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Cost-based modeling for optimal energy management of smart buildings with renewable energy resources and electric vehicles using a scenario-based algorithm

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Highlights

- The proposed study system contains various generation and controllable and uncontrollable loads
- this paper considers optimal operation of household energy hubs and the simultaneous optimization of planning and operation problems with an emphasis on the solar system
- efficieny increasing beside the reducing of operation costs is the effectiveness of the proposed method
- modelling and considering different generation and load conditions in household energy hub

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Abstract

The growth of electricity consumption and demand for higher quality of electricity have directed the electricity industry towards using new technologies. The rising trend of privatization, competitive nature of the electricity market and transformation of large investors into smaller ones have motivated electricity industry managers to pay more attention to increasing the generated power and grid equipment with maximum energy efficiency and minimum operation costs. Simultaneous use of different infrastructures for energy transfer and generation has led to the concept of energy hubs. Herein, a novel method is proposed to bridge the research gap in simultaneous optimization of solar system capacity and household energy hub operation. The proposed method is implemented on a household energy hub including controllable and uncontrollable loads, combined heat and power unit (CHP), grid-connected hybrid electric vehicles (EVs), heating loads and solar system. Studies were conducted in different conditions to compare the proposed method with the existing methods of optimal operation of household energy hubs and the simultaneous optimization of planning and operation problems with an emphasis on the solar system to highlight the benefits of the proposed method. The results indicate the efficiency of the proposed method in reducing operating costs and increasing the efficiency of the household energy hub while maintaining the user comfort level at the highest level.

Nomenclature

Indices		E_{app}	*Household appliances consumed energy*
$C_{O\&M}$	*Annual cost of operation, maintenance and repair of solar panel system components*	Inv_{size}	*Inverter capacity*
S_{pv}	*Area required for installing each module*	$\eta_{Inverter}$	*Inverter efficiency*
T_a	*Ambient temperature*	C_{Inv}	*Inverter investment cost*
C_{BoS}	*Balance system investment cost*	C_{Mudule}	*Investment cost for each module*
K	*Characteristic of the number of controllable devices*	E_{dch}^{max}	*Minimum EV charge rate*
T_c	*Cell temperature*	E_{max}^{CHP}	*Maximum generated power by the CHP unit*

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E_CHP	*CHP unit output power*	E_{grid}	*Power received from the electricity grid*
H_CHP	*CHP generated heat*	H_{ch}^{max}	*Maximum charge rate of the heat storage unit*
H_{ch}^{HSS}	*Charge level of the heat storage unit*	H_{dch}^{max}	*Maximum discharge rate of the heat storage unit*
$NOCT$	*Cell operational nominal temperature*	E_{PV}^{max}	*Maximum output power of the solar panel*
E_{ch}^{BSS}	*Charge level of the electricity storage unit*	E_{k}^{max}	*Maximum permissible power consumed by controllable devices*
SOC^BSS	*Charge level of the electricity storage unit*	E_{k}^{min}	*Minimum permissible power consumed by controllable devices*
SOC^HSS	*Charge level of the heat storage unit*	E_{ch}^{max}	*Maximum EV charge rate*
η_{ch}^{s}	*Charge efficiency of the heat storage unit*	E_{ch}^{max}	*Maximum charge level of the electricity storage unit*
η_{g-h}	*CHP efficiency in gas to heat conversion*	E_{dch}^{max}	*Maximum charge level of the electricity storage unit*
η_{g-e}	*CHP efficiency in gas to electric power conversion*	SOC_{min}^{BSS}	*Minimum charge level of the electricity storage unit*
C_{Gas}	*Daily cost of natural gas purchased from the grid*	SOC_{max}^{BSS}	*Maximum charge level of the electricity storage unit*
C_{PV}	*Daily cost of ESS units*	SOC_{min}^{HSS}	*Minimum charge level of the heat storage unit*
r	*Discount rate*	SOC_{max}^{HSS}	*Maximum charge level of the heat storage unit*
η_{dch}^{s}	*Discharge rate of the electricity storage unit*	η_{pv}	*Module efficiency*
H_{dch}^{HSS}	*Discharge level of the heat storage unit*	C_{Elec}	*Net daily cost of electric power purchased from the grid*
C	*Energy producers' cost function*	N_{pv}	*Number of modules*
E_{0}^{PHEV}	*EV charge level at the beginning of each day*	$S_{Rooftop}$	*Net installable area for the modules*
E^{PHEV}	*Electric power stored in the EV*	G	*Natural gas received from the grid*
H^{HSS}	*Energy stored in the heat storage unit*	E_{pv}	*Output power of the solar panel*
H_{0}^{HSS}	*Energy stored in the heat storage unit at the beginning of each day*	CRF	*Return on capital index*
Cap^{PHEV}	*EV battery capacity*	I	*Solar irradiation on the area*
E^{c}	*Electricity demand of controllable devices*	T_{stc}	*Standard temperature*
E^{uc}	*Electricity demand of uncontrollable electric devices*	η_{wire}	*Solar system wires and links' efficiency*
E^{BSS}	*Energy stored in the electricity storage unit*	η_{gapp}	*Total efficiency of gas-burning devices*
E_{0}^{BSS}	*Energy stored in the electricity storage unit at the beginning of each day*	β_{ref}	*Temperature correction coefficient*
λ_{g}	*Gas tariff*	t	*Time step (hour)*
H^{c}	*Heat demand of controllable devices*	n	*Useful life of the components of the solar panel system*
H^{uc}	*Heat demand by uncontrollable devices*		

1. Introduction

TIn recent years, due to various reasons such as limited fossil fuel resources, increasing impacts of global warming, stochastic nature of renewable energy sources (RES) and political impacts of energy dependence, improving electricity efficiency methods has received great attention [1]. High-cost thermal power plants must be commissioned during peak daily and seasonal consumption; these peak loads may also necessitate the construction of new power plants and upgrading of equipment capacity [2]. To prevent the need for serious investment in the equipment construction and development, use of smart grids with consumer participation on the demand side has been proposed. Therefore, smart homes that can take the necessary measures to optimize their energy consumption and reduce their electricity bills are of particular importance [3]. One of the most important issues that has been considered by most industrialized and developing countries in recent decades is preventing energy waste in the residential and construction sectors. This issue has found more significance with the rising demands for oil reserves and oil-generated energy. The need for constructing new residential, administrative and educational buildings and the tendency to using new equipment have increased energy consumption in this sector. The global energy loss statistics shows that wasteful energy consumption is higher in residential and commercial buildings than in other sectors. At present, about 40% of the globally consumed energy belongs to the residential and commercial sectors [4]. Energy and electricity, more specifically, are the major factors affecting the economic growth of countries. Traditionally, adequate and safe provision for the supply of demands need the expansion of the power system's generation and transfer capacities [5]. Energy management has long been a basic sector of power systems. In recent years, energy management in microgrids has gained momentum. Industrial, commercial and residential consumers are connected to local energy carrier networks, e.g., electricity, natural gas, heating or cooling [6]. So far, various studies have been conducted on energy infrastructure, but the integration of these systems that confer significant advantages has been scarcely studied. One such advantage is the use of integrated and flexible features of such systems. For instance, natural gas networks can store energy simply and inexpensively. The electricity system can transfer energy to long distances with relatively low losses. Thus, the integration of these two networks and the use of the advantages of both will promote the system's efficiency, reliability and optimal performance [7]. This flexible structure and operation require a composition framework to explain the effects of integrating different energy carriers on economic and technical indicators of the energy systems. In recent years, the general characteristics of such frameworks have been proposed to enable the integration of different energy carriers, converting and storing them in order to supply the consumer-side demand. A key method to reduce the demand for electricity on the demand side is energy management plans for the residential sector. Energy management plans in the form of household energy hubs provide a novel approach. Using energy management programs, subscribers can control or change their energy consumption time and amount to reduce energy costs [8].

