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Load management in a residential energy hub with renewable distributed energy resources

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ABSTRACT

This paper presents a residential energy hub model for a smart multi-carrier energy home consisting of plug-in hybrid electric vehicle (PHEV), combined heat and power (CHP), solar panels, and electrical storage system (ESS). The energy hub inputs are electricity and natural gas that provide electrical and heat demands at the output ports. In this paper, an optimization-based program is proposed to determine the optimal operation mode of the energy hub, to manage the energy consumption of responsive appliances, to schedule charging/discharging of PHEV and the storage system, and to coordinate solar panels operation with household responsive demand in response to day-ahead time-varying tariffs of electricity. The objective function is to minimize customer payment cost considering vehicle to grid (V2G) capability. Different case studies are conducted to probe the effectiveness of the proposed method and study the impacts of different electrical time-differentiated tariffs on the optimization results on daily and yearly basis.

1. Introduction

Accommodating the distributed energy resources (DERs) and storage options, activating the customer participation in the utility and ISO programs, employing modern technologies, and facilitating two-way flow of energy and information are the main consequences of realizing smart grid [1]. At the residential customer level, smart home appears as a small sample of smart grid to pursue the abovementioned goals. Smart home is a residential building/home equipped with devices synchronized with each other using communication channels in order to manage household energy consumption, provide customer comfort and security, and provide home-based health care. In the context of the energy management, demand response (DR) programs have been proposed to realize a smart home [2]. Several references certify that proper application of residential DR programs not only benefits the system operators by preventing probable system failure, but also provides an opportunity for customers to track their energy prices and consumption, which can lead to lower costs [3–5]. In this regard, home load management (HLM) is designed as an automatic program to facilitate the implementation of residential price-based DR programs. In HLM, a home load controller can automatically manage household controllable load in response to price changes, taking into account customer satisfaction [3,6,7]. Accordingly, household appliances are divided into two classes of responsive and nonresponsive to time-differentiated pricings. In addition to usual appliances, plug-in hybrid electric vehicles (PHEVs) and storage systems have recently penetrated into smart homes. Although utilities became concerned about the challenges associated with multiple domestic PHEV charging activities, PHEV charging control algorithms can lessen these concerns [8,9]. In addition, vehicle to grid (V2G) capability of PHEVs and storage systems, i.e. returning the stored energy to the grid, can bring environmental and economic benefits to the system operators and customers [10,11]. To achieve more benefits from the presence of PHEV and storage system, charge and discharge cycling of them should be optimally scheduled in conjunction with the implementation of HLM programs [3].

Smart home applications drive the increasing need to develop small-scale renewable DERs (RDERs) like new wind or solar power generators [12,13]. These resources are fast improving, reaching a close parity with the conventional generation from the economic perspective [14]. Such resources impose significant investment

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Abbreviations: CHP, combined heat and power; DR, demand response; DER, distributed energy resource; EV, electric vehicle; HLM, home load management; IBR, inclining block rate; PHEV, plug-in hybrid electric vehicle; RDER, renewable distributed energy resource; TOU, time of use.

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Nomenclature

Sets and indices

M	set of on/off controlled appliances
m	index of on/off controlled appliances
N	set of consumption level controlled appliances
n	index of consumption level controlled appliances
t	hour index

Parameters, variables, and functions

b_m	first hour of allowable operation interval for appliance m
b_n	first hour of allowable operation interval for appliance n
Cost	total energy cost for the customer in the next day [¢]
c^{PH}	last hour of daily trip
$C_{\mathrm{CHP}}^{\max}$	maximum allowable natural gas input of CHP [kW]
cap^s	ESS capacity [kW h]
$\mathrm{ch}_{\max}^{S}$	maximum allowable charging rate of ESS at each hour [kW]
$\mathrm{cap}^{\mathrm{PHEV}}$	PHEV battery capacity [kW h]
$\mathrm{ch}_{\max}^{\mathrm{PHEV}}$	maximum allowable charging rate of PHEV at each hour [kW]
$\mathrm{dch}_{\max}^{\mathrm{PHEV}}$	maximum allowable discharging rate of PHEV at each hour [kW]
$\mathrm{dch}_{\max}^{S}$	maximum allowable discharging rate of ESS at each hour [kW]
$E_{\mathrm{grid}}(t)$	electrical power provided by grid at hour t [kW]
$E_{\mathrm{RDER}}(t)$	electrical power provided by RDER at hour t [kW]
$E_{\mathrm{CHP}}(t)$	electrical power provided by CHP at hour t [kW]
$E_{\mathrm{dch}}^{\mathrm{PHEV}}(t)$	in-home discharging energy of PHEV at hour t [kW h]
$E_{\mathrm{dch}}^{S}(t)$	discharged energy of ESS at hour t [kW h]
$E_{\mathrm{app}}(t)$	energy consumption of electrical household appliances at hour t [kW h]
$E_{\mathrm{ch}}^{S}(t)$	charging energy of ESS at hour t [kW h]
$E_{\mathrm{ch}}^{\mathrm{PHEV}}(t)$	in-home charging energy of PHEV at hour t [kW h]
$E_{\mathrm{V2G}}(t)$	amount of energy returned to the grid at hour t [kW h]
$E_{\min}^{\mathrm{PHEV}}$	minimum allowable charge state of PHEV [kW h]
$E_{\min}^{S}$	minimum allowable charge state of ESS [kW h]
E_{f}^{S}	final charge state of ESS in a day [kW h]
E_{0}^{S}	initial charge state of ESS in a day [kW h]
$E_m(t)$	energy consumption of appliance m at hour t [kW h]
E_m	energy consumption of appliance m at each operating hour [kW h]
$E_n(t)$	energy consumption of appliance n at hour t [kW h]
E_n	total electrical energy consumption of appliance n in its operation interval [kW h]
$E_n^{\min}(t)$	minimum allowable energy consumption of appliance n at hour t [kW h]
$E_n^{\max}(t)$	maximum allowable energy consumption of appliance n at hour t [kW h]
$E_{\mathrm{app}}^{R}(t)$	responsive appliances' energy consumption at hour t [kW h]
$E_{\mathrm{app}}^{\mathrm{NR}}(t)$	non-responsive appliances' energy consumption at hour t [kW h]
E_{0}^{PHEV}	initial charge state of PHEV in a day [kW h]
E_{f}^{PHEV}	final charge state of PHEV in a day [kW h]
E_{out}	expected electrical energy consumption during daily trip [kW h]
$G(t)$	received natural gas at energy hub input at hour t [kW h]
g^{PH}	first hour of daily trip
$H_d(t)$	total household heat demand at hour t [kW]
$H_{\mathrm{CHP}}(t)$	heat power provided by CHP at hour t [kW]
$\mathrm{IBR}_{\mathrm{th}}$	hourly IBR tariff threshold [kW]
$I_m(t)$	binary indicator of operation of appliance m, which is 1 when appliance m is on at hour t
l_m	last hour of allowable operation interval for appliance m
l_n	last hour of allowable operation interval for appliance n
$\mathrm{PH}(t)$	PHEV charge state at the end of hour t [kW]
$R(t)$	solar radiation at hour t [W/m^2]
S	solar panel surface area [m^2]
$S(t)$	ESS charge state at the end of hour t [kW h]
$T(t)$	solar panel temperature at hour t [°C]
U_m	required operation time of appliance m in the day [h]
η	solar panel conversion efficiency of photovoltaic array
η_{ch}^{S}	efficiency of ESS charging
$\eta_{\mathrm{ch}}^{\mathrm{PHEV}}$	efficiency of PHEV battery charging
η_{dch}^{S}	efficiency of ESS discharging
$\eta_{\mathrm{dch}}^{\mathrm{PHEV}}$	efficiency of PHEV battery discharging
$\eta_{\mathrm{DC/AC}}$	efficiency of DC/AC converter beside RDER
η_{eapp}	efficiency of household electrical appliances
η_{gapp}	efficiency of household gas-consuming appliances
η_{g-h}	gas to heat conversion efficiency of CHP
η_{g-e}	gas to electricity conversion efficiency of CHP
$\lambda_g(t)$	natural gas tariff at hour t [¢/kW h]
$\lambda_e(t)$	electricity tariff at hour t [¢/kW h]
$\nu(t)$	dispatch factor of natural gas at hour t

