplied by this system in heating mode; while in case 2, A.B is the main supplier of required heating energy for the building. As a matter of fact, EHP consumes most of its input electrical energy for heating in case 1; while in case 2, meeting the cooling loads is the first priority of this unit and considering high cooling load of the building in this case, EHP operates in cooling mode only. Therefore, in case 2, other sources of fulfilling heating load such as CHP, TES and A.B are responsible for satisfying thermal loads. In case 1, EHP is set in cooling mode in the hours between 19 and 23 in order to reduce electric energy consumption at these hours, in which, electricity price is high. More to the point, in case 2, in the hours between 11 and 15, heat generation is reduced regarding electricity price. Shares of thermal load's supply for both cases are shown in Table 9b. In case 1, at the hours between 11 and 14 in which, electricity price and heating load are high, A.B and TES are set into operation in order to fulfill part of the heating load. In this way, electrical energy consumption for satisfying input electrical energy to EHP decreases. A similar scenario is repeated at the hours between 19 and 23, but, since the amount of required thermal load has decreased at these hours, EHP will be set out of operation and other resources will be in charge of meeting the heating load. In case 2, at the hours between 1 and 5 and the hour 24, regarding low thermal load of the building in comparison with case 1 and low electricity price, thermal load is fulfilled by the CHP at these hours. At these hours, since electricity buy from EDS is cost efficient, CHP is concentrated on generating heat energy. With cooling load being increased at the following hours, most of the thermal load will be supplied by A.B and the heat generated by CHP is used for Ab.chiller.

In Fig. 10c and d, cooling load fulfill has been shown regarding its resources. EHP, considering its high COP, is the main cooling and heating load supplier in cases 1 and 2 respectively. Considering the amount of cooling load of the building in the middle hours of the day, in case 2, employment of the Ab.chiller is inevitable. The reason is that, at these hours, required cooling load is more than EHP cooling power and the only cooling alternative is the Ab.chiller. In case 1, EHP is mostly operated for heating purpose, but, in the hours between 19 and 23 (in which, electricity price is high) generates cooling power. At these hours, required heating energy for the building is supplied via CHP, TES and A.B in order to reduce electricity consumption.

As it can be seen, at the hour 19, EHP has an operating mode change; in case C_{min} value is supposed to be more than 20, the results change and there will be no mode change. Defining optimized C_{min} of EHP is actually a tradeoff between the decrease in life cycle of EHP caused by changing mode and the increase in income caused by the flexibility of energy hub and electricity sale to the network which is beyond the scope of this paper.

4.4. CHP operation

In Fig. 11, operation points in the co-generation system are shown in the two studied cases. As it appears in this figure, the operating points are different in the two cases and the optimization model has considered a different operational scenario for co-generation system in these two cases. CHP operation points in case 1 are appeared in the area with higher electricity values and

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Table 5
Capacity power of Units.

Power	Value (kW)
$P^{max, EES}$	70
$P^{max, TES}$	150
$H^{max,AB}$, $H^{min, AB}$	250, 20
$H^{max, EHP}$, $H^{min, EHP}$	450, 20
$C^{max, EHP}$,$C^{min, EHP}$	450,20
$C^{max, Ab.Chiller}$,$C^{min, Ab.Chiller}$	300,0
CLC	300
GLC	550

Table 7
Characteristics of energy storage systems.