In [9], a two-level energy management strategy was proposed to optimize microgrid operating costs and uncertainty management. This method was examined by using different scenarios under a standard sample system. In [10], an independent hybrid microgrid system was introduced that included a combination of batteries and renewable sources such as wind, solar, FC and energy storage system (ESS). To maintain energy balance in the hybrid system, an energy management strategy based on battery state of charge (SOC) was developed and implemented experimentally. [11] studied the reconfiguration of a dynamic DN in the presence of DG and EVs with various objective functions including energy losses, cost of operations and energy. The time of use (TOU) of the mechanism was introduced as a demand response (DR) request to increase consumers' electricity consumption. To generalize the proposed approach, time-variable electricity price and different load levels were considered to satisfy the precise scheduling of DG and EVs in the real space of the electricity grid.

In [12], economic programming of generation in multiple MGs in smart grids was presented by considering different types of DG, environmental pollution and energy price. This study was based on economic power flow and did not examine the structure of the grid and the losses. [13]presented a hybrid structure of market operator and distribution network operator in grids involving multiple MGs, in which different objectives were included for the grid players. [14] proposed a novel demand-side management method for programming the operation of home appliances to minimize energy supply costs by considering time-variable energy prices. Due to the uncertainty in predicting the performance of home appliances and solar RES generation, stochastic programming was conducted by considering the energy adjustment variable β to model the uncertainty in time and appliance energy consumption. [15] dealt with the performance of a smart house in the presence of EVs, solar panels and time-shiftable loads.[16] formulated DR optimization as a linear optimization problem to minimize the household bills and the waiting time of appliances. Linear programming was conducted to optimize the objective function and find the optimal consumption of different appliances at different times. A combination of RTP and IBR programs was adopted as the DR program. [17] determined the optimal charge/discharge pattern and BESS capacity in smart house energy management with a solar system by using a metaheuristic optimization algorithm and stochastic mixed-integer nonlinear programming (MINLP) and by taking into account uncertainty in solar-generated power prediction. In [18], the neural network algorithm was used to manage the energy of a smart house including solar system and ESS; however, the impact of price variations and DR strategies was not evaluated. In [19], the peak of a smart household energy management strategy was presented to minimize energy consumption costs based on energy price variations and constraints such as user comfort requirements with the ability to optimize a compromise between user comfort and energy consumption costs. [20] presented an MILP to examine the impact of energy prices and DR strategies in a smart home with a solar power generation system, EVs and energy storage system, but did not take into account the uncertainty of solar power prediction. In [21], the studied energy hub (2012) included a solar panel, battery and hybrid EVs. This study showed that implementing an energy management plan on a residential energy hub in Ontario, Canada, would result in a 20% reduction in overall energy costs and 50% reduction in peak load costs.

In [22] presented a predictive energy management strategy for smart community, which features water-based district cooling for a cluster of buildings driven by a multi-chiller central plant, and each building hosts a number of EV charging stations. In [23] investigated optimal sizing and realtime control of electrical and thermal distributed energy resources (DERs) in smart buildings. Initially, comprehensive system architecture is presented considering both electrical and thermal DERs. In [24], for optimal power dispatch of a grid-connected micro-grid, a new stochastic model has been built up to minimize the operating cost of micro-grid that equipped with plug-in hybrid electric vehicles, renewable energy sources, and storage devices. Impact of electric vehicles on power dispatch is studied by considering its uncertainty charging characteristics. Monte–Carlo simulation is employed for uncertainty modeling. In [25] deployed harmonized natural gas and fuel cell CHP technologies alongside RES and battery energy storage systems (BESS) to facilitate EVs' G2V and vehicle-to-grid (V2G) operations. While the BESS supports V2G operations and stores excess power from the CHP and RES, the CHP's by-product heat could be employed in heating homes and industrial facilities. In [26] proposed a smart decision-making algorithm to be utilized in electric vehicle stations. The suggested approach emphasizes the prediction of queuing delay seeking for minimum total charging time. For this purpose, artificial neural network (ANN) model is used, where a dataset is pre-generated to be seeded into the model. In [27]combined a reinforcement learning machine and a myopic optimization model to improve the real-time energy decisions in microgrids with renewable sources and energy storage devices. The reinforcement learning-based agent is built as an actor-critic agent making the aggregated near-optimal charging/discharging energy decisions of the microgrid energy storage devices from a discrete action space relying on a reward related to the microgrid online optimal objective function value.

In this paper, a novel method is proposed for optimal energy management of a household energy hub to optimize the capacity of the photovoltaic system along with the optimal operation of the hub. The household energy hub studied in this paper involves a micro-CHP, hybrid EVs with V2G ability, electric power storage unit (battery), heat storage unit, electric appliances, heating loads and solar panel as a renewable energy source.

In the proposed optimization problem that simultaneously determines the optimal operation of the hub and the optimal capacity of solar panels, the optimization variable related to the capacity of solar panels is added to the variables of scheduling the controllable components of the energy hub, gas distribution factor, etc. By implementing the proposed method, it will be possible to increase the capacity of the solar panel to the extent that the benefits of increasing the capacity become less than the costs imposed on the energy system.

2. Structure of the studied household energy hub

The energy hub consists of several inputs and several outputs, and energy is converted into different forms to reach the system loads. The structure of the household energy hub considered in this paper is displayed in Fig (1).

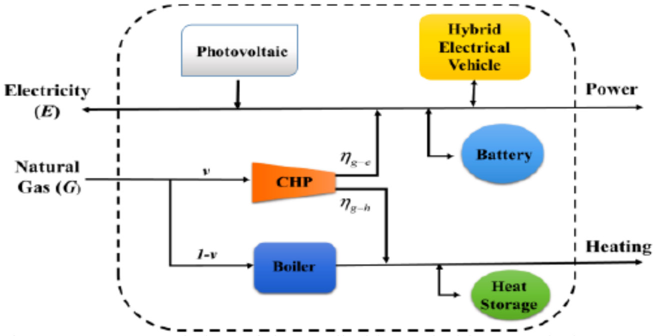


Fig. 1. A conceptual view of the studied household energy hub

The energy hub studied includes a grid-connected hybrid EV, a solar renewable energy generation unit, a micro-CHP, heating loads, boilers and storage units. The inputs to the power hub are electricity and natural gas. Since natural gas is consumed by the boiler and micro-CHP, a variable called the distribution factor v is defined.