cost and negligible operation cost to the customer. So, if they are installed at a home, they should be optimally utilized to maximally benefit the customer. This can be achieved by coordinating between the demand and RDERs generation. Therefore, operation of RDER and responsive demand should be synchronized with each other in a smart home [15].

Along with the proliferation of smart home concepts, combined heat and power (CHP) technology, has become popular at homes due to the expansion of natural gas networks and benefits of this energy carrier [16]. Advent of CHP and other converters between different energy carriers makes the analysis of residential energy system more complicated. The *energy hub* model has been recently presented to simplify the analysis of such multi-carrier energy systems [17,18].

Energy hub can be identified as a unit with in- and output ports that transmits, converts and stores multiple energy carriers. Typically, energy hubs receive common energy carriers such as electricity and natural gas at input ports and supply electrical and heat demands at output ports. In a smart multi-carrier energy home, CHP, PHEV, and storage system can act as the hub components. This paper presents a *residential energy hub* model for such a smart home incorporating RDERs. Studies on the energy hub concept, modeling, and operation have recently seen a growing trend. The main operational question is about the dispatch of received energy carriers into the energy hub components. Various algorithms have been proposed in previous studies to optimally solve the energy hub operation problem [15,17,18].

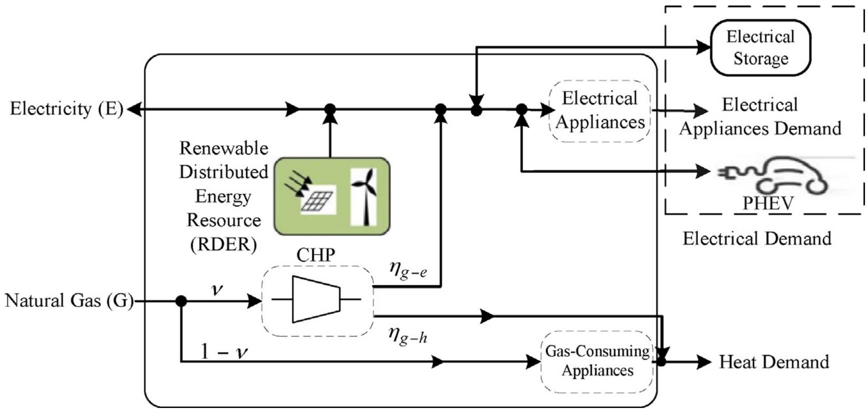

Fig. 1. Residential energy hub.

To the best of authors' knowledge, none of the previous works properly addresses the application of HLM in a multi-carrier energy home considering RDERs. In this regard, this paper not only presents an optimization-based formulation for optimal operation of residential energy hub and management of household demands, but also employs solar panels and storage system in the proposed model to optimally match the solar panels operation and HLM program. The output power of the solar system is mathematically calculated based on the proven methods. The objective function minimizes the customer payment cost, subjected to all operational and technical constraints of the customer and hub components. The output of solving the problem will be the charge/discharge scheduling of PHEV and storage system, the energy consumption scheduling of responsive appliances, and the dispatch of energy carriers in the residential energy hub for the next day. In addition to the studies effectuated to probe the proposed method's effectiveness, the impacts of incorporating common residential price-based DR programs, i.e. time of use (TOU) and inclining block rate (IBR), on the results of solving the optimization problem are investigated and compared with each other. Hence, contributions of this paper can be highlighted as follows:

- Residential energy hub framework is designed to show the interaction between energy carriers at a smart home including CHP, PHEV, ESS, solar panels, and appliances.
- An optimization problem developed in this paper to optimize the operation of residential energy hub, manage the household appliances operation, schedule the charge/discharge scheduling of PHEV and ESS, and coordinate the solar panels' generation and controllable appliances demand as much as possible.
- The impacts of prevalent residential electricity pricings on the proposed HLM model are separately investigated for the winter and summer days.

2. Renewable-based residential energy hub model

Due to presence of different energy carriers at homes, it is essential to present a model for a multi-carrier energy home. Residential energy hub is designated to model the operation of such an environment. An overview of the proposed renewable-based residential energy hub model in this paper is presented in Fig. 1.

As presented in Fig. 1, electrical and natural gas energies at the hub input ports are transferred to the electrical and heat demand at the output ports in different ways. Electrical demand consists of electrical appliances consumption, PHEV battery charging, and electrical storage charging. The electrical grid and RDER can directly provide the electrical demand. In addition, the inputted natural gas can supply a part of the electrical demand through CHP. RDER's generation can be stored in the storage system and PHEV battery or can be directly sold to the grid, if possible and profitable. Based on V2G capability, the stored energy in the electrical storage system (ESS) and the PHEV battery not only can supply the household demand, but also can be returned to the electrical grid. Storing energy at low-tariff periods and returning it to the grid at high-tariff ones greatly benefit the customer.