Parameter	Value (kWh)
$SOC^{max, EES}$	1000
$SOC^{min, EES}$	100
$SOC^{max, TES}$	2000
$SOC^{min, TES}$	200
Eng^{EES} (0)	500
Eng^{TES} (0)	1000

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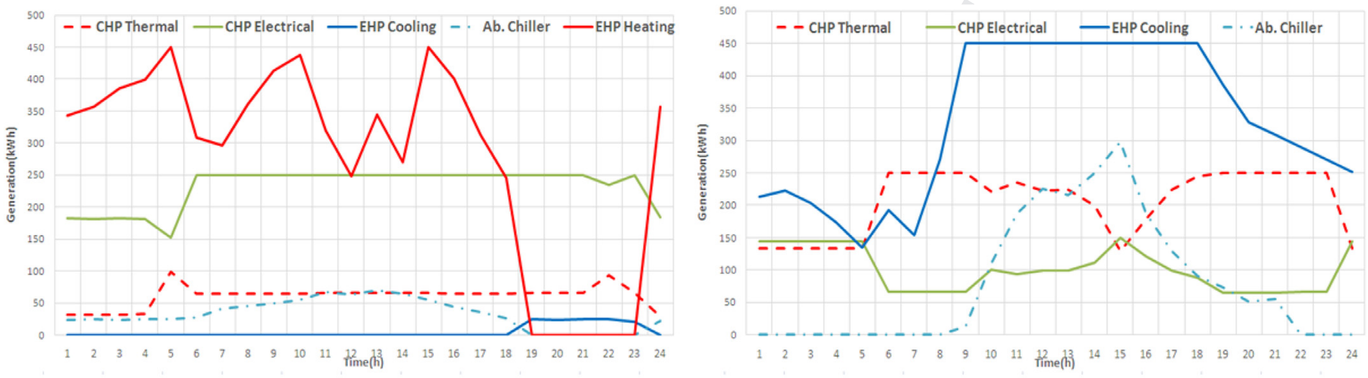
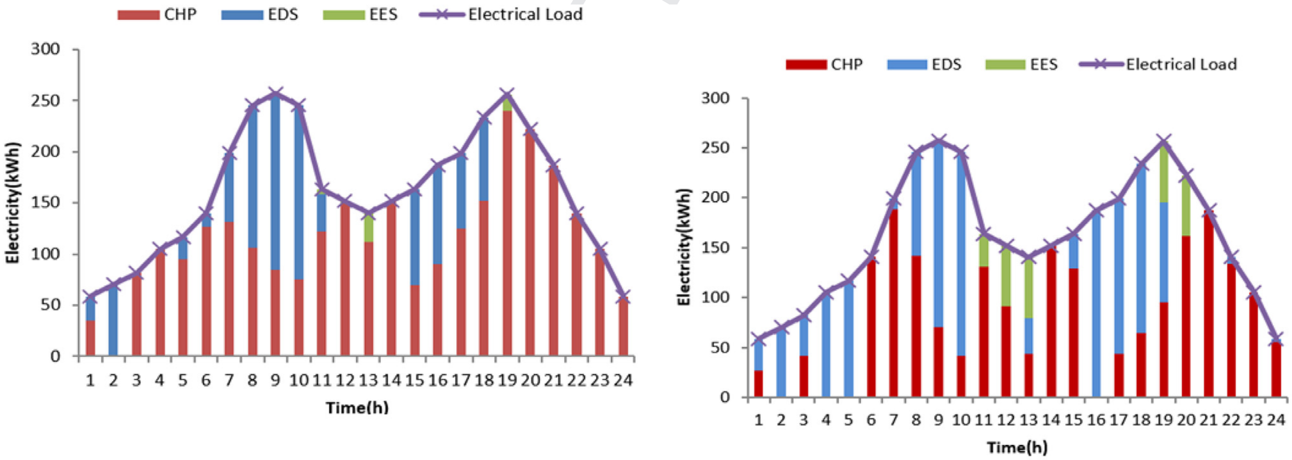
Table 8
Numerical results of optimization model.

	Netcost (Mu)	Cost (Mu)	Income (Mu)	Exported electricity (kWh)	Imported electricity (kWh)	Natural gas consumption (kWh)
Case1	208,928.1	234,807.7	25,879.5	517.180	1785.7	10,670.4
Case2	269,079.9	271,969.8	2890.4	68.82	2393.0	10,854.9



(a) (b)

Fig. 8. Operation of the main equipment. a) Case 1 b) Case 2.