A part of the gas entering the energy hub is consumed by CHP (v) and another part by the boiler (v-1). The distribution factor has a value between 0 and 1, and its value per hour is determined by the optimization problem.

The heat required by the hub is supplied by gas appliances, micro-CHP output heat and heat storage. The electrical power required by the energy hub is supplied by the power grid, the electrical output of the micro-CHP, EV battery, heat storage unit and solar panel output power. The energy hub can sell electricity to the grid during the day and night, when the selling price of electricity to the grid is the same as the purchase price of electricity from the grid at any hour.

The hybrid EV acts like an energy storage unit during hours when it is present at home. The hybrid EV and the electric power storage unit consume electricity at some hours and inject electricity into the system at other hours. As a result, the presence of these storage devices along with solar panels improves performance, productivity, efficiency and reliability of the use of solar panels.

3. Energy hub energy management optimization problem

Cooperation and participation of subscribers in energy management are critical. The comfort and welfare of residents and consumers of electricity at home is a prerequisite for optimal energy management. Considerations for the comfort and welfare of the residents of a household energy hub should be included in the optimization problem constraints. Based on the constraints corresponding to the comfort of the residents, the possible space for solving the optimization problem is determined. The level of customer satisfaction and comfort indicators will have a significant effect on specifying the possible space for problem-solving and optimal final solutions. Finding the minimum operating cost of a household energy hub as the objective function is the goal of this paper. In this paper, the cost of the studied system will be minimized by presenting the optimal scheduling program for different uses, suitable gas distribution factor, charging and discharging scheduling of hybrid EVs and heat and electric power storage units as independent variables of the problem.

In (1), the objective function used to manage the energy of the household energy hub is given like the objective function presented. The objective function proposed in this paper includes the cost of the energy hub, including the cost of purchasing electricity from the grid and the gas input to the hub. System energy management will be optimized for one day (24 hours) in different seasons. In this paper, minimizing the cost of different energy carriers for subscribers along with the daily cost of small-scale household solar generators is proposed as an objective function. The proposed objective function for simultaneous optimization of operation and determination of solar power plant capacity is expressed as (1). Moreover, in Fig (2), the procedure for implementing the proposed method is displayed.

$$Min\ C = C_{Elec} + C_{Gas} + C_{PV} \tag{1}$$

where C_{Elec} is the net electric power cost entering the energy hub, C_{Gas} is the cost of purchasing natural gas from the grid and C_{PV} is the daily cost of the solar panel.

Costs related to electric power and natural gas received from the grid are calculated as:

$$C_{Elec} = \sum_{t=1}^{24} \lambda_e(t)\, E_{grid}(t) \tag{2}$$

$$C_{Gas} = \sum_{t=1}^{24} \lambda_g(t)\, G(t) \tag{3}$$

where λ_e and λ_g respectively show the electricity and natural gas tariff per hour, $E_{grid}(t)$ is the electric power received from the grid and $G(t)$ is the natural gas received from the grid per hour.

3.1.Daily cost of the solar panel system

The cost of the solar panel system involves the cost of the module, inverter, balance system, repair and maintenance Eq (4).

$$C_{PV} = C_{Module} + C_{inv} + C_{BoS} + C_{O\&M} \tag{4}$$

Each of these components has a useful life presented by the manufacturer. By using the CRF in Equation 5, the annual cost of each component can be obtained (2019). Note that maintenance and repair costs are given per annum.

$$CRF_n = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{5}$$

where r is the annual discount rate and n is the lifetime or time of changing the part. Assuming a constant discount rate over a year, the daily costs can be obtained by dividing the annual costs by the number of days of a year; therefore, the daily cost of the solar panel system is obtained as (2019):

$$C_{PV} = \frac{\begin{bmatrix} CRF_n \times C_{Module} + CRF_n \times C_{inv} \\ +CRF_n \times C_{BoS} + C_{O\&M} \end{bmatrix}}{365} \tag{6}$$

3.2. Optimization constraints

The optimization constraints belong to the electric power, heat and household appliances equations in the energy hub. The optimization is performed in the intended user range by using these constraints. These constraints are defined as follows:

3-2-1- Electric power and heat equations

Based on Figure (1), there must always be a balance between the input and output energy of a household energy hub (7 and 8):

$$\begin{aligned} E_{grid}(t) + \eta_{inverter} E_{PV}(t) + E_{chp}(t) + \eta_{dch}^{PHEV} E_{dch}^{PHEV}(t) \\ + \eta_{dch}^{BSS} E_{dch}^{BSS}(t) \end{aligned}$$

$$= \frac{1}{\eta_{app}}(t) + \frac{1}{\eta_{ch}^{PHEV}} E_{ch}^{PHEV}(t) + \frac{1}{\eta_{ch}^{BSS}}(t) H_{app}(t) \tag{7}$$

$$+H_{chp}(t) + \eta_{dch}^{HS} H_{dch}^{HS}$$

$$= \mathrm{H_d(t)} + \frac{1}{\eta_{\mathrm{ch}}^{\mathrm{HS}}} \mathrm{H_{ch}^{HS}(t)} \tag{8}$$

3-2-2- Household appliances

A large part of the electrical energy consumed in houses belongs to electric appliances; therefore, planning for the management of their consumption is essential for reducing costs.

Electric appliances can be divided into two of controllable and uncontrollable groups. The first group includes uncontrollable devices such as lighting, television, laptops, etc. Users decide to use these devices regardless of the price and demand for electricity per hour. The second group includes controllable devices, the time and level of use of which in different hours can be controlled by the user. Loads such as the washing machine, dishwasher, dryer, electric water heater, air conditioner, etc. belong to this group.

It is assumed that the electricity and heat demand of uncontrollable devices are specified and defined in the optimization problem. To promote the users' comfort, these devices are chosen by them. For instance, users decide that lighting, television, refrigerator, etc. are uncontrollable. Herein, water heater, washing machine and air conditioner are regarded as controllable electric devices.

Accordingly, the total demand for electric devices in the energy hub is equal to the sum of power required by the controllable and uncontrollable devices per hour:

$$E_{app}(t) = E^{c}(t) + E^{uc}(t) \tag{9}$$

The constraints for controllable devices can be divided into two groups. The first group involves devices such as air conditioner that may be used continuously throughout the day. Constants for these devices are given in (10-12). The second group involves controllable devices such as a washing machine that may be used for a limited time per day. Therefore, the user can determine a time interval during the day $[t_1, t_2]$ and maximum time required to complete the process Δt for these controllable devices.

$$E_k^{min}(t) \leq E_k(t) \leq E_k^{max}(t) \quad \forall k \in K, \forall t \in AI_k \tag{10}$$

$$\sum_{t \in AI_k} E_{k(t)} \geq E_k \qquad \forall k \in K \tag{11}$$

$$E^{c}(t) = \sum_{k \in K} E_k(t) \qquad \forall t \tag{12}$$

(10) shows the minimum and maximum permissible power consumed by each controllable device. These values are obtained based on statistical data for each device. Beside a minimum and a maximum for each controllable device, to promote users' comfort and welfare, the sum of power consumed by controllable devices should be above a certain level (Equation 11). At any hour, the total energy consumed by controllable devices is $E^{c}(t)$ (Energy 12).