The received natural gas at the hub input supplies heat demand through the gas-consumed appliances or by CHP. The amount of dispatch factor ν determines the dispatch manner of natural gas between different possible ways.

Based on the above descriptions and Fig. 1, power flow equations of the residential energy hub are mathematically presented in the following equations:

$$\begin{aligned} &E_{\text{grid}}(t)+\eta_{\text{DC/AC}}E_{\text{RDER}}(t)+E_{\text{CHP}}(t)+\eta_{\text{dch}}^{S}E_{\text{dch}}^{S}(t)+\eta_{\text{dch}}^{\text{PHEV}}E_{\text{dch}}^{\text{PHEV}}(t)\\ &=\left(\frac{1}{\eta_{eapp}}\right)E_{\text{app}}(t)+\left(\frac{1}{\eta_{\text{ch}}^{S}}\right)E_{\text{ch}}^{S}(t)+\left(\frac{1}{\eta_{\text{ch}}^{\text{PHEV}}}\right)E_{\text{ch}}^{\text{PHEV}}(t)+E_{\text{V2G}}(t),\quad \forall t, \end{aligned} \tag{1}$$

$$(1-\nu(t))\left(\frac{1}{\eta_{\text{gapp}}}\right)G(t)+H_{\text{CHP}}(t)=H_{d}(t),\quad \forall t, \tag{2}$$

where in (1), t is hour index, $E_{\text{grid}}(t)$, $E_{\text{RDER}}(t)$, and $E_{\text{CHP}}(t)$ are the provided electrical energy by, respectively, the grid, RDER, and CHP at hour t. $E_{\text{dch}}^{S}(t)$ and $E_{\text{dch}}^{\text{PHEV}}(t)$ are, respectively, the discharged energy of the storage system and PHEV battery at hour t. In the right-hand side of Eq. (1), $E_{\text{app}}(t)$, $E_{\text{ch}}^{S}(t)$, and $E_{\text{ch}}^{\text{PHEV}}(t)$ are, respectively, the energy consumption of electrical household appliances, charging energy of storage system, and charging energy of PHEV battery at hour t. In addition, $E_{\text{V2G}}(t)$ is the amount of energy returned to the grid at hour t according to V2G capability. $\eta_{\text{DC/AC}}$, η_{eapp}, η_{gapp}, η_{ch}^{S} (η_{dch}^{S}), and $\eta_{\text{ch}}^{\text{PHEV}}$ ($\eta_{\text{dch}}^{\text{PHEV}}$) are efficiencies of, respectively, DC/AC converter beside RDER, household electrical appliances, household gas-consumed appliances, ESS charging (discharging), and PHEV battery charging (discharging). In (2), $G(t)$ and $\nu(t)$ are, respectively, the input natural gas of the energy hub and the associated dispatch factor at hour t. Also, $H_d(t)$ is the total household heat demand at hour t. In the abovementioned equations, $E_{\text{CHP}}(t)$ and $H_{\text{CHP}}(t)$ are the electrical and heat outputs of CHP. They are calculated based on the dispatch factor $\nu(t)$ and CHP conversion efficiencies as expressed in the following equations:

$$E_{\text{CHP}}(t)=\nu(t)G(t)\eta_{g-e} \tag{3}$$

$$H_{\text{CHP}}(t)=\nu(t)G(t)\eta_{g-h} \tag{4}$$

where η_{g-h} and η_{g-e} are, respectively, the gas to heat and gas to electricity conversion efficiencies of CHP. The CHP capacity is usually bounded by an inequality such as in the following equation:

$$\nu(t)G(t)\le C_{\text{CHP}}^{\max} \tag{5}$$

where $\nu(t)G(t)$ is the input power of CHP and $C_{\mathrm{CHP}}^{\max}$ is the capacity of CHP.

In the studies conducted in this paper, the RDER is assumed to be a solar system. The most critical problem in operating a solar system arises from the fact that renewable sources cannot be dispatched in the same manner as conventional DERs. The reason for this is that solar radiation and other environmental characters affecting the solar panel output power cannot be precisely predicted for the future. However, this issue is less important for a day ahead scheduling due to possible high precision of weather forecasting for the next 24 h. Nonetheless, the battery storage can be utilized as one of the solutions to the random availability of solar panel generation. The results presented in [19] show that, solar systems in conjunction with battery storage play a unique role in demand-side management. The instantaneous output power of the solar network ($E_{\mathrm{RDER}}(t)$ in Eq. (1)) can be estimated as (6) [20].

$$E_{\mathrm{RDER}}(t) = S\eta R(t)[1 - 0.005(T(t) - 25)], \tag{6}$$

where $R(t)$ is the solar radiation at hour t [W/m^2], η is solar panel conversion efficiency of photovoltaic array, S is the solar panel area [m^2], and $T(t)$ is the solar panel temperature [°C]. This equation shows that the solar panel output power is a function of radiation and ambient temperature. It seems that as long as solar radiation panel's temperature is predicted accurately, any solar system's output power can be calculated accordingly.

In the problem formulation of the energy hub operation, efficiencies are usually assumed to be constant while the dispatch factors and amounts of received electricity and natural gas at the hub inputs are derived from solving an optimization-based problem. In addition, since a part of household demand is responsive to energy prices, the optimization problem's solution should optimally manage the household responsive load.

3. Problem formulation

As mentioned before, an optimization problem should be designed to:

1. determine the optimal operation of the residential energy hub;
2. manage the household load; and
3. coordinate the solar panels operation and consumption of household electrical responsive appliances.

In this section, an optimization-based problem is formulated to achieve these goals. Solving the optimization problem should result in obtaining the energy hub dispatch factors, received electrical and natural gas power at the input of energy hub, scheduling of responsive appliances' operation, and charging/discharging of PHEV battery and the storage system. Scheduling problem is designed from the customer perspective in order to minimize the customer payment cost. The problem should also consider operational constraints of the appliances and PHEV.

