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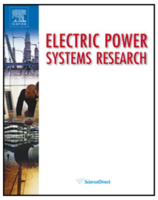

Home load management in a residential energy hub

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ABSTRACT

One way of more efficiently utilizing the existing gas and electrical infrastructures is to consider them as one integrated system in planning and operation of energy systems. The energy hub framework is adopted to determine a modeling procedure for such multi carrier energy systems. This paper presents a residential energy hub model for a smart home. A residential combined heat and power (CHP) as a cogeneration technology, and a plug-in hybrid electric vehicle are employed in the model. Operation of the hub is optimized through a proposed optimization-based formulation. The objective is to minimize customer payment cost. Solving the problem determines how much of each energy carrier the hubs should consume and how they should be converted in order to meet the load at hub's outputs. Since home load management (HLM) plays a key role in realizing household demand response programs, performing HLM in the proposed residential energy hub model is also studied in this paper. To do this, the optimization problem is extended by considering different operational constraints of the responsive appliances determined by the customer. The proposed optimization-based formulation is applied to a home to deeply study the different aspects of the propounded method.

1. Introduction

Following the expansion of natural gas networks and also benefits of this energy carrier, combined heat and power (CHP) technologies have attained unexpected level of popularity [1,2]. CHP as a cogeneration technology is a well-known distributed energy resource for producing heat and power simultaneously onsite. The conversion of energy between different carriers ascertains a link between the corresponding power flows resulting in system interactions. Recent publications suggest an integrated frame of energy systems including multiple energy carriers [3–5], instead of focusing on a single energy carrier [6,7]. Since the design and operation of such systems are complicated due to the interlinked system layouts, it is important to provide tools to help select the best system configuration and mix of energy sources.

The energy hub framework is adopted to determine a modeling procedure for such multi carrier energy systems [5,8]. Energy hubs can be recognized as interfaces between energy infrastructures and network participants, or between different energy infrastructures, for example electricity and natural gas systems. Energy hub's tasks consist of converting, storing, conditioning, and possibly managing energy. Various operational problems can be identified when considering integrated multi carrier energy systems. Recently, the combined modeling and analysis of energy systems including multiple energy carriers have been addressed in a number of publications [9–14]. The basic operational question in these references is how much of each energy carriers the hubs should consume and how they should be converted in order to meet the loads at their outputs.

Increasing interest is currently being addressed to household multi carrier energy systems [15]. These systems integrate different energy sources in order to provide the household load. At homes, all demands, i.e. electrical and heating, are supplied from the electricity or natural gas systems. A residential energy hub can model a multi carrier energy home, where the input energy sources are electricity and natural gas, and the outputs are electrical and heating demands [16]. In addition, plug in hybrid electric vehicle (PHEV) is one of the new grown technologies that can act as a storage system as well as a supplier of electrical demand at home. PHEV characteristics, depended on either the PHEV owner's behavior or its manufacturer standards, should be incorporated in the modeling [17]. Different energy sources and novel technologies such as PHEV and CHP in the residential energy hub model draw attention to the optimum selecting of energy sources and the manner of energy flowing. Despite the extensive researches in the field of multi

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Nomenclature

Sets and indices

i	index of on/off controlled appliance
j	index of responsive appliances whose consumption level can be controlled
t	hour index

Variables and functions

$D_e(t)$	household electrical demand at hub output at hour t
$D_h(t)$	household heat demand at hub output at hour t
$D_e^{\text{res}}(t)$	responsive electrical demand at hub output at hour t
$D_h^{\text{res}}(t)$	responsive heat demand at hub output at hour t
EPC	energy payment cost function
$E^{\text{PHEV}}(t)$	charge state of the PHEV battery at hour t [kWh]
$E_{(.)}(t)$	electrical energy consumption of appliance (.) at hour t
$E_{\text{ch}}^{\text{PHEV}}(t)$	PHEV charging energy at hour t [kWh]
$E_{\text{dch}}^{\text{PHEV}}(t)$	PHEV discharging energy at hour t [kWh]
$E_e(t)$	received electrical energy at hub input at hour t [kWh]
$E_e^{\text{CHP}}(t)$	power output of CHP at hour t [kWh]
$E_g(t)$	received natural gas at hub input at hour t [kWh]
$E_h^{\text{CHP}}(t)$	heat output of CHP at hour t [kWh]
$I_i^e(t)$	binary indicator of ith electrical appliance status, which 1 means the ith electrical appliance is on at hour t
$\nu(t)$	dispatch factor of natural gas at hour t