(a) (b)

Fig. 9. Optimal hourly electrical demand balance a) case1, b) case2.

Table 9
Share of units in demand balance. a) electrical, b) thermal balance. Q3

(a)

	CHP	EDS	EES
Case1	71.3%	27.4%	1.3%
Case2	52.6%	40.3%	7.1%

(b)

	CHP	A.B	TES	EHP
Case1	7.7%	12.5%	7.1%	72.7%
Case2	35.9%	59.5%	4.6%	0%

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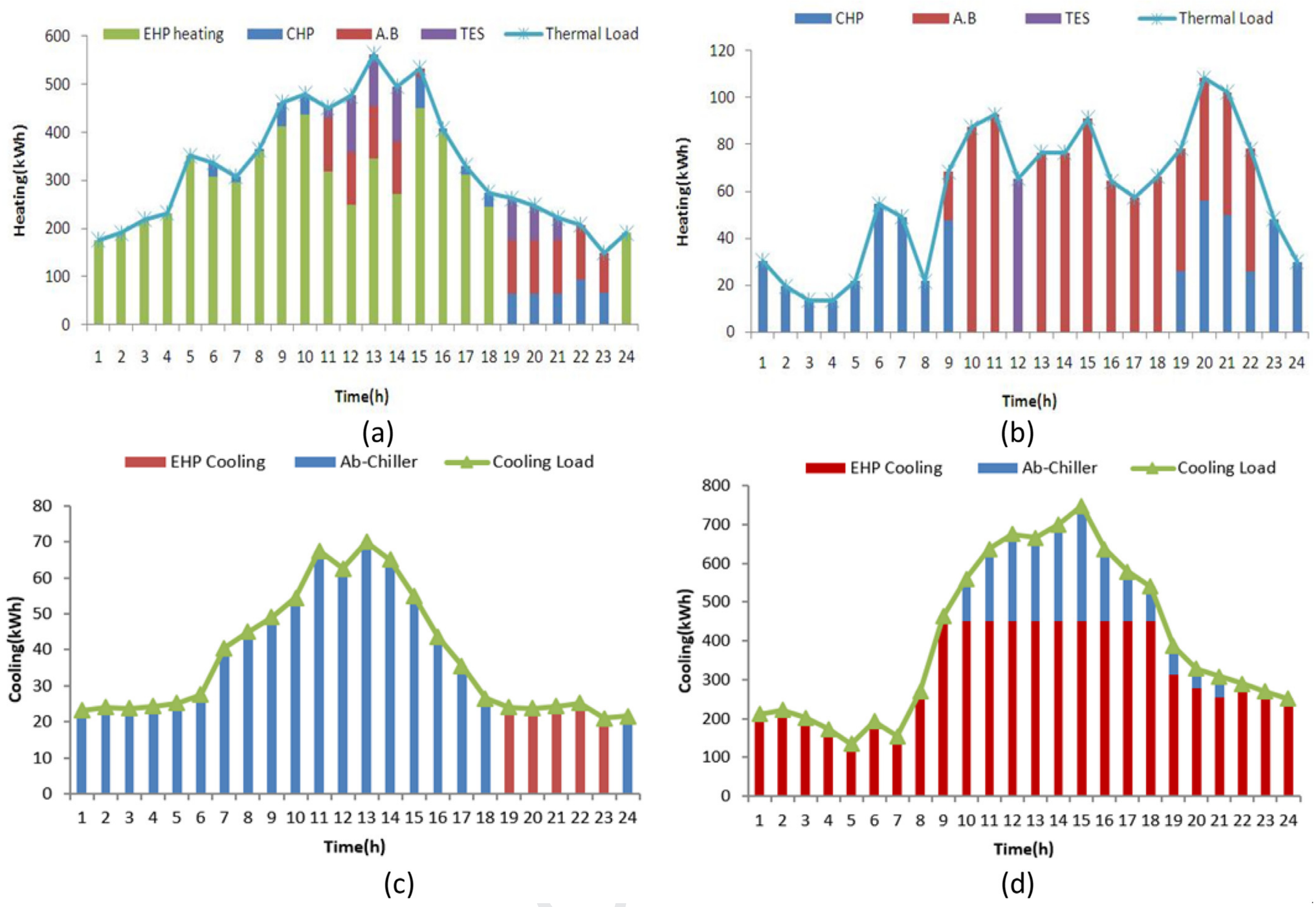