The objective function is mathematically presented as in the following equation:

$$\text{Min Cost} = \sum_{t=1}^{24} \left[\lambda_g(t)G(t) + \lambda_e(t)(E_{\mathrm{grid}}(t) - E_{\mathrm{V2G}}(t))\right] \tag{7}$$

where Cost is the total energy payment cost for the customer in the next day, and $\lambda_g(t)$ and $\lambda_e(t)$ are, respectively, the gas and electricity tariffs at hour t. The gas price is usually constant during a day in contrast to the electricity prices. Different time-varying electricity prices can be applied according to the price-based DR programs. Time of use (TOU) tariff and inclining block rate (IBR) are the two common time-differentiated pricing strategies for residential customers [21]. The minus sign of $E_{\mathrm{V2G}}(t)$, in (7), shows the opposite direction of energy flow to the grid. As expressed in Eq. (7), the tariff of selling energy to the grid is assumed to be the same as the tariff of buying electricity at each hour [3].

The objective function is subjected to the power flow equation mentioned in (1)–(5), and operational constraints of appliances, PHEV, and other hub components which are noted and formulated below.

Due to fixed rates of natural gas tariff, *gas-consuming* appliances are assumed non-responsive and their consumption is estimated for the next day. With respect to DR programs, *electrical* appliances are divided into two main groups; responsive and non-responsive. So:

$$E_{\mathrm{app}}(t) = E_{\mathrm{app}}^{R}(t) + E_{\mathrm{app}}^{\mathrm{NR}}(t), \quad \forall t \tag{8}$$

where $E_{\mathrm{app}}^{R}(t)$ and $E_{\mathrm{app}}^{\mathrm{NR}}(t)$ are, respectively, responsive and non-responsive appliances' energy consumption at hour t. The responsive appliances participate in HLM programs by responding to time-varying prices of electricity. In this paper, responsive appliances are studied in two sets:

- Set ***M:*** Appliances whose energy consumption at each operating hour is known and only their operation times can be determined by HLM program;
- Set ***N:*** Appliances whose total energy consumption in a time interval (likely more than 1 h) is defined and their energy consumption level at each hour can be determined by HLM program.

Each appliance in set $\boldsymbol{M}$ has a definite operation time (U_m), which should be within an allowable interval ($[b_m, l_m]$) specified by the customer. This is mathematically presented in the following equation:

$$\sum_{t=b_m}^{l_m} I_m(t) = U_m, \quad \forall m, \tag{9}$$

where m is the index of responsive appliances in set $\boldsymbol{M}$, b_m and l_m are, respectively, the beginning and last hours of the specified allowable operation interval for appliance m, and $I_m(t)$ is the binary indicator of operation of appliance m, which is 1 when appliance m is on at hour t. For example, it is assumed that a washing machine (WM) should operate 2 h to wash the clothes and a customer would like to have clean clothes before 2 p.m. in the next day. So, $U_{\mathrm{WM}} = 2$, $b_{\mathrm{WM}} = 1$, and $l_{\mathrm{WM}} = 14$.

Appliance m consumes a definite value of E_m at each operating hour. So:

$$E_m(t) = E_m I_m(t), \quad \forall m, \tag{10}$$

where $E_m(t)$ is the energy consumption of appliance m at hour t in the next day. It is obvious that E_m is the input of the problem and $I_m(t)$ is determined by solving the optimization problem.

As mentioned before, total energy consumption of appliances in set $\boldsymbol{N}$ is definite for the allowable operation interval specified by the customer. However, the energy consumption of appliance n at hour t, i.e. $E_n(t)$, should be determined by solving HLM. So:

$$\sum_{t=b_n}^{l_n} E_n(t) = E_n, \quad \forall n, \tag{11}$$

where E_n is total electrical energy consumption of appliance n in the specified operation interval, and b_n and l_n are, respectively, the beginning and last hours of the specified operation interval for appliance n. Duration of interval $[b_n, l_n]$ should be more than 1 h to provide several choices for scheduling the energy consumption of appliance n.

Table 1
TOU tariff.

	Winter periods	Summer periods	Price [¢/kW h]
Peak	–	12:00 pm to 5:00 pm	16.1
Partial peak	4:00 pm to 8:00 pm	10 am to 12 pm and 5:00 pm to 7:00 pm	14.5
Off-Peak	Other hours	Other hours	10.8

$E_n(t)$ can be limited by the customer to definite minimum and maximum values by:

$$E_n^{\min}(t) \le E_n(t) \le E_n^{\max}(t), \quad \forall t, \tag{12}$$

where $E_n^{\min}(t)$ and $E_n^{\max}(t)$ are, respectively, the minimum and maximum allowable energy consumption of appliance n at hour t.

In conclusion, the responsive appliances' energy consumption is the summation of responsive appliances consumption in sets $\boldsymbol{M}$ and $\boldsymbol{N}$, as:

$$E_{\text{app}}^R(t) = E_m(t) + E_n(t), \quad \forall t, \tag{13}$$

In addition to these constraints, PHEV and the ESS have some operational constraints that should be considered as optimization constraints.

Constraints associated with PHEV operation are expressed as follows.

$$\text{PH}(t) = E_0^{\text{PHEV}} + \sum_{j=1}^{t} \begin{cases} E_{\text{ch}}^{\text{PHEV}}(j) - E_{\text{dch}}^{\text{PHEV}}(j) & t \le g^{\text{PH}} \\ E_{\text{ch}}^{\text{PHEV}}(j) - E_{\text{dch}}^{\text{PHEV}}(j) - E_{\text{out}} & t \ge c^{\text{PH}} \end{cases} \tag{14}$$

$$E_{\min}^{\text{PHEV}} \le \text{PH}(t) \le \text{cap}^{\text{PHEV}}, \quad \forall t \tag{15}$$

$$\text{PH}(g^{\text{PH}} - 1) = \text{cap}^{\text{PHEV}} \tag{16}$$

$$E_{\text{ch}}^{\text{PHEV}}(t) \le \text{ch}_{\max}^{\text{PHEV}}, \quad \forall t \tag{17}$$

$$E_{\text{dch}}^{\text{PHEV}}(t) \le \text{dch}_{\max}^{\text{PHEV}}, \quad \forall t \tag{18}$$

where $\text{PH}(t)$, $E_{\text{ch}}^{\text{PHEV}}(t)$, and $E_{\text{dch}}^{\text{PHEV}}(t)$ are, respectively, PHEV charge state at the end of hour t, in-home charging amount, and in-home discharging amount at hour t. E_0^{PHEV} and cap^{PHEV}, respectively, show the initial charge state of PHEV in the day and the PHEV battery capacity. Consider that PHEV has to travel the next day. The travel duration, i.e. from hour g^{PH} to hour c^{PH}, and electrical energy consumption during the travel, i.e. E_{out}, are assumed to be known in the above equations. These data can be extracted from available travel surveys [10,22] with the lowest error. $\text{ch}_{\max}^{\text{PHEV}}$ and $\text{dch}_{\max}^{\text{PHEV}}$ are maximum allowable charging and discharging rates of PHEV at each hour.