Constants

b_i^e	beginning hour of allowable operation time interval for appliance i
c	arrival time of PHEV
Cap^{PHEV}	PHEV battery capacity [kWh]
$D_e^{\text{fix}}(t)$	nonresponsive electrical demand at hour t
$D_h^{\text{fix}}(t)$	nonresponsive heat demand at hour t
$E_{\text{ch}}^{\max}$	maximum charging rate of PHEV at each hour [kW]
$E_{\text{dch}}^{\max}$	maximum discharging rate of PHEV at each hour [kW]
$E_e^{\max}$	maximum allowable amount of electrical energy received from the grid at each hour
$E_g^{\max}$	maximum allowable amount of natural gas received from the grid at each hour
E_i	energy consumption of appliance i at each operating hour [kWh]
E_j	total energy consumption of appliance j in a day [kWh/day]
$E_j^{\min}(t)$	minimum allowable energy consumption level of appliance j at hour t
$E_j^{\max}(t)$	maximum allowable energy consumption level of appliance j at hour t
$E_{\max}^{\text{CHP}}$	maximum allowable natural gas input of the CHP
$E_{\text{out}}^{\text{PHEV}}$	electrical energy consumption of PHEV in the out-of-home interval [kWh]
E_0^{PHEV}	charge level of the PHEV battery at initial time of the day [kWh]
e_i^e	last hour of allowable operation time interval for appliance i
g	departure time of PHEV
U_i^e	required uptime of electrical appliance i to properly do its task
η_{ch}	AC to DC energy conversion efficiency of PHEV battery
η_{dch}	DC to AC energy conversion efficiency of PHEV battery
η_e	overall efficiency of electrical appliances
η_e^{CHP}	gas to power conversion efficiency of CHP
η_h	overall efficiency of gas-consumed appliances
η_h^{CHP}	gas to heat conversion efficiency of CHP
$\lambda_e(t)$	electricity tariff at hour t [¢/kWh]
$\lambda_g(t)$	natural gas tariff at hour t [¢/kWh]

carrier energy system and energy hub, few works such as [6,18] have addressed the modeling and operation of a residential energy hub. Ref. [6] concentrates on the elaboration of a methodology that is able to model and optimize the coupling between energy demand and energy supplies in a building at the design concept stage, taking into account all the constraints that arise in real building design. Some of the operational issues of residential hubs are addressed in [18], where an optimal dispatch of the residential hub is proposed.

Along with the development of multi carrier energy systems, smart grid concepts have been also grown in recent years. In the customer level, demand response (DR) programs play a prominent role in realizing the smart grid. The automatic control of household demand from the customer viewpoint referred to as *home load management* (HLM) persuades the customers to participate in DR programs actively. In the HLM procedure, demands may shift to the low load hours in response to time varying tariffs of energy [19,20]. HLM program can be employed in the optimization process of residential energy hub operation. To do this, household electrical and heating appliances are divided into responsive and nonresponsive groups. Operation times and energy consumption of responsive appliances can be controlled in HLM procedure, considering the operational constraints determined by the customer. To the best of authors' knowledge, the previous works have not properly focused on employing the HLM program in the residential energy hub model. Even though the authors of [16] explain the residential energy hub concept to control all major residential loads, the energy hub model is not incorporated in mathematical approaches of HLM. In addition, although [21] controls the electrical and thermal demands of a residential microgrid, the energy hub concept is not employed in the modeling procedure.

This paper firstly focuses on the modeling of a home as an energy hub, considering different electrical and heating appliances, residential CHP, and a PHEV. Then, operation of the energy hub is optimized and the household load is optimally managed in the proposed framework. The objective function is to minimize the customer payment cost in response to time varying prices of the electricity and fixed prices of natural gas during a day. Solving the propounded problem determines the amount of inputted energies, the manner of energy flowing in the hub, the charge/discharge scheduling of PHEV, and the energy consumption scheduling of responsive appliances at each hour. All the technical and operational constrains related to CHP and PHEV are taken into account in the problem formulation. Due to technological constraints in solving the optimization problem at homes, the formulation is proposed as simple as possible to make the method applicable. The approached model is applied to a home to outline the positive impacts of the proposed optimization problem.

2. Residential energy hub model

An energy hub represents an interface between different energy infrastructures and/or loads. An overarching view of the energy

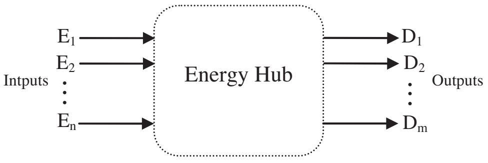

Fig. 1. An overarching view of energy hub model.

hub is presented in Fig. 1. Generally speaking, if E is vector of the hub inputs and D is vector of the hub outputs, the mathematical relation between the input and output vectors of an energy hub [13] is presented by:

$$D = C \times E, \tag{1}$$

where C is the coupling matrix of the inputs and the outputs. Values of coupling factors depend on the hub configuration, converter structure, and efficiency of the converters. As mentioned in [13], the coupling matrix can be expressed as the product of two matrices, efficiency and dispatch factor matrices. This is shown in Eq. (2) as:

$$C = \eta \times V, \tag{2}$$

where η and V are, respectively, efficiency and dispatch factor matrices. Elements of the efficiency matrix show the converters' efficiencies. When an input carrier splits to more than one converter, the dispatch factor determines how power from an input carrier is distributed between the hub's convertors. Dispatch factors are determined through solving an optimization problem. However, the efficiency matrix is usually known in the operation problems [13].

Fig. 2 shows an overview of the residential energy hub. At a smart home, responsive and nonresponsive appliances consume electricity or natural gas to provide electrical and heat demands. Therefore, appliances play the role of converters or conditioners in the residential energy hub. A controller at home, i.e. an energy hub controller, can determine on/off statuses of some of responsive appliances such as washing machine, dishwasher, and vacuum cleaner at each time. Also, the energy consumption level of other responsive appliances such as cooler, gas stove, and water heater at each time period can be set by the controller. The customer can set the operational constraints such as allowable operation time interval for each of these appliances. A micro CHP as a residential distributed generation consumes natural gas to provide heat and power. The gas to power and gas to heat conversion efficiencies of CHP are respectively presented in Fig. 2 by η_e^{CHP} and η_h^{CHP}. In addition, PHEV acts as an electrical storage system in the energy hub, considering that it can provide household electrical demand if it is possible and profitable. In the presented residential energy hub model, the electrical demand can be provided by the electrical grid, by discharging the PHEV battery, and by the electrical energy extracted from CHP. According to Fig. 2, the inputted natural gas can be flown to the gas-consumed appliances or CHP. As mentioned before, the distribution of natural gas between the two options is determined based on the dispatch factor ν.