3-3-3 EV

In the present study, the EV model is assumed to be similar to the battery model. The mathematical modeling of EV resembles that of the ESS system, with the difference that EVs are in the parking lot at certain and limited times, while the BESS constantly participates in the HEM program. The constraints on EV modeling are described below.

$$P_{ts}^{EV,ch} \leq CR^{EV} u_t^{EV} Z_t^{EV} \quad \forall t,s \tag{13}$$

$$P_{ts}^{EV,dis} \leq DR^{EV} \left(1 - u_t^{EV}\right) Z_t^{EV} \quad \forall t,s \tag{14}$$

$$\mathrm{SOE}_{ts}^{EV} = SOE_{t-1s}^{EV} + CE^{EV} \frac{P_{ts}^{EV,ch}}{\Delta T} - \frac{P_{ts}^{EV,dis}}{\Delta T} \quad \forall t \neq t_{ent}, s \tag{15}$$

$$\mathrm{SOE}_{t_{ent}s}^{EV} = SOE^{EV,ini} \quad \forall s \tag{16}$$

$$\mathrm{Z}_t^{EV} SOE^{EV,ini} \leq SOE_{ts}^{EV} \leq Z_t^{EV,\max} \quad \forall t,s \tag{17}$$

$$\mathrm{SOE}_{t_{dep}s}^{EV} \geq MSOE^{EV,\max} \tag{18}$$

In Equations 13 and 14, the EV battery charge and discharge power is constrained at hours when the EV is in the parking lot. Equation 15 calculates the EV battery's charge level at hours when the EV is in the parking lot. Based on Equation 16, when the EV enters the parking lot, it has a certain level of energy. Constraint 17 specifies the minimum and maximum permissible levels of EV energy. Constraint 18 allows the homeowner to determine an optional EV charge level when exiting the house.

3-2-4- Heat storage unit

Heat storage units such as water tanks and heat storage units can be used to reduce energy consumption and management energy in smart energy systems. These units greatly reduce costs and increase energy efficiency. At the end of each hour, the energy stored in the heat storage unit is obtained from (19). Like EVs, at any hour, the charge and discharge levels of the heat storage unit must be less than or equal to a defined limit (Equations 20 and 21). It is assumed that at the end of each day (24:00), the charge level of the heat storage unit is equal to or greater than a defined value. This constraint is given in (22).

$$H^{HSS}(t) = H_0^{HSS} + \sum_{h=1}^{t} H_{ch}^{HSS}(h) - H_{dch}^{HSS}(h) \tag{19}$$

$$H_{ch}^{HSS}(t) \leq H_{ch}^{max} \tag{20}$$

$$H_{dch}^{HSS}(t) \leq H_{dch}^{max} \tag{21}$$

$$H^{HSS}(24) \geq H_0^{s} \tag{22}$$

The charge level of the heat storage unit per hour is obtained from (23). The charge level of the heat storage unit per hour should fall within the two defined values (2020). This constraint is given in (24).

$$SOC^{HSS}(t) = \frac{H_{HSS}(t)}{Cap^{HSS}} \tag{23}$$

$$SOC_{min}^{HSS} \leq SOC^{HSS}(t) \leq SOC_{max}^{HSS} \tag{24}$$

3-2-5- micro-CHP unit

CHP units in energy hubs confer numerous advantages such as increasing the system reliability and efficiency, reducing energy consumption costs and the environmental pollution. The main constraint for micro-CHP units is the level of gas input to them which is limited to E_{max}^{CHP} based on (25).

$$v(t)G(t) \leq E_{max}^{CHP} \tag{25}$$

3-2-6- Solar panel

The sun, as an unlimited source of energy, can solve many energy-related and environmental problems. This energy that radiates to the Earth is thousands of times greater than our needs and consumption. In PV, radiation energy is converted into electrical energy without using mechanical mechanisms. PV systems comprise three general parts of solar panels, converters and batteries that convert solar energy into electricity without any pollution. PV cells or panels convert solar energy into electricity. The following equation estimates the maximum power that can be generated by PV systems at different radiations and temperatures. The output power depends on the solar irradiation intensity and temperature.

$$\mathrm{P_t^{PV}} = \mathrm{G_t}.\mathrm{A_{PV}}.\mathrm{N_{PV}}.\eta_{\mathrm{PV}} \tag{26}$$

Here, Gt, Apv and Npv are respectively solar irradiation intensity at time t, the area of the cell and the number of solar cells. The efficiency of the solar cells is calculated from the following equation and is a function of solar irradiation intensity and ambient temperature:

$$\eta_{\mathrm{PV}} = \eta_{\mathrm{PV,ref}} \left\lfloor 1 - \mathrm{a}(\mathrm{T_t} + \mathrm{G_t} \times \frac{\mathrm{NOCT} - 20}{800} - \mathrm{T_{ref}}) \right\rfloor \tag{27}$$

Here, $\eta_{\mathrm{PV,ref}}$ is the cell's efficiency in standard conditions, Tref is the standard temperature, a is the temperature coefficient, NOCT is the cell's temperature in nominal operation and Tt is the ambient temperature.

3-2-7- Inverter

Inverters convert the DC output power of the solar panel into the AC power consumable by household loads. DC to AC conversion does not have 100% efficiency and has some losses; in this case, efficiency of η_{Inverter} is determined for each inverter. To convert a certain amount of power into AC, a larger amount of DC power is required. Thus, for an efficient and reliable solar panel operation, the capacity of the inverter must be 10% more than the maximum power of the modules. (28) shows the effective capacity of the inverter per number of modules.

$$\mathrm{Inv_{size}} = 1.1 \times \mathrm{E_{PV}^{max}} \times \mathrm{N_{PV}} \tag{28}$$

3-2-8 Electric power storage unit

Although RES have considerable advantages, they have an unpredictable nature and their output power is uncertain depending on the climatic condition. Thus, to promote their efficiency, their produced energy must be stored when surplus energy is generated or depending on the electrical energy price. An ESS or battery has technical constraints. The level of energy stored in it and its charge and discharge power are related and constrained as follows:

$$P_{ts}^{ESS,ch} \le CR^{ESS} \mu_t^{ESS} \quad \forall \mathrm{t,s} \tag{29}$$

$$P_{ts}^{ESS,dis} \le DR^{ESS} \left(1 - \mu_t^{ESS}\right) \quad \forall \mathrm{t,s} \tag{30}$$

$$\mathrm{SOE}_{ts}^{ESS} = \mathrm{SOE}_{t-1s}^{ESS} + \mathrm{CE}^{ESS} \frac{P_{ts}^{ESS,ch}}{\Delta T} - \frac{P_{ts}^{ESS,dis}}{\Delta T} \quad \forall \mathrm{t} \ge 1,\mathrm{s} \tag{31}$$

$$\mathrm{SOE}_{1s}^{ESS} = \mathrm{SOE}^{ESS,ini} \quad \forall \mathrm{s} \tag{32}$$

$$\mathrm{SOE}^{ESS,\min} \le \mathrm{SOE}_{ts}^{ESS} \le \mathrm{SOE}^{ESS,\max} \quad \forall t,\mathrm{s} \tag{33}$$

(29) and (30) constrain the battery charge and discharge power. At any time, the battery can have a state of charge or discharge, which is specified by the binary variable μ_t^{ESS}. Equations (31) to (32) are the constraints at the level of energy stored in the battery. Based on (31), the energy level of the battery in each interval is equal to the amount of energy stored in the previous interval plus the energy inputted to it through charging or the energy exiting it through discharging. (32) shows the initial energy level of the ESS at the beginning of the programming period. Based on (33), the level of energy stored in the battery at any time of the programming period must be constrained to the minimum and maximum values of battery capacity.