Eq. (14) determines the PHEV charge state at each hour before and after the PHEV travel. Eq. (15) guarantees that the PHEV charge state is lower than the PHEV battery capacity and more than a predetermined value at every hour. PHEV owner usually expects to have a fully charged battery before going out of home. This is certified in (16). In addition, Eqs. (17) and (18), respectively, confine the charging and discharging rates at each hour.

In equations related to PHEV, $E_{\text{ch}}^{\text{PHEV}}(t)$ and $E_{\text{dch}}^{\text{PHEV}}(t)$ are determined by solving the optimization problem. After substituting $\text{PH}(t)$, E_0^{PHEV}, $E_{\text{ch}}^{\text{PHEV}}(t)$, $E_{\text{dch}}^{\text{PHEV}}(t)$, cap^{PHEV}, $E_{\min}^{\text{PHEV}}$, $\text{ch}_{\max}^{\text{PHEV}}$, and $\text{dch}_{\max}^{\text{PHEV}}$ by $S(t)$, E_0^S, $E_{\text{ch}}^S(t)$, $E_{\text{dch}}^S(t)$, cap^S, $E_{\min}^S$, $\text{ch}_{\max}^S$, and $\text{dch}_{\max}^S$, similar equations are applicable for the ESS. Note that, unlike PHEV, the storage system is available at each hour.

In conclusion, the objective function (7) is subjected to (1)–(5) and (8)–(18). Solving this optimization problem not only leads to an optimal operation of the residential energy hub, but also manages the household electrical demand in response to time-varying tariffs. In addition, the solar panels operation is optimally coordinated with the responsive demand through the optimization procedure.

4. Numerical study

In this section, the proposed formulations are implemented to different case studies to investigate different aspects of the propounded method. Impacts of V2G implementation, RDER presence, and different pricing methods on the optimization results are probed in this section. To this end, three different case studies are conducted.

Case I—A residential energy hub without solar panels and without V2G capability incorporating TOU electricity tariff;
Case II—Case I with solar panels and V2G capability;
Case III—Case II incorporating IBR electricity tariff.

In these cases, the optimization problem is solved for the next 24 h. The results are reported for a sample winter day and a sample summer day in each case. Accordingly, the customer cost is reported for a year, considering different uncontrollable demand profiles for winter and summer days, different TOU and IBR tariff for winter and summer seasons, and forecasted hourly generation for solar panels in different days of a year.

4.1. Assumptions

In this subsection, required assumptions and input data for solving the proposed optimization problem are presented. Note that almost all the assumptions are extracted from available published reports and papers. Electricity and gas tariffs play a major role in solving the designed optimization problem. Here, the gas price is assumed to be 1.3 ¢/kW h as a fixed rate [23]. The electricity tariff is determined based on the DR program type chosen by the residential customer. As mentioned before, TOU and IBR are the common applicable DR programs for residential customers. In TOU tariff, different price levels, usually two or three levels, are introduced for a day. In cases I and II, a two level TOU tariff, taken from Pacific Gas and Electric (PG&E) Company, is assumed as the electricity price [24]. PG&E declares that residential TOU schedule for a winter day and a summer day can be as Table 1.

In the hourly IBR tariff, utilized recently by many companies for residential customers, a threshold (IBR_{th}) is defined for the hourly electrical consumption. The hourly customer consumptions lower and higher than this threshold are calculated by using different rates. The IBR tariff data considered in Case III is presented in Table 2.

In this study, IBR_{th} is assumed to be 2 kW for winter days and 2.5 kW for summer days. Therefore, at each hour of winter (summer), the tariff associated with the electrical energy consumption less than 2 (2.5) kW h is 10.1 (11.27) [¢/kW h]. The tariff of hourly consumption more than the threshold in winter (summer) is 15.9 (17.53) [¢/kW h]. In the considered household energy hub, different

Table 2
IBR tariff [¢/kW h] [24].

Winter		Summer	
Lower than IBR_{th}	More than IBR_{th}	Lower than IBR_{th}	More than IBR_{th}
10.1	15.9	11.27	17.53

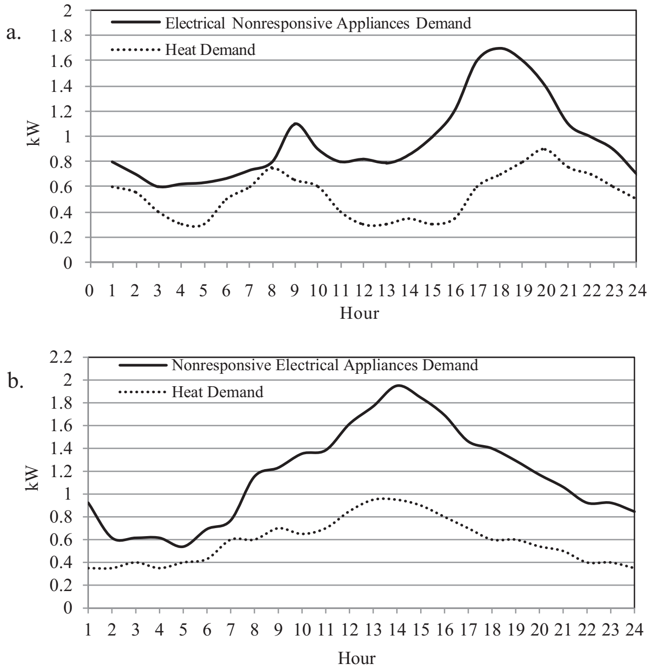

Fig. 2. Nonresponsive electrical and heat demands in, (a) sample winter day, (b) sample summer day.

Table 3
Data of responsive appliances in Set ***M*** [25].

Appliance	U_m [h]	E_m [kW h]	b_m	l_m
Dishwasher (DW)	2	0.35	1	24
Washing machine (WM)	1	0.12	9	13
Clothes dryer (CD)	1	1.2	14	22

Table 4
WHC data [4].