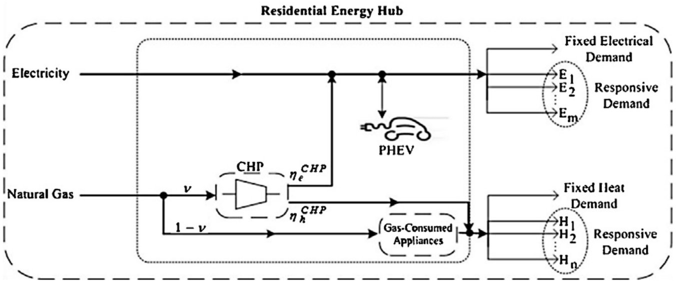

Fig. 2. Residential energy hub model.

3. Problem formulation

In this section, an optimization problem is formulated leading to optimal operation of the energy hub as well as optimal management of the household demands for the next day. The objective is to minimize the customer payment cost in response to energy tariffs. The outputs of the problem would be the dispatch factors of the energy hub, the amount of received energy carriers at hub inputs at each time, the operation scheduling of responsive appliances, and charge/discharge scheduling of PHEV. The objective function is presented in Eq. (3) as:

$$\min \text{EPC} = \sum_t [\lambda_g(t)E_g(t) + \lambda_e(t)E_e(t)] \tag{3}$$

Based on the residential hub shown in Fig. 2, the following power flow equations are derived:

$$E_e(t) + E_e^{\text{CHP}}(t) + \eta_{\text{dch}}E_{\text{dch}}^{\text{PHEV}}(t) = \frac{1}{\eta_e} \times D_e(t) + \frac{1}{\eta_{\text{ch}}} \times E_{\text{ch}}^{\text{PHEV}} \tag{4}$$

$$(1-\nu(t))E_g(t)\eta_h + E_h^{\text{CHP}}(t) = D_h(t) \tag{5}$$

Note that $E_{\text{ch}}^{\text{PHEV}}(t)$ and $E_{\text{dch}}^{\text{PHEV}}(t)$ respectively present the *chemical* energy consumed or produced in the battery. The actual *electrical* charged/discharged energy is calculated by multiplying or dividing the chemical energy by the conversion efficiencies. If HLM application is not possible, the electrical and heat demands will be estimated for the next day. If HLM is possible, a part of demand, which is flexible to the energy price, will be controlled. HLM application is formulated later in this section. Also, in Eq. (5), $(1-\nu(t))$ determines proportion of the inputted natural gas which directly flows to the gas-consumed appliances at hour t. It should be noted that $\nu(t)$ varies between 0 and 1.

The output energy of CHP at hour t depends on the dispatch factor $\nu(t)$, and the efficiencies of gas to power (η_e^{CHP}) and gas to heat conversions (η_h^{CHP}). So:

$$E_e^{\text{CHP}}(t) = \nu(t) \times E_g(t) \times \eta_e^{\text{CHP}} \tag{6}$$

$$E_h^{\text{CHP}}(t) = \nu(t) \times E_g(t) \times \eta_h^{\text{CHP}} \tag{7}$$

In the mentioned equations, all the efficiencies, i.e. η_{dch}, η_{ch}, η_e^{CHP}, η_h^{CHP}, η_e, and η_h, are definite and other parameters are unknown variables.

So far, the objective function and power flow equations of energy hub were completely presented. Now, related constraints to PHEV and CHP are introduced.

The charging and discharging rates of PHEV battery are capped to definite values in Eqs. (8) and (9), known as charge/discharge limits in the literature.

$$E_{\text{ch}}^{\text{PHEV}}(t) \le E_{\text{ch}}^{\max} \tag{8}$$

$$E_{\text{dch}}^{\text{PHEV}}(t) \le E_{\text{dch}}^{\max} \tag{9}$$

It is assumed that, PHEV is going out from and coming back to home in definite hours of a day, respectively named g and c. Obviously, in the interval [g, c], the in-home charging and discharging is not possible. In addition, the electrical energy consumption of PHEV in the out-of-home interval, referred to as $E_{\text{out}}^{\text{PHEV}}$ is estimated by the PHEV owner. So, the charge level of the PHEV battery at hour t, $E^{\mathrm{PHEV}}(t)$, can be calculated before and after the out-of-home interval based on Eq. (10).

$$E^{\mathrm{PHEV}}(t)=\begin{cases} E_0^{\mathrm{PHEV}}+\sum\limits_{h=1}^{t-1}[E_{\mathrm{ch}}^{\mathrm{PHEV}}(h)-E_{\mathrm{dch}}^{\mathrm{PHEV}}(h)], & \forall t\le g \\ E_0^{\mathrm{PHEV}}+\sum\limits_{h=1}^{t-1}[E_{\mathrm{ch}}^{\mathrm{PHEV}}(h)-E_{\mathrm{dch}}^{\mathrm{PHEV}}(h)]-E_{\mathrm{out}}^{\mathrm{PHEV}}, & \forall t\ge c \end{cases} \quad (10)$$