3-2-9- Optimization algorithm

Large optimization problems can be divided into several local optimization problems for different systems. The general formula of the Ith unit in the multiple problem can be defined as (1):

$$\begin{aligned} &\min_{x_l, y_l} \ \mathrm{M}_l^T X_l + N_l^T Y_l \\ &s.t. \ \mathrm{A}_l X_l + B_l Y_l \le K_l \end{aligned} \tag{34}$$

where X_l and Y_l are the decision-making vectors of the l th unit, M_l and N_l the objective function vectors of the l th unit and A_l, B_l and K_l are the vectors of coefficients related to the constraints [28].

Herein, an algorithm based on the one introduced in [29] and the concept of progressive hedging (PH) [30] is proposed. The PH algorithm is a scenario-based analysis method for solving mixed-integer programs. This algorithm has mostly been used for stochastic optimization problems, but there are various reasons for applying it to deterministic optimization problems as well. One such reason is its use in problems with high computational volume and arriving at an acceptable solution. Another reason is that, in this algorithm, the weights in the objective function can be easily changed without altering its structure. The third reason is that, in this algorithm, parallel computations can be carried out simultaneously to solve multiple separate problems, which increases computational speed [31].

4. Results of implementing the proposed method

In this section, the energy management plan of the household energy hub is implemented on an independent house. Here, to evaluate the effectiveness of the proposed scheme, three case studies are reviewed.

In Case Study 1, the energy management plan of a household energy hub is implemented without considering the solar panel or battery. The value of the natural gas distribution factor per hour, charging and discharging planning of hybrid EVs and planning the use of controllable electrical devices will be determined.

In Case Study 2, the solar panel is added to the household energy hub. This section examines the impact of adding solar panels to the household energy hub and optimizing the capacity of solar panels with respect to fixed costs, variable costs and electricity tariffs, resulting in the optimal planning of time and charge and discharge rates of this unit to reduce the energy costs of the energy hub.

The examined house has a micro-CHP unit, a hybrid EV, a solar panel and three controllable electric appliances and other appliances consuming electricity and gas. The controllable appliances include an electric water heater, washing machine and air conditioner. For the washing machine, it is assumed that the subscriber needs 1 hour to use the device between 12 and 19 pm. Also, the power consumption of controllable electrical devices per hour is defined within a certain range (information given in Tables (1) and (2)). It is assumed that the total electricity consumption of electric water heater and air conditioner in the entire day is respectively more than 7.5 and 5.6 KWh. Specifications of the micro-CHP, heat storage unit and EV, assuming this EV is out of the house only once a day from 8 to 17 o'clock, are presented in Table (3).

Given that the energy management plan proposed in this article will be implemented for the day ahead, it is assumed that at the end of each day, the charge level of storage units is more than a certain level. In many studies on energy management, the SOC of the storage unit at the end of each day has a specified and defined value. However, the cost of operating the energy hub is not the same for different values of the SOC at the end of each day. The demand for power of uncontrolled electrical appliances, the demand for heating energy required by the energy hub, electricity and natural gas tariff are given in Figure (2) on an hourly basis.

Table 1. Permissible range for electric water heater power consumption.

hour	Minimum allowable power (kW)	Maximum allowable power (kW)
5-1and24	0	0/25
23-6	0/25	0/5

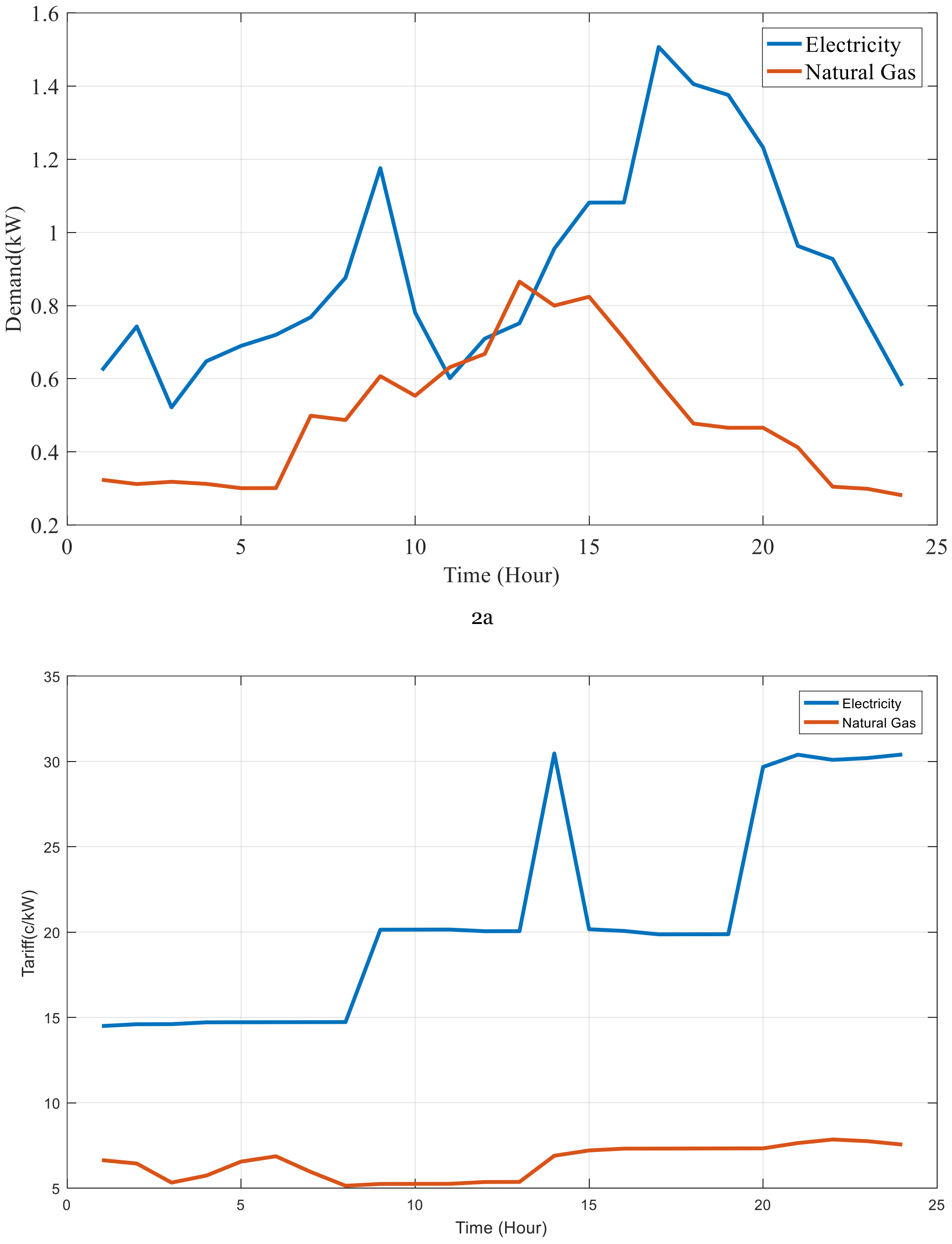
Table 2. Permissible range for air conditioner power consumption