E_n [kW h/day]	b_n	l_n
4.5	6	23

nonresponsive electrical and gas-consuming appliances, such as refrigerator, television, vacuum cleaner, radio, lights, gas oven, gas stove, etc., exist. Non-responsive electrical appliances demand and household heat demand for the sample days of winter and summer are assumed as shown in Fig. 2.

As can be seen in this figure, the peaks of nonresponsive electrical and heat demands in winter are, respectively, 1.7 kW at hour 18 and 0.9 kW at hour 20, and in summer are, respectively, 1.95 kW at hour 14 and 0.95 at hour 13. The average demand of nonresponsive appliances in the summer day is 1.16 kW, which is higher than that of the winter day, i.e., 0.96 kW. In addition to these nonresponsive demands, four responsive electrical appliances are considered in the model. Dishwasher (DW), washing machine (WM), clothes dryer (CD) are assumed as the responsive appliances in Set ***M*** and electrical water heater/cooler (WHC) is considered as an appliance in Set ***N***. Related data of responsive appliances are summarized in Tables 3 and 4.

Table 6
CHP characteristics [16].

η_{g-h}	η_{g-e}	C^{max}_{CHP} [kW h]
0.4	0.3	1

According to Table 4, WHC should consume 4.5 kW h between hours 6 and 23. As mentioned before, the hourly maximum and minimum energy consumption of WHC can be specified by the customer. In these case studies, maximum and minimum levels of energy consumption are, respectively, assumed to be 0.5 kW h and 0 at all allowable hours (hours 6 to 23). It should be noted that the appliances' operation efficiencies (η_{eapp} and η_{gapp}) are assumed to be one in this study.

The assumed operational characteristics associated with PHEV and ESS are summarized in Table 5. (.) can be substituted by s and PH indices for, respectively, storage system and PHEV.

In addition, g^{PH}, c^{PH}, and E_{out} are assumed to be hour 10, hour 19, and 4 kW h. Nonresponsive demands in Fig. 2 and responsive appliances data in Tables 3 and 4 show that, in the case without load management, a high peak load may occur at hours 17–19 due to concurrency of CD operation, charging of PHEV and storage system, and nonresponsive electrical peak load. This not only may cause damages to household facilities and impose a higher payment cost to the customer, but also degrades distribution system reliability. Therefore, applying HLM in such a home seems necessary from both the customer and operator viewpoints. However, presence of CHP and solar panels at home can alleviate a part of stress on the customer and electrical network. This will be studied in the designed cases. CHP specifications employed in the proposed model are presented in Table 6.

Solar panels play a major role in this paper's studies. Free charge generation of solar panels is an incentive for residential customers to install solar panels at home. It is assumed in this paper that a 20 m^2 panel has been installed in the smart home. The efficiency of DC/AC converter and panel conversion efficiency of photovoltaic array are, respectively, assumed to be 0.95 and 0.15. According to (6), hourly temperature and radiation should be estimated to determine the output power of solar panel. $R(t)$ and $T(t)$ for a sample sunny day of Tehran in winter are presented in Table 7 [27]. According to these assumptions, output power of solar panel ($E_{RDER}(t)$) is presented in the last column of Table 7.

Note that, in the following studies, daily study is based on this sample day in winter. In the case of yearly studies, radiation and temperature of all days are forecasted according to presented data in [27] and incorporated in the study. It should be noted that in the cases without V2G, vehicle to home (V2H) is possible. It means that, discharged energy can supply household demand, although it cannot be returned to the grid.

4.2. Case I

Case I is a base case for the numerical studies, in which, a residential energy hub includes all the presented components in Fig. 1, but RDER. In addition, V2G capability is not considered in this case.

Hub dispatch factors, scheduling of responsive appliances, and customer payment cost for all cases are summarized in Tables 8–11. The daily energy cost is reported for a sample winter day. Annual cost is the summation of daily customer costs in winter and

Table 5
PHEV and storage system characteristics [26].

$ch^{(.)}_{max}$[kW/h]	$dch^{(.)}_{max}$ [kW/h]	$cap^{(.)}$ [kW h]	$E^{(.)}_{0}$ [kW h]	$E^{(.)}_{min}$ [kW h]	$\eta^{(.)}_{ch}$	$\eta^{(.)}_{dch}$
1.4	1.4	7.8	2	2	0.88	0.88

Table 7
Solar cell operational characteristics in a sample winter day.

Hour	$T(t)$ [°C]	$R(t)$ [W/m^2]	$E_{\mathrm{RDER}}(t)$ [kW]
1	−1.9	0	0
2	−2	0	0
3	−2	0	0
4	−2.1	0	0
5	−2	0	0
6	−2	0	0
7	−1.7	0	0
8	−1	53.57	0.182
9	0	283.5	0.957
10	0.8	550.4	1.851
11	2	786.21	2.630
12	3	962.07	3.204
13	4.4	1061.56	3.513
14	8	1076.20	3.503
15	8	1004.65	3.270
16	8.2	852.56	2.773
17	8	633.06	2.061
18	7	369.31	1.208
19	7	111.91	0.366
20	7	0	0
21	4	0	0
22	2	0	0
23	1	0	0
24	1	0	0

Table 8
$v(t)$ in different cases.

Hour	Case I	Case II	Case III
1	0.813	0.767	0.765
2	0.830	0.812	0.800
3	0.776	0.920	0.920
4	0.741	0.908	0.908
5	0.852	0.754	0.754
6	0.717	0.703	0.703
7	0.738	0.830	0.830
8	0.741	0.741	0.741
9	0.801	0.801	0.801
10	0.834	0.834	0.834
11	0.769	0.709	0.710
12	1	1	1
13	0.858	0.725	0.725
14	1	1	1
15	1	1	1
16	1	1	1
17	0.834	0.832	0.834
18	0.745	0.747	0.753
19	0.714	0.714	0.714
20	0.666	0.666	0.666
21	0.741	0.741	0.741
22	0.770	0.770	0.770
23	0.675	0.727	0.726
24	0.705	0.787	0.787

summer days. Received power at input of household energy hub and charge/discharge scheduling of PHEV and storage system for the sample day in winter resulted from solving the proposed optimization problem in Case I are, respectively, presented in Figs. 3 and 4.