In other words, Eq. (10) is the state of the charge balance equation. Clearly, $E^{\mathrm{PHEV}}(t)$ has a positive value. The discharged energy at each hour should be less than the charge level of the PHEV battery as expressed in Eq. (11).

$$E_{\mathrm{dch}}^{\mathrm{PHEV}}(t)\le E^{\mathrm{PHEV}}(t) \quad (11)$$

In addition, the charge level should be limited to the battery capacity. This state of charge limit is mathematically expressed in Eq. (12).

$$E^{\mathrm{PHEV}}(t)\le \mathrm{Cap}^{\mathrm{PHEV}} \quad (12)$$

A customer usually expects to have a fully charged PHEV at the departure time (hour g). This is verified by:

$$E^{\mathrm{PHEV}}(g)=\mathrm{Cap}^{\mathrm{PHEV}} \quad (13)$$

The charge level of PHEV battery at the end of the day (hour 24) is rationally assumed to be more than or equal to the initial charge level of PHEV battery. This is shown by:

$$E^{\mathrm{PHEV}}(24)\ge E_0^{\mathrm{PHEV}} \quad (14)$$

In addition to the mentioned PHEV constraints, CHP operational restriction is presented in (15) as another problem constraint.

$$\nu(t)E_g(t)\le E_{\max}^{\mathrm{CHP}} \quad (15)$$

The received electrical and natural gas at hub inputs can be limited due to the following constraints.

$$E_e(t)\le E_e^{\max} \quad (16)$$

$$E_g(t)\le E_g^{\max} \quad (17)$$

As stated before, for HLM implementation, heat and electrical demands are divided into responsive and nonresponsive (fixed) demands. So,

$$D_e(t)=D_e^{\mathrm{fix}}(t)+D_e^{\mathrm{res}}(t) \quad (18)$$

$$D_h(t)=D_h^{\mathrm{fix}}(t)+D_h^{\mathrm{res}}(t) \quad (19)$$

It is assumed that nonresponsive appliances, such as television and personal computer, have estimated fixed demand in different hours. Some responsive appliances such as washing machine operate in on/off manner. Such an appliance needs a definite operation time to complete its task. This operation time should lie in an allowable time interval determined by the customer. This constraint is verified in Eq. (20) for electrical appliances.

$$\sum_{t=b_i^e}^{e_i^e} I_i^e(t)=U_i^e \quad (20)$$

The energy consumption of this type of responsive appliances is as Eq. (21).

$$E_i(t)=E_i I_i^e(t) \quad (21)$$

In addition to the on/off controlled electrical appliances, the energy consumption level of some other responsive appliances such as water heater can be controlled. However, the energy consumption of this type of responsive appliances at each hour can be bounded to definite values. This range is determined according to technical settings of the appliances and customer habits [22,23]. This is mathematically presented in Eq. (22) for electrical appliances.

$$E_j^{\min}(t)\le E_j(t)\le E_j^{\max}(t) \quad (22)$$

Total energy consumption of appliance j in a day is mathematically calculated in Eq. (23).

$$\sum_t E_j(t)=E_j \quad (23)$$

Based on the provided explanations, the following expression is concluded.

$$\sum_i E_i(t)+\sum_j E_j(t)=D_e^{\mathrm{res}}(t) \quad (24)$$

This equation shows that the summation of energy consumption of each kind of electrical responsive appliances at each hour is the responsive electrical demand at that hour. Substituting $E_i(t)$, $E_j(t)$, $I_i^e(t)$, U_i^e, E_i, $E_j^{\min}(t)$, $E_j^{\max}(t)$, E_j, and $D_e^{\mathrm{res}}(t)$ by $H_i(t)$, $H_j(t)$, $I_i^h(t)$, U_i^h, H_i, $H_j^{\min}(t)$, $H_j^{\max}(t)$, H_j, and $D_h^{\mathrm{res}}(t)$, respectively, Eqs. (20)–(24) are applicable to responsive gas-consumed appliances and heating demands.

The declared formulations finally result in the optimal operation of the residential energy hubs and optimal management of the household electrical and heat demands to minimize the customer payment cost.

4. Numerical studies

In this section, the proposed method and formulations are applied to a sample home. The study is simple enough to deeply analyze the impacts of the proposed residential energy hub model and HLM implementation on the household load curve and the customer payment cost. Two cases are designed here. In the first case, the heat and electrical demands are assumed to be nonresponsive to price. In this case, only the operation of the energy hub is optimized. During this optimization process, the amount of each input energy carrier, the dispatch factor, and the charge scheduling of PHEV are determined for each hour. In another case, a part of demand is considered responsive to energy prices, and HLM is applied to the residential energy hub. In this case, the optimization procedure results in the optimal operation of the responsive appliances in addition to the mentioned outcomes for the former case. The required assumptions are summarized in the following subsection. The introduced cases are investigated in later subsections. The proposed optimization problems are solved using a Mixed integer programming (MIP) solver under GAMS environment [24]. Computation times are not reported in detail as they all were less than 10 s on a PC equipped with a 3.2 GHz Pentium 4 processor and 4 GB of RAM.