(a) (b)

(c) (d)

Fig. 10. Optimal 24 h thermal and cooling demand balance a) thermal-case1, b) thermal-case2, c) cooling-case1, d) cooling-case2.

lower thermal values in comparison with case 2. In case 1, since, EHP is the main supplier of heat generation and as it appears in Fig. 10a, CHP meets a small part of thermal load at the hours from 18 to 23. So, electricity generation in comparison with heat generation in this case, is of higher priority.

In case 2, thermal load at the hours between 1 and 8 is completely met by CHP and at the hours between 19 and 24 and part of the thermal load of the building is met by CHP. On the other hand, at the hours of peak cooling demand, supplying of input thermal energy required for Ab.chiller is CHP responsibility. Hence, in this case, heat generation by CHP is prioritized in comparison with case 1. Generally, in case 1, the CHP system is mainly concentrated on generating power while in case 2, heat production is of more importance. As it appears in Fig. 11, concentration of operation points in case 1 is in low heat generation area, but, in case 2, these points have more heat in comparison with case 1. In this regard, a remarkable issue to be considered is the difference between thermal to electrical transformation coefficients in two cases. Considering the difference between indicated operation points in two studied cases, using the co-generation system with the same transformation coefficient, results in energy dissipation. In Table 10, average efficiencies of the CHP system and the average transformation coefficient in 24 h are shown.

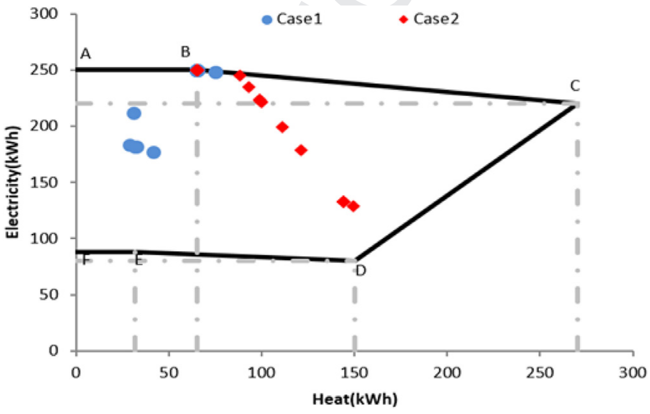

Fig. 11. Operation points of CHP.

4.4.1. Electrical generation of CHP

Fig. 12a and Fig. 12b, show the distribution of producing electric energy via CHP in the both cases, respectively. In case 1, as it appears in Fig. 12a, most of produced electric energy by CHP is sent to EHP in order to meet thermal loads. The rest of producing energy is mostly dedicated to electric loads of the building. In this case, at the hours between 1 and 5 and the hour 24 in which, electricity price is low; electrical energy is supplied via EDS and generated electricity by CHP is lower in comparison with other hours. Any increase in electricity price and demands, especially heating demands, results in an increase in generating electricity by CHP in order to reduce the need for energy imports

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Table 10
Average efficiencies of CHP system.