As shown in Fig. 3, the peak of household electrical demands in winter and summer are, respectively, 3.79 kW and 5.58 kW at hour 9 due to concurrent charging of PHEV and storage system at this low tariff hour. The reason for higher peak in summer is the higher electrical demand in summer than winter according to Fig. 2. Because of lower price of natural gas compared to electricity, it is profitable to provide electrical demand through CHP as much as the capacity of CHP allows (Eq. (5)). As presented in Fig. 3, the natural gas consumption at peak hours of electrical demand in Fig. 2 is higher than other hours. Since, it is profitable to provide a part of electrical demand through CHP at these high tariff hours. It is worthwhile to note that the customer energy cost of the given home

Table 9
Operation hours of appliances of set ***M*** in different cases.

Appliance	Case I	Case II	Case III
DW	8–9	13–14	13–14
WM	12	13	13
CD	15	15	15

Table 10
Energy consumption of WHC at allowable hours [kW h].

Hour	Case I	Case II	Case III
6 (b_{WHC})	0.5	0.5	0
7	0	0	0
8	0.5	0	0.327
9	0	0.5	0.173
10	0.5	0.5	0.5
11	0.5	0.5	0.5
12	0.5	0.437	0.5
13	0.5	0.064	0.5
14	0.5	0.5	0.5
15	0.5	0.5	0.5
16	0.5	0.5	0.5
17	0	0	0.5
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0.5	0
22	0	0	0
23 (l_{WHC})	0	0	0

Table 11
Daily and annual energy cost in different cases [$].

Case I		Case II		Case III	
Daily	Annual	Daily	Annual	Daily	Annual
4.47	1801.28	1.68	631.45	1.63	658.5

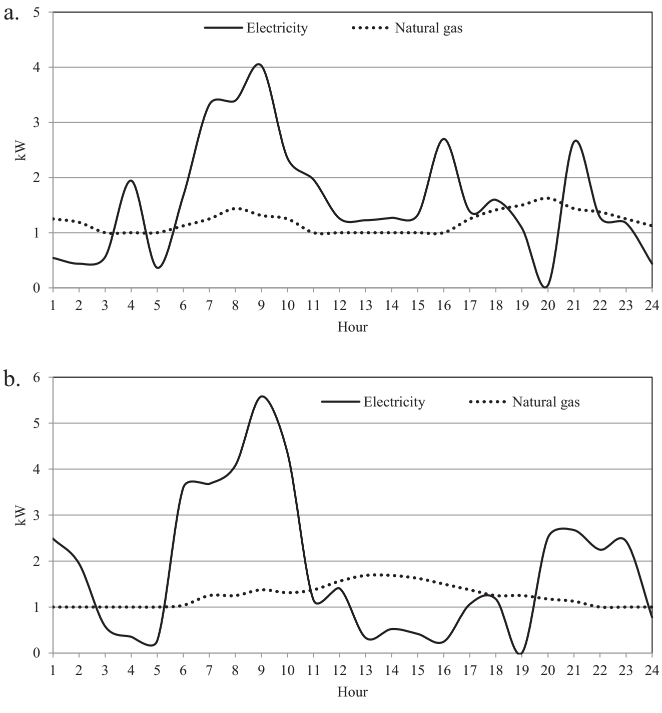

Fig. 3. Received power at input of household energy hub in Case I for the day in, (a) winter; (b) summer.

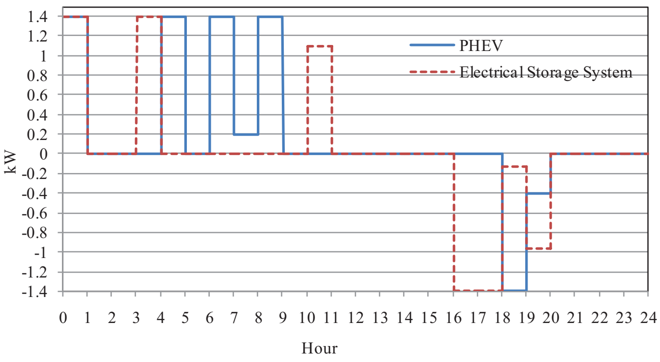

Fig. 4. PHEV and storage charge/discharge scheduling in Case I for the winter day.

in the winter day without CHP would be ¢511.51, which is 15% more than that of Case 1.

Fig. 3 shows that peak of household natural gas demand occurs at hour 20. The reason for this is that the household heat demand reaches its peak at this hour according to Fig. 2. In addition, Table 8 shows that $v(20)$ is the lowest dispatch factor in the day, which enables more gas consumption in CHP.

Fig. 4 verifies the aforementioned expectation that PHEV and storage systems are charged at low tariff hours and discharged at high tariff ones. Storage system is charged at hours 1, 4, and 14, and discharged at hours 16–20. It is worthwhile to note that PHEV is charged before the departure time (hour 10) to have a fully charged battery and discharged at the remained high tariff hours (hours 19–20) after arrival time (hour 19). Since V2G is not possible in this case, all the discharged energy is consumed at home. This leads to low input electrical power at hours 16–20, according to Fig. 3, in which PHEV and storage system provide household electrical demand at these hours.

According to Table 9, responsive appliances in set $\boldsymbol{M}$ expectedly operate at lower tariff hours. This is true for all cases. In addition, water heater/cooler, as presented in Table 10, operates with its maximum allowable consumption level (0.5 kW h) at low tariff hours as well as the allowable operation interval (hours 6–23).

4.3. Case II

In this case, solar panels and V2G capability are considered. Received power at the input port of the hub and charge/discharge scheduling of PHEV and ESS for the sample winter day resulted from solving the optimization problem are shown in Figs. 5 and 6.

The received electricity at the input of energy hub reaches its peak at hour 6 in the winter day and at hour 9 in the summer day as shown in Fig. 5, due to the simultaneous charging of storage system and PHEV at these low tariff hours. Presented results in Tables 9 and 10 demonstrate that energy consumption of responsive appliances shifts to sunny hours of the day, in which solar panels can supply the household demand. The reason for lower peak of electricity demand in this Case in comparison with that of previous case is the synergy between the solar cell generation and load demand. It should be noted that output power of solar panels more than the electrical appliances demand can be sold to the grid in Case II. This leads to lower customer payment cost in comparison with the previous case. According to Table 11, the customer energy costs for the winter day and for the full year are, respectively, reduced by 61% and 65% in Case II in comparison with Case I. This shows that although the average tariff is higher in summer than winter, customer cost reduction in summer days is more than winter days. Since, the average solar radiation is higher in summer days.