4.1. Assumptions

Since the objective function is to minimize the payment cost, the energy tariff has an important role in the presented optimization problem. The gas tariff is usually assumed to be a fixed rate in a day. Here, it is taken from [25] and is assumed to be 5.5 ¢/kWh. On the other hand, different time varying pricings have been designed for electricity. Price based DR programs focuses on the pricing methods. The most common time differentiated electrical tariff for residential customer is time of use (TOU) pricing [26]. Different price levels, usually two or three levels, are introduced in TOU tariff for a day. Here, a three-level TOU is assumed as the electricity price as shown in Fig. 3 [27]. Note as well that such a tariff is

Table 1
PHEV data.

$\mathrm{Cap}^{\mathrm{PHEV}}$	$E_{\mathrm{ch}}^{\max}$ [kWh/h]	$E_{\mathrm{dch}}^{\max}$ [kWh/h]	E_0^{PHEV}	g	c	$E_{\mathrm{out}}^{\mathrm{PHEV}}$	η_{ch}	η_{dch}
7.8	1.4	1.4	3.9	8 a.m.	5 p.m.	5	0.88	0.88

Table 2
CHP data.

η_e^{CHP}	η_h^{CHP}	$E_{\max}^{\mathrm{CHP}}$ [kW]
0.3	0.4	1

designed based on the load demand behavior in a day. The electrical energy price would be high when the estimated consumption is high. Table 1 summarizes the assumed parameters related to PHEV. The PHEV battery capacity, maximum charging/discharging rates, initial charge level, departure time, arrival time, out-of-home electrical energy consumption, and conversion efficiencies are outlined in this table according to [19,28]. The CHP data, i.e., the gas to power and heat conversion efficiencies, and the maximum amount of inputted natural gas, are declared in Table 2. The overall electrical and gas-consumed appliances efficiencies, η_e and η_h, are respectively assumed to be 0.99 and 0.95. The amount of received energies at hub inputs is not limited in the following cases. The household electrical and heating demands are declared in each case.

4.2. Case 1

In this case, all appliances, but PHEV, are considered nonresponsive to prices. Therefore, HLM is not applicable in this case. The electrical demand contains the consumption of appliances such as washing machine, dishwasher, television, lighting, cooler, fan, etc. The heat demand includes the consumption of water heater, gas oven, gas stove, etc. The electrical and heat demands in a typical day in winter are considered to be the same as the one shown in Fig. 4. Accordingly, the peak of electrical demand is about 2.2 kW at hour 18 and the peak of heat demand is about 0.9 kW at hour 20. It should be noted that, in addition to this demand, the charging demand of PHEV should be provided by the received energy carriers at hub inputs.

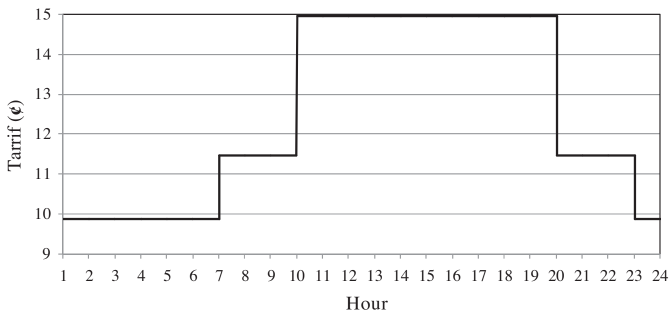

Fig. 3. Three-level TOU tariffs for a day.

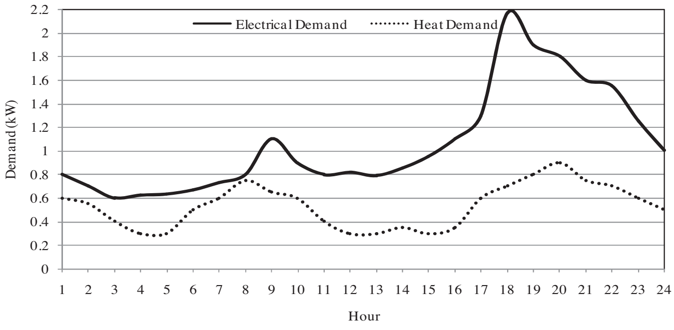

Fig. 4. Electrical and heat demand in a sample day in winter.

The operation of energy hub is optimized by Eq. (3), subjected to (4)–(17). The results show the payment cost of ¢445.504 for energy consumption in the day. The dispatch factor $\nu(t)$ is also determined as the outcome of the problem. $\nu(t)$ is zero at hours 1–7 and 24. The reason for this is that these hours are the low-peak tariff hours of electricity, and all the electrical demand is provided from the input electrical energy. However, in mid-, and on-peak tariff hours for electricity, it would be profitable to provide a part of electrical demand by inputted natural gas through CHP operation. Therefore, the dispatch factors would be nonzero at these hours. The nonzero dispatch factors are concluded in Table 3.

It is worthwhile to note that CHP capacity limit, i.e., 1 kW for inputted natural gas, makes $\nu(t)$ to be lower than one in some of mid- and high-peak tariff hours. The inputted natural gas and electrical power of residential energy hub, i.e., the received power from the grid, resulted from solving the proposed optimization based problem are depicted in Fig. 5.