	Ave. electrical efficiency (%)	Ave. thermal efficiency (%)	Ave. overall efficiency (%)	Ave. power to heat conversion factor
Case1	59.3	15.4	74.7	4.1
Case2	47.1	28.9	76.0	2.1

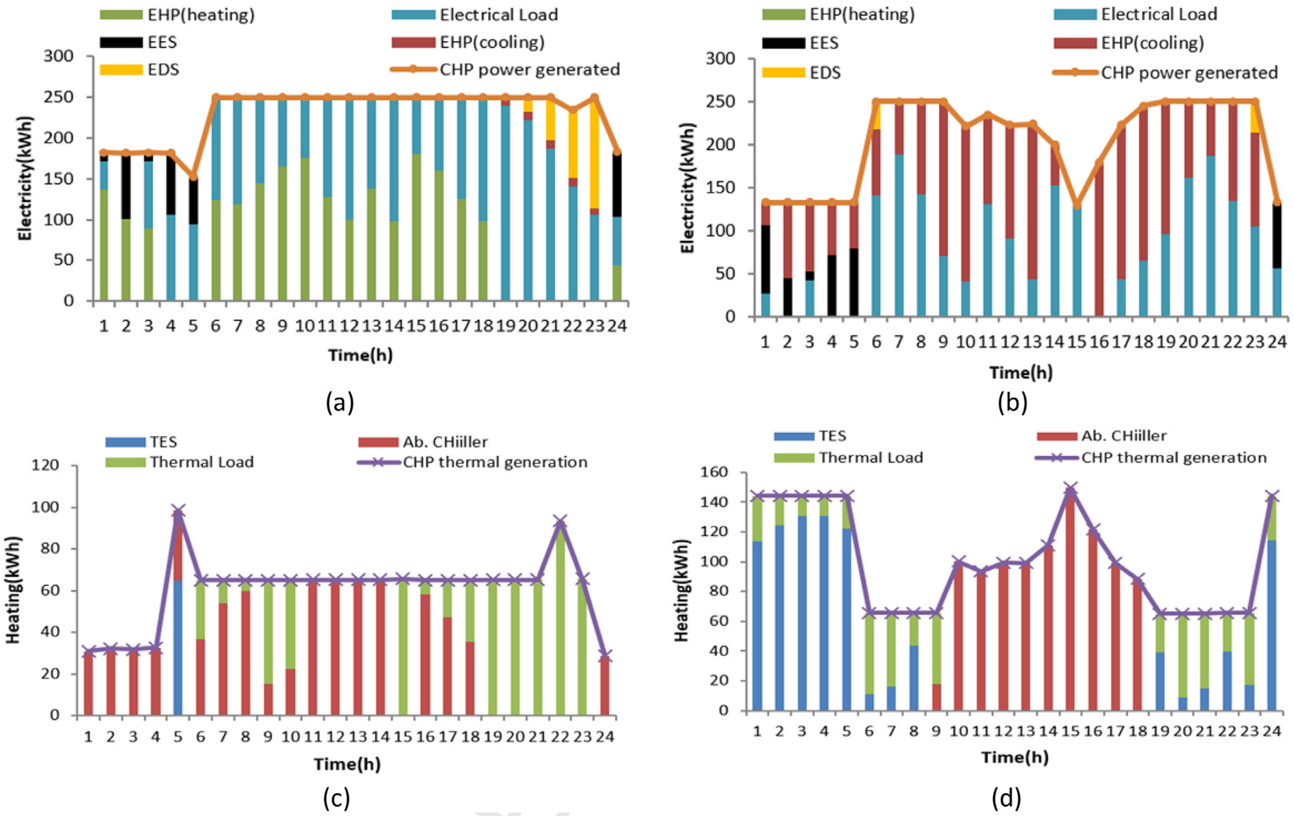

Fig. 12. Optimal CHP electrical and thermal output power and dispatching a) electrical-Case1, b) electrical-Case2, c) thermal-case1, d) thermal-case2.

from EDS and supplying required electricity for EHP. In case 2, most of electric energy produced by CHP is used for electric loads and supply of electric energy for the EHP system in cooling mode is of second priority. In this case, as in case 1, at the hours of low electricity price, electricity generation by CHP is minimized. Increase in demand, especially in the hours of peak cooling demands (11–19), the need for electrical energy for EHP and the need for thermal energy for Ab.chiller, not only result in an increase in electrical energy generated by CHP, but also, causes an increase in thermal energy generated by CHP. Therefore, as it can be implied comparing Fig. 12a and b, electrical energy generation in case 2 is lower than the case 1. Also, in both cases, battery is charged by CHP at the early hours in the morning and late hours at night in which electricity price is low. On the other hand, electricity is transmitted to distribution network in the hours between 20 and 23 in case 1 and in the hours 6 and 23 in case 2. In Table 11a, values of dedicated electric energy produced by CHP to each consumer are shown in percent.