hour	Minimum allowable power (kW)	Maximum allowable power (kW)
17-8	0/1	0/2
5-1and20-18	0/2	0/3
7-6and24-21	0/3	0/4

Table 3. CHP unit and EV specifications

Parameter	Value	Unit
EV battery capacity	10	KWh
EV charge/discharge efficiency	95	%
Maximum EV charge/discharge efficiency	3/3	kW
Initial charge of the EV battery	5	KWh
Micro-CHP efficiency in gas to electricity conversion	0/35	Percentage
Micro-CHP efficiency in gas to heat conversion	0/4	%
Maximum micro-CHP generation power	1	kW
ESS capacity	3	KWh
Heat storage unit charge/discharge efficiency	95	%
Heat storage unit maximum charge/discharge rate	3	kW
Initial charge level of the heat storage unit	1/5	KWh

explained, in this case, the studied household energy hub is considered without a solar panel system or battery. By solving the optimization problem and extracting the optimal operation strategy, the amount of electricity and natural gas received from the grid is shown in Figure (3).



2a

2b

Fig. 2. (A) Demand for uncontrollable electrical and heating appliances; and (b) Tariff for purchasing electricity and natural gas from the grid.

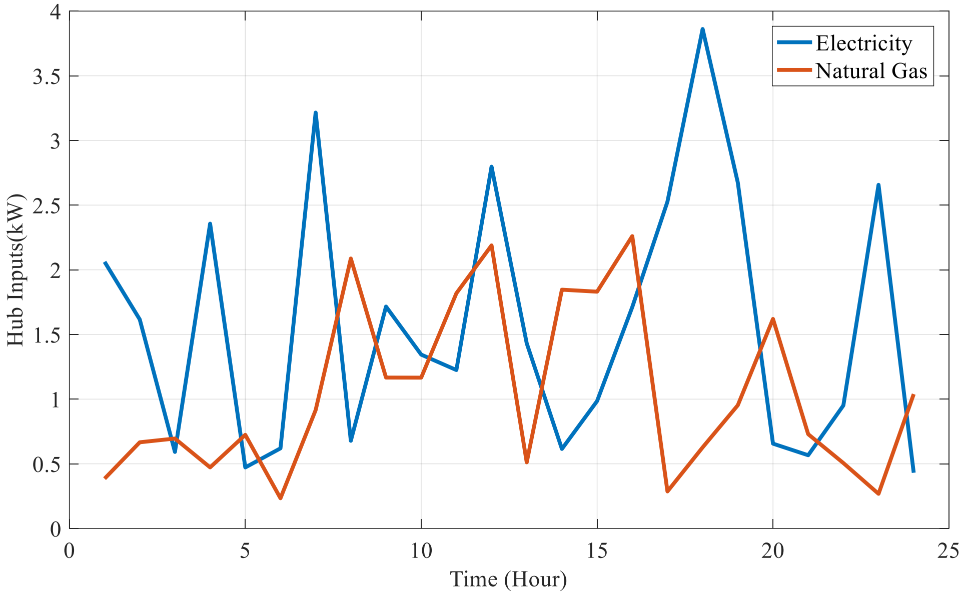


Fig. 3. (A) Electric power and natural gas received from the grid in case study 1

In addition, by solving the proposed optimization problem in the household energy hub in case study 1 based on the operation optimization view, the optimal charging and discharging scheduling of the hybrid EV battery and heat storage unit is obtained as shown in Figure (4).