According to Figs. 4 and 5, when $\nu(t)$ is zero, the pattern of the inputted natural gas and heat consumption are similar. Due to PHEV presence, Fig. 5 shows a higher household peak demand of electricity, i.e. 2.6 kW, than the output electrical consumption, i.e. 2.2 kW. Clearly, this peak value will be higher if CHP does not exist at home. As another output of the optimization problem, charging schedule of PHEV is reported in Fig. 6. Since PHEV should be fully charged at

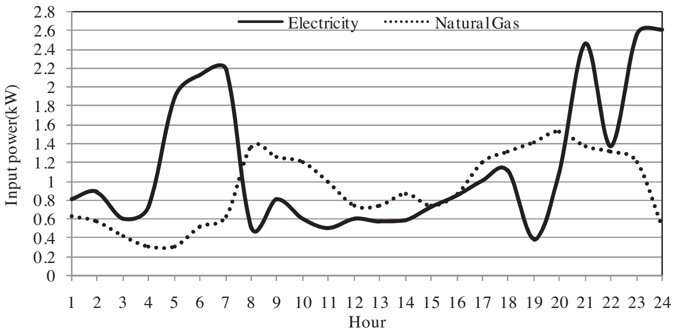

Fig. 5. Input electricity and natural gas of residential energy hub in Case 1.

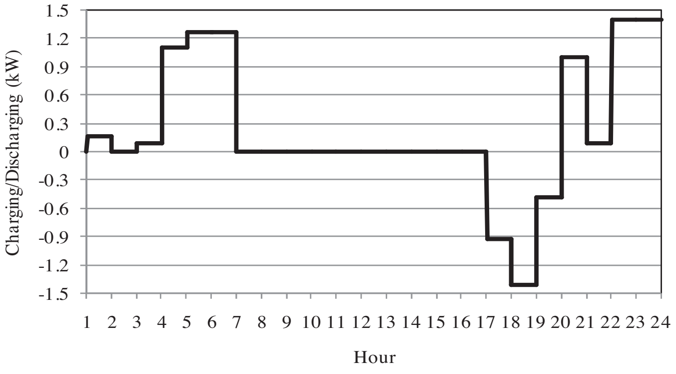

Fig. 6. PHEV charging/discharging pattern in Case 1.

Table 3
Non-zero dispatch factor $\nu(t)$ in Case 1.

Hour	8	9	10	11	12	13	14	15
	0.731	0.792	0.826	1	1	1	1	1
Hour	16	17	18	19	20	21	22	23
	1	0.826	0.760	0.704	0.655	0.731	0.760	0.826

hour 8, it is charged within hours 2, and 4–7. Note that, the received electrical power in Fig. 5 peaks at these hours. After arrival time (hour 18), PHEV is discharged at hours 18–20 to provide a part of electrical consumption in these high-peak tariff hours. This leads to lower payment cost. Again, the PHEV is charged at hours 21–24 to reach the minimum allowable charge level at hour 24, i.e. 3.9 kWh. As expected, all the charging hours lie in the low- and mid-peak tariff periods.

4.3. Case 2

In this case, HLM program is employed in the optimization procedure of residential energy hub. To do this, the operational constraints of responsive appliances should be taken into account. For the sake of simplicity, just one on/off controlled appliance and one appliance whose energy consumption level can be controlled are considered here. Washing machine is the on/off electrical controlled appliance and water heater is a heating appliance whose energy consumption level at each hour can be controlled in the allowable interval. The allowable operation time interval of washing machine (WM) is assumed to be between hours 8 and 24. In addition, the required uptime of WM is 1 h and the energy consumption at the operating hour is 1 kWh. So, $b^{e}_{WM}=8$, $e^{e}_{WM}=24$, $I^{e}_{WM}(t)=0\ \forall t\in[1,7]$, $U^{e}_{WM}=1$ h, and $E_{WM}=1$ kWh. It is also supposed that, the customer determines that the water heater (WH) should consume lower than 0.1 kWh between hours 8 and 17, and should consume between 0.1 kWh and 0.3 kWh at other hours. In addition, total energy consumption of WH in the day should be 3.8 kWh. So, $H^{\min}_{WH}(t)=\begin{cases}0 & 8\le t\le 17\\ 0.1 & t\le 7 \text{ or } t\ge 18\end{cases}$, $H^{\max}_{WH}(t)=\begin{cases}0.1 & 8\le t\le 17\\ 0.3 & t\le 7 \text{ or } t\ge 18\end{cases}$, and $H_{WH}=3.8$ kWh.

The responsive appliances consumption is excluded from Fig. 4. It is considered that WM operates at hour 18, and WH consumes 0.1 kWh between hours 8 and 17, and 0.2 kWh at other hours, based on the demand shown in Fig. 4. So, the nonresponsive appliances demand will be according to Fig. 7. In this figure, the peak demand of nonresponsive electrical appliances is about 1.9 kW, and the peak demand of nonresponsive heating appliances is about 0.65 kW.

The objective function in Eq. (3) is minimized subjected to (4)–(24). The resulted payment cost is ¢430.371 which is 4% lower than the payment in Case 1 due to HLM application. It is worthwhile to note that in the cases with more responsive appliances, the decrement in payment cost can be more than 10% by HLM implementation. The results show that the operation period of WM is shifted from hour 18 which is a high-peak tariff hour to hour 24 which is low-peak tariff one. Also, the energy consumption level of WH at different hours is summarized in Table 4. It can be seen from the results shown in this table that the total energy consumption of WH is expectedly equal to 3.8 kWh and all the hourly energy consumptions are in the predetermined ranges.