4.4.2. Thermal generation of CHP

In Fig. 12c and d, the amount of thermal energy produced by CHP and its distribution to each consumer is shown. The amount of producing thermal energy in total is lower in case 1 than in case 2. The reason is that in case 1, most of heating loads of the building (nearly 73%) are met by EHP in heating mode; so, electric energy of the co-generation system is more needed than its thermal energy. However, regarding the high amount of cooling load in case 2, requirement of Ab.chiller is inevitable. Hence, the CHP system generates more thermal energy during the peak hours of cooling load (10–18) in order to supply the Ab.chiller. On the other hand, in the case 2, at the early hours in the morning, in which, electricity price and thermal load are low, EHP produces a high amount of heating energy to charge TES and uses this heat in order to supply cooling energy via Ab.chiller in the middle hours of the day.

In Table 11b values of dedicated thermal energy produced by CHP to each consumer are shown in percent.

Table 11
Dedicated energy produced by CHP a) electrical, b) thermal.

(a)

	EDS	EES	EHP cooling	EHP heating	Electrical load
Case1	5.3%	5.7%	0.9%	38.3%	49.9%
Case2	1.4%	7.4%	49.7%	0%	41.5%

(b)

	CHP	TES	A.B	EHP heating
Case1	7.7%	7.1%	12.5%	72.7%
Case2	35.9%	4.6%	59.5%	0%

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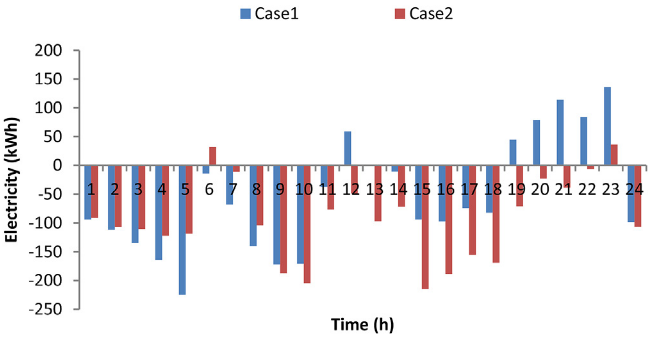

Fig. 13. Optima exchange power with EDS, negative (purchasing) and positive (selling) with EES.

4.5. Exchange with EDS

In Fig. 13 interaction of electric energy with power distribution system in both cases is shown. As it is evident in Fig. 12b and d, in case 2, the co-generation system uses most of its input fossil energy for heat generation and generates lower electric energy in comparison with case 1. Therefore, in this case, the energy hub needs to receive more electrical energy from EDS in order to meet electrical loads. Most of electrical energy sales in case 1 are in the high tariff hours between 19 and 23. At these hours, fulfilling of thermal loads is switched from EHP to other heat generating equipment and energy hub gains the capability of transmission of electricity to the distribution network.

4.6. Evaluation of energy hub flexibility

Fig. 14, shows the response of the proposed model for meeting loads in situation of minimum natural gas consumption and consuming of input electrical energy from the EDS.

As it can be seen in Table 12, in a wide range of input energy changes, proposed energy hub is capable of meeting its electrical, thermal and cooling loads.