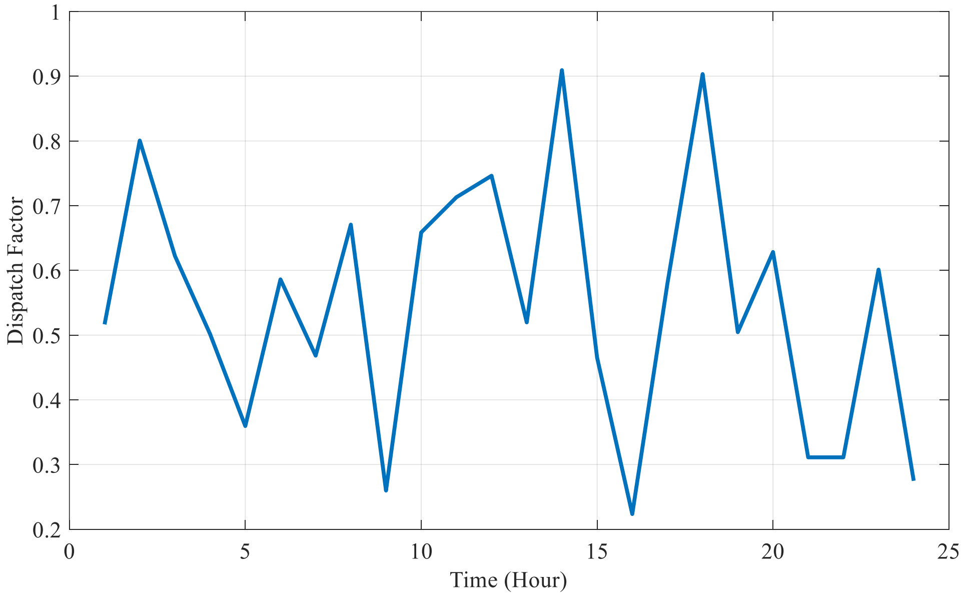
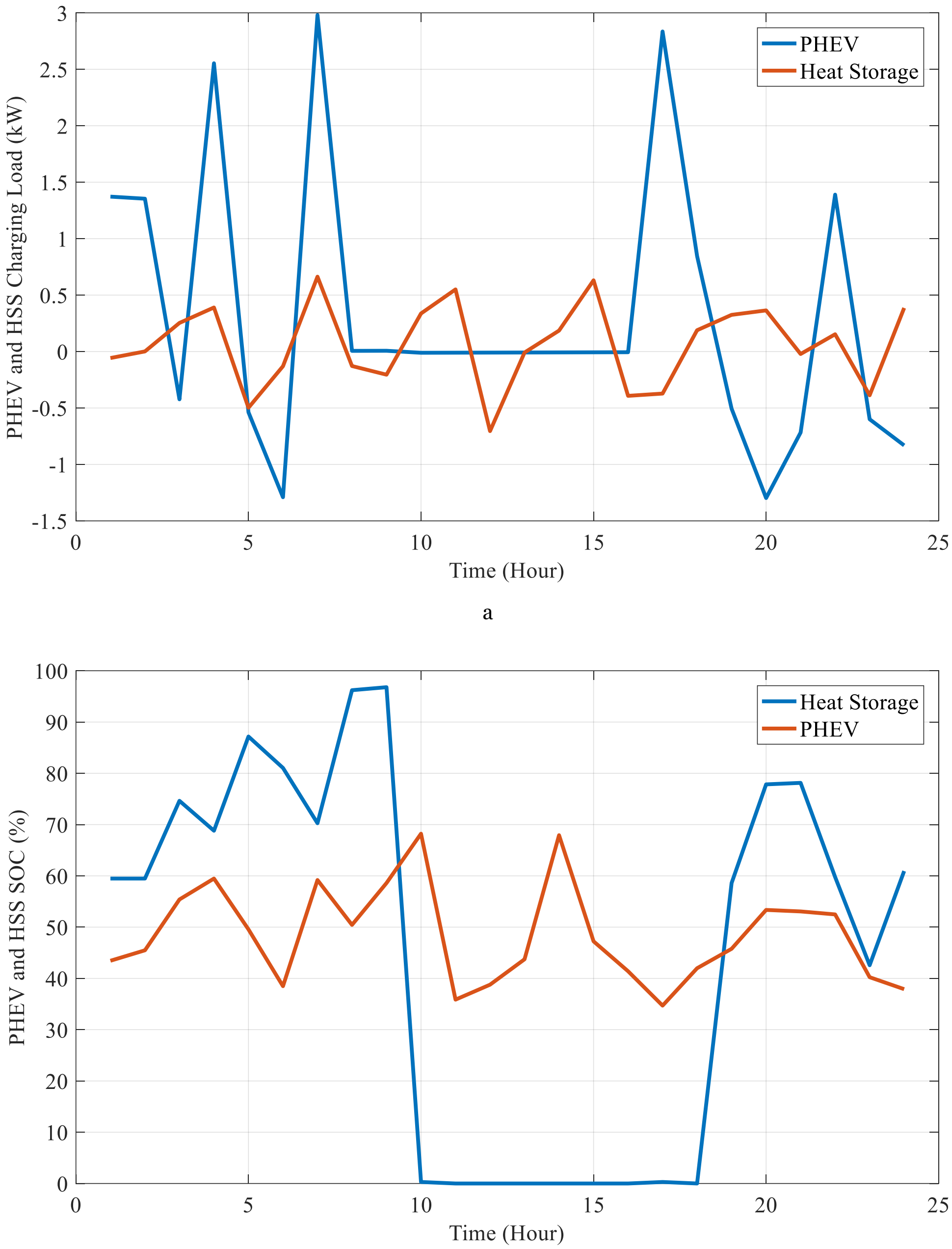


Fig. 4. Hourly value of natural gas distribution factor

In all the seasons, the charging and discharging rates of EV batteries per hour are constrained between 3.3 and 3.3. It is also assumed that the EV is not at home every day at certain hours from 9 to 17:00, so there is practically no charging or discharging during these hours of the day.

The EV battery is usually charged in the hours before departure to reach the maximum capacity of the battery. Furthermore, the EV at the time of leaving the house is assumed to be a fixed value and consumes 5.63 KWh of energy



a

b

Fig. 5. Results of optimal operation of EV battery and heat storage in case study 1: (A) Optimal charging and discharging of hybrid EV and heat storage unit, and (b) Charging level of hybrid EV and heat storage unit

As shown in Figure (5), to maintain the user's comfort, the EV battery charge level is 100% when leaving the house; for this purpose, the battery is charged before leaving the house and during the hours when the electricity tariff is low. Upon entering the house, the EV is charged at 18 and 19:00 when the electricity tariff is lower and is discharged at 0 to 22:00. Also, the charge and discharge rate of the heat storage unit is always between 3 and -3. The charge level of the EV and the heat storage unit at 24:00 every day is half of its nominal capacity (50%).

Figure (6) depicts the optimal scheduling of electric power demand of electric water heater, washing machine and air conditioner as three controllable electrical devices in this paper. By controlling the amount and time of use of these devices and transferring them to non-peak hours and hours when electricity tariffs are low, the energy consumption costs of the energy hub can be reduced by about 15%.

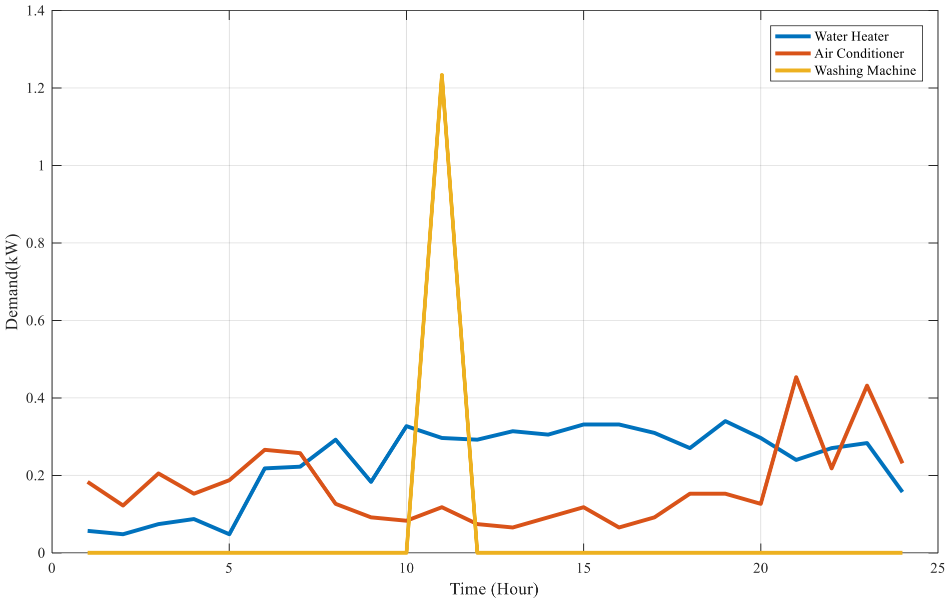
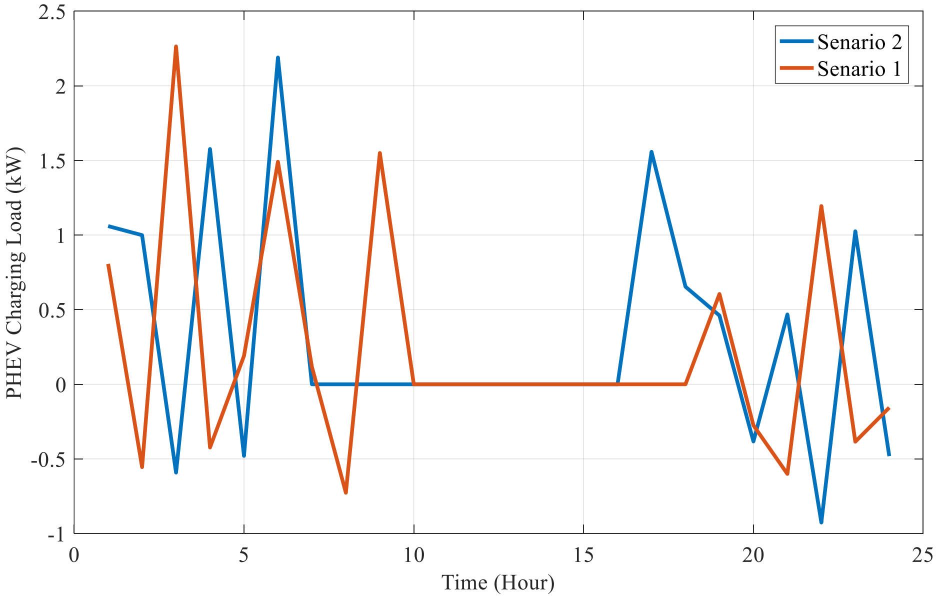