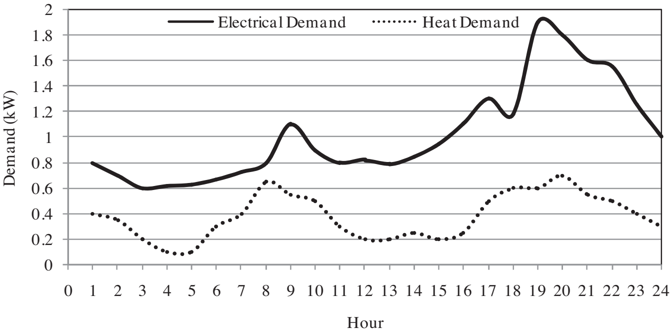

Fig. 7. Nonresponsive electrical and heat demand in a sample day in winter.

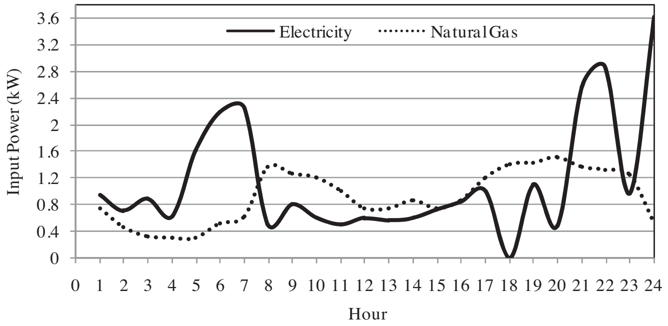

Fig. 8. Input electricity and natural gas of residential energy hub in Case 2.

The hub input electricity and natural gas which are received from the grid is presented in Fig. 8. As can be seen in Fig. 8, the peak of received electrical power is 3.6 kW, which is higher than the previous case. Since the tariff is low at hour 24, WM operates and PHEV is charged with its maximum rate at this hour and, consequently, a high peak occurs at hour 24. As indicated in Fig. 8, the natural gas consumption reaches to a peak value at hour 20. The reason for this is that, according to Fig. 7, the heat demand peaks at hour 20. In addition, $\nu(20)=0.659$ which shows that a part of electrical demand is provided by consuming natural gas in CHP at this hour.

As another outcome of solving the proposed optimization problem in a residential energy hub, the charge/discharge scheduling of

Table 4
WH energy consumption at each hours in Case 2 [kWh].

Hour	1	2	3	4	5	6	7	8
	0.100	0.105	0.220	0.220	0.220	0.300	0.220	0.100
Hour	9	10	11	12	13	14	15	16
	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Hour	17	18	19	20	21	22	23	24
	0.100	0.111	0.105	0.300	0.300	0.278	0.220	0.100

Table 5
Nonzero dispatch factor $\nu(t)$ in Case 2.

Hour	8	9	10	11	12	13	14	15
	0.731	0.792	0.826	1	1	1	1	1
Hour	16	17	18	19	20	21	22	23
	1	0.826	0.710	0.697	0.659	0.735	0.756	0.799

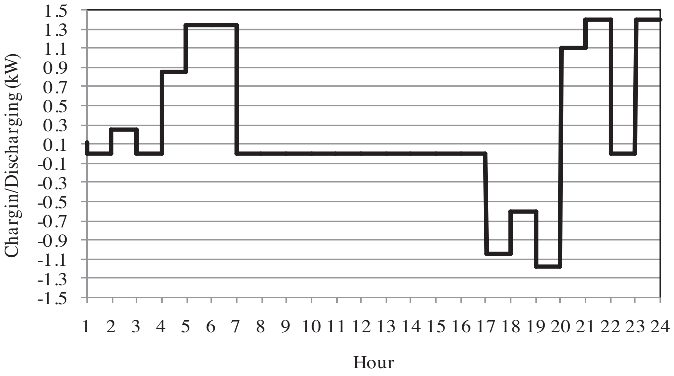

Fig. 9. PHEV charging/discharging pattern in Case 2.

PHEV are declared in Fig. 9. PHEV is charged at low- and mid-tariff hours 1, 3, 5–7, 21–22, and 24 to reach its required charge level at the departure time (hour 8) and at the end of the day. Also, similar to Case 1, PHEV is discharged at high-peak tariff hours, i.e. hours 18–20, to supply the household electrical load.

The dispatch factor $\nu(t)$ will be zero at hours 1–7 and 24, similar to Case 1. The nonzero dispatch factors are reported in Table 5. Since energy consumption scheduling of responsive appliances and charge/discharge scheduling of PHEV in Case 2 are the same as Case 1 between hours 8 and 17, the resulted dispatch factors are similar at these hours according to Table 5.

5. Conclusion

The presence of different energy carriers as well as the advent of new cogeneration technologies such as CHP at homes necessitates designing an integrated model for operation of such multi carrier energy system. A residential energy hub model is developed in this paper to show the multi carrier energy home operation. In the proposed integrated infrastructure for energy carriers, HLM can be performed to perfect the operation of the residential energy hub. An optimization problem is proposed in this paper to optimize the operation of a sample smart home. The hub outputs, i.e. electrical and heating demands, are considered nonresponsive in the first case study. The optimization results show that, at low-tariff hours, the electrical consumption is directly supplied from the electrical grid. However, at mid- and high-tariff hours, a part of electrical consumption is provided by CHP. Consequently, the flow of natural gas to CHP is increased at these hours. As expected, PHEV is charged at low tariff hours and discharged at high tariff ones to decrease the cost of supplying the electrical demand. In the case of applying HLM, the electrical demands shift to low tariff hours. Although the customer payment cost decreases by applying HLM, this leads to a higher peak in received power in comparison with the case without HLM. Tackling the issue of peak increment in the case of applying HLM is currently going on by the authors. In addition, considering uncertainties associated with customer behaviors can affect the HLM results. This topic is proposed as an interesting research area for future works.