As it implies with comparison of Table 13 with Table 8, minimization of consumption input energy to the hub, regarding the variation of electricity price at different hours of the day and diversity of the ways of meeting loads of the building, does not necessarily result to reduction of its operating costs. In this regard, management of energy flow inside the hub and determining the consumption of each energy form and optimized energy dispatching between units inside the hub in each time step is of unique significance.

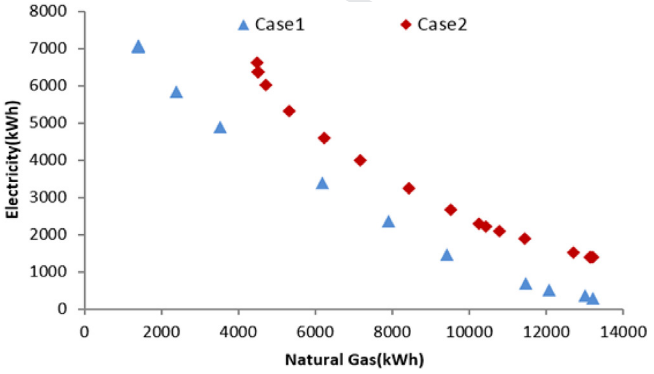

Fig. 14. Pareto optimal front of electricity and natural gas consumption minimization.

Table 12
Flexibility of natural gas and electricity consumption.

	Case 1		Case 2	
	W = 1	W = 0	W = 1	W = 0
From GDS (kWh)	1389	13,200	4493	13,200
From EDS (kWh)	7082	305	6612	1398
Total Cost (Mu)	325,476	225,050	360,586	278,227

Table 13
Results of minimization of consumption input energy.

Parameter	Case1	Case2
From GDS (kWh)	2350.8	5329.6
From EDS (kWh)	5872.9	5327.9
Total Cost (Mu)	295,722.5	321,973.9

5. Conclusions

The high number of constituent equipment of energy hub and the connections between them result in the increase in efficiency of energy hub and in return, the increase in complexity of its control and optimization. Using the presented method in this paper, modeling of complex energy hubs is easily accomplished. In this paper, a generic energy hub with electrical energy and natural gas inputs was introduced in order to meet electrical, heating and cooling demands. A profit based MINLP model was developed to schedule the proposed energy hub generation. Considering electrical energy and natural gas price, the model can adopt complicated strategies to maximize the profit of the energy hub with high accuracy. While meeting the hypothetical building demands, the proposed hub can exchange electrical energy with distribution grid. This model considers also a wide range of economic and technical constraints related to the constituting parts of energy hub.

The performance of presented model is confirmed analyzing cold and hot day cases. Investigating the operating points of co-generation system inside FOR region, it can be seen that CHP behavior in these two sample days is completely different. Average electrical and thermal efficiencies for cold day are 59.3% and 15.4% respectively. These values for hot day are 47.1% and 28.9% respectively. Moreover, analysis of the results shows that EHP, due to its efficiency of more than 100%, has been used as the main generation source of heating and cooling in cold and hot days respectively. EHP has fulfilled 72.7% of the heating loads of the building in cold day and 80% of cooling loads in hot day as per calculations.

While complicating the modeling and controlling mechanism of the energy hub, the existence of interconnections between constituents of the hub enhances model flexibility in different conditions. Numerical results show that in cold day and hot day, the ratio of maximum of required electric energy for meeting loads of the building throughout a day to the minimum of value is 23.2 and 4.73 respectively. Furthermore, in cold day, the ratio of maximum of required natural gas for meeting loads of the building throughout a day to the minimum of value is 9.5. Also, this ratio is 2.93 in hot day. These ratios indicate that in case of shortage of gas or electricity, the energy hub, due to the its flexibility, is capable of meeting its demands via electric energy or natural gas respectively. The flexibility of energy hub enables the hub to participate in demand response programs which will be put in focus by authors later.

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Please cite this article in press as: Moghaddam IG, et al., A comprehensive model for self-scheduling an energy hub to supply cooling, heating and electrical demands of a building, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.10.137

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