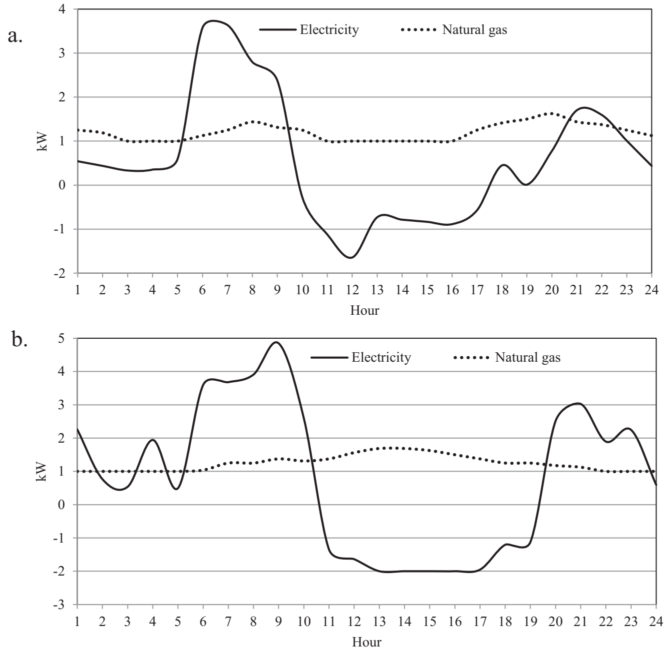

Fig. 5. Received power at input of household energy hub in Case II for the day in (a) winter; (b) summer.

It is worthwhile to note that, in Cases I and II, natural gas demand approximately follows the heat demand. Peak of natural gas demand is about 1.5 kW in all cases. In addition, the peak of received electricity is about 3 kW in these cases. Although this peak value is much less than the possible peak demand in the case without load management, it can also be reduced by designing a proper time-varying tariff for the HLM procedure. Note that this tariff should be user-friendly and should not endanger customer satisfaction.

As mentioned before, IBR pricing is another common tariff for residential customers. For the sake of comparison with previous cases, impact of incorporating IBR on the received power at the hub input is studied in the next case.

4.4. Case III

In this case, IBR pricing is incorporated in the study in Case II instead of TOU tariff. The results of solving the optimization problem in the winter day are presented in Fig. 7.

As shown in Fig. 7, the household electrical demand in the winter (summer) day is capped to the IBR threshold, i.e., 2 kW (2.5 kW) and is distributed during the day. Although this result may not be important from the customer point of view, it is appealing from system operator's viewpoint. In this case, according to Tables 9 and 10

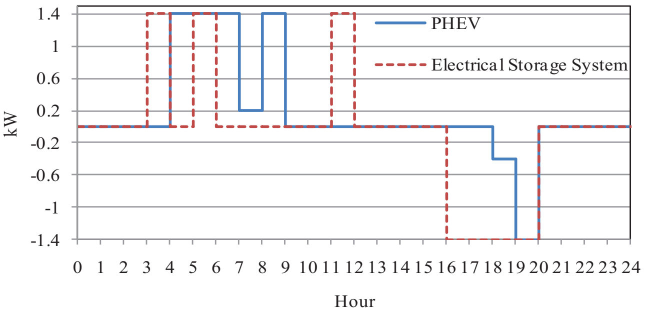

Fig. 6. PHEV and storage charge/discharge scheduling in Case II for the winter day.

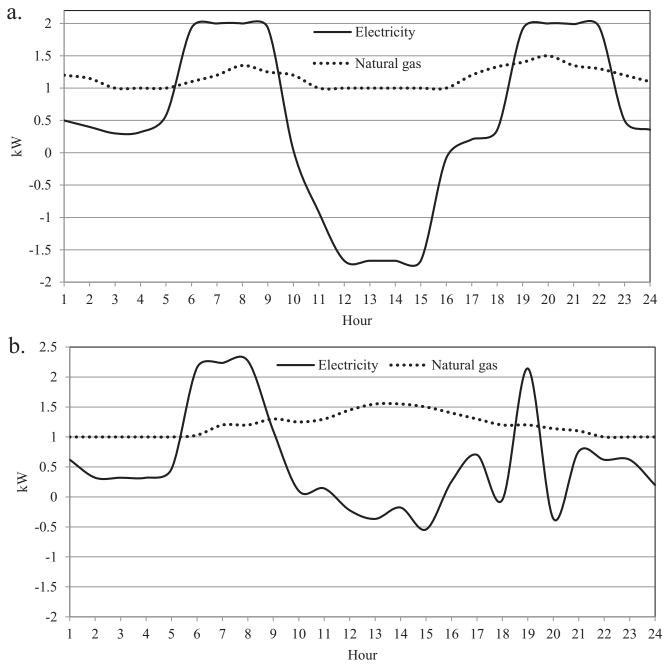

Fig. 7. Received power at input of household energy hub in Case III for the day in, (a) winter; (b) summer.

and Fig. 7, solar panels not only supply responsive appliances at hours 9–17, but also sell the generated energy to the grid. This reduces the customer cost. According to Table 11, since IBR electricity rate below the threshold in winter is lower than TOU tariff rates, the daily payment cost is lower in this case in comparison with the previous case. This result encourages the customer to actively participate in this type of DR program in winter days. However, in summer, the IBR rate below the threshold is higher than the lowest TOU tariff. This leads to higher annual energy cost in Case III than Case II, as presented in Table 11.

5. Conclusion

This paper proposed an optimization problem in a renewable-based residential energy hub model to not only achieve optimal operation of the residential energy hub, but also manage the responsive household load. The studies in this paper demonstrate that the proposed method properly coordinates the operation of solar panels and responsive demands, which leads to lower customer payment cost and lower household electrical peak demand. The results in the case of incorporating TOU tariff show that operation of responsive appliances shift to the lower tariff hours. If solar panels exist at home, appliances will usually operate at sunny hours of the day to be supplied from free generation of solar panels. This leads to 61% and 65% reduction in, respectively, daily and annual payment cost, in the case of solar panels presence in comparison with the case without them. In addition, considering V2G capability in the studies leads to further reduction in customer cost. Designed studies also illustrate that HLM generally prevents possible high peak load that can be occurred due to presence of PHEV, storage system, and high consumed appliances in smart homes. Type of incorporated residential DR program plays a major role in the results of applying the proposed method. This paper shows that incorporating IBR instead of TOU in HLM, although, provides the operator benefits by decreasing electricity peak demand, may result in increment in the annual cost of the customer. Designing a proper tariff to address both the customer's and operator's concerns is suggested as an open research area for future works.

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