References

[1] B. Mohammadi-Ivatloo, M. Moradi-Dalvand, A. Rabiee, Combined heat and power economic dispatch problem solution using particle swarm optimization with time varying acceleration coefficients, Electr. Power Syst. Res. 95 (2013) 9–18.
[2] H. Ren, W. Gao, Y. Ruan, Optimal sizing for residential CHP system, Appl. Therm. Eng. 28 (2008) 514–523.
[3] M. Geidl, Integrated Modelling and Optimization of Multi-carrier Energy Systems (PhD thesis), Swiss Fed. Inst. Technol. (ETH), Zürich, Switzerland, 2007.
[4] P. Favre-Perrod, Hybrid Energy Transmission for Multi-energy Networks (PhD thesis), Swiss Fed. Inst. Technol. (ETH), Zürich, Switzerland, 2008.
[5] B.C. Erdener, K.A. Pambour, R.B. Lavin, B. Dengiz, An integrated simulation model for analysing electricity and gas systems, Electr. Power Energy Syst. 54 (2014) 26–37.
[6] J. Carpentier, A. Merlin, Optimization methods in planning and operation, Int. J. Electr. Power Energy Syst. 4 (1982) 11–18.
[7] K.F. Pratt, J.G. Wilson, Optimization of the operation of gas transmission systems, Trans. Inst. Meas. Control 6 (1984) 261–269.
[8] M. Geidl, et al., Energy hubs for the future, IEEE Power Energy Mag. 5 (2007) 24–30.
[9] O.D. de Mello, T. Ohishi, An integrated dispatch model of gas supply and thermoelectric systems, in: Proceed. 15th Power Syst. Comput. Conf. (PSCC), Liège, Belgium, 2005.
[10] M. Geidl, G. Andersson, Optimal power dispatch and conversion in systems with multiple energy carriers, in: Proceed. 15th Power Systems Computation Conference, Liège, Belgium, 2005.
[11] M. Geidl, G. Andersson, Optimal power flow of multiple energy carriers, IEEE Trans. Power Syst. 22 (2007) 145–155.
[12] C. Unsihuay-Vila, et al., A model to long-term, multiarea, multistage, and integrated expansion planning of electricity and natural gas systems, IEEE Trans. Power Syst. 25 (2010) 1154–1168.
[13] M. Moeini-Aghtaie, P. Dehghanian, M. Fotuhi-Firuzabad, A. Abbaspour, Multiagent genetic algorithm: an online probabilistic view on economic dispatch of energy hubs constrained by wind availability, IEEE Trans. Sustain. Energy 5 (2013) 699–708.
[14] A. Parisio, C.D. Vecchio, A. Vaccaro, A robust optimization approach to energy hub management, Int. J. Electr. Power Energy Syst. 42 (2012) 98–104.
[15] E. Fabrizio, V. Corrado, M. Filippi, A model to design and optimize multi-energy systems in buildings at the design concept stage, Renew. Energy 35 (2010) 644–655.
[16] M.C. Bozchalui, et al., Optimal operation of residential energy hubs in smart grids, IEEE Trans. Smart Grid 3 (2012) 1755–1766.
[17] S. Shafiee, M. Fotuhi-Firuzabad, M. Rastegar, Investigating the impacts of plug-in hybrid electric vehicles on power distribution systems, IEEE Trans. Smart Grid 4 (2013) 1351–1360.
[18] F. Kienzle, P. Ahcin, G. Andersson, Valuing investments in multienergy conversion, storage, and demand-side management systems under uncertainty, IEEE Trans. Sustain. Energy 2 (2011) 194–202.
[19] M. Rastegar, M. Fotuhi-Firuzabad, F. Aminifar, Load commitment in a smart home, Appl. Energy 96 (2012) 45–54.
[20] D. Setlhaolo, X. Xia, J. Zhang, Optimal scheduling of household appliances for demand response, Electr. Power Syst. Res. 116 (2014) 24–28.
[21] P.O. Kriett, M. Salani, Optimal control of a residential microgrid, Energy 42 (2012) 321–330.
[22] P. Du, N. Lu, Appliance commitment for household load scheduling, IEEE Trans. Smart Grid 2 (2011) 411–419.
[23] M. Rastegar, M. Fotuhi-Firuzabad, Outage management in residential demand response programs, IEEE Trans. Smart Grid (2014), http://dx.doi.org/10.1109/TSG.2014.2338794 (in press).
[24] A. Brooke, D. Kendrick, A. Meeraus, R. Raman, GAMS. A User's Guide, GAMS Development Corp., Washington, DC, 2003.
[25] Gas Commodity Fact Sheet for Maryland Public Service Commission, 2014, Available: http://webapp.psc.state.md.us/intranet/gas/gasCommodity_new.cfm
[26] Y. Tang, H. Song, F. Hu, Y. Zou, Investigating on TOU pricing principles, in: Proceeding IEEE PES Transmission Distribution Conference Expos, Dalian, China, 2005.
[27] Home Electricity Price, 2014, Available: http://www.opc.state.md.us/ConsumerCorner/Electricity.aspx
[28] K. Clement-Nyns, E. Haesen, J. Driesen, The impact of charging plug-in hybrid electric vehicles on a residential distribution grid, IEEE Trans. Power Syst. 25 (2010) 371–380.