Fig. 6. Electric power consumption of electric water heater and air conditioner in case study 1

EVs and their effects on energy management plans and household energy hubs are among the challenges facing the system operator; this issue will be doubly important in the coming years. In the proposed scheme of the household energy hub management, it is assumed that the EV is not home only once during the day and at certain times [g – c], and its battery is not charged or discharged during these hours. To examine the impact of the EV time of departure and arrival on the optimization problem, in Case Study 1, two scenarios are included based on EV arrival and departure times. In the first scenario, based on the energy hub information, the EV is not present in the house in the period of 8 to 17:00; in the second scenario, the EV is not in the house from 10 to 17:00 when there is no charging or discharging.



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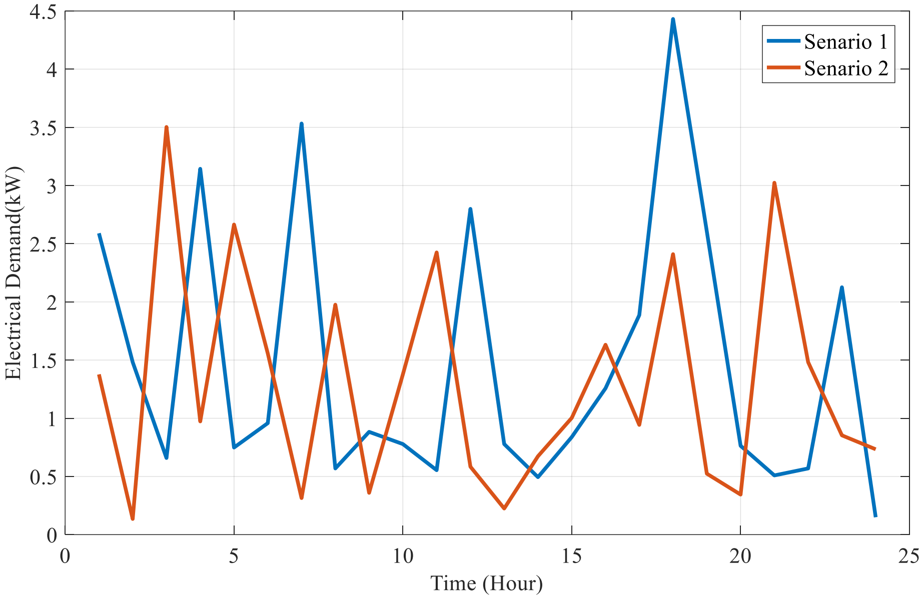

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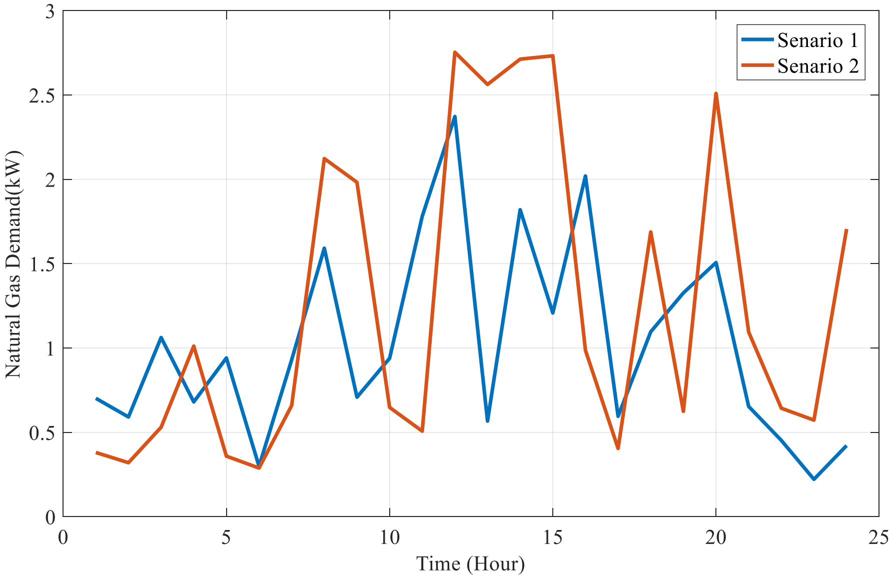


c

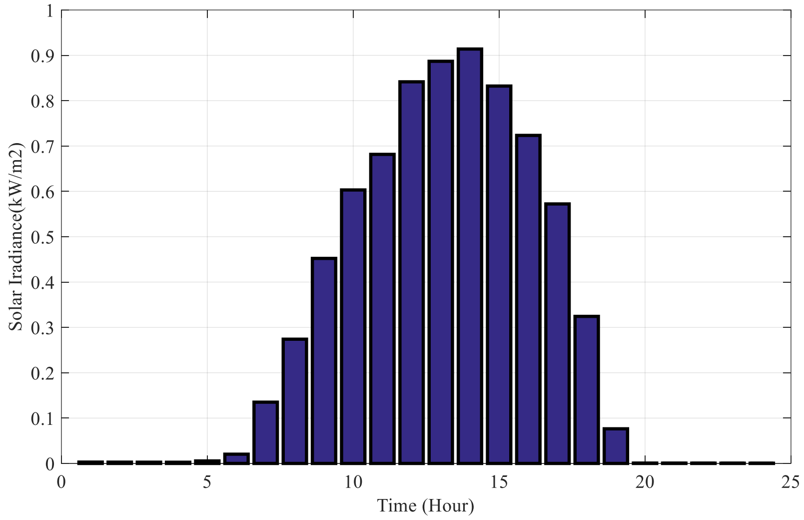
Fig. 7. Results of comparing different scenarios of EV arrival and departure times in case study 1: (A) optimal charging and discharging of hybrid EV and heat storage unit, (b) electrical power input of the energy hub and (c) amount of gas consumed by the energy hub

The results show that by changing the departure and arrival time of the EV, the optimal scheduling of the components of the energy hub changes. In the second scenario, due to the increase in the time of presence of the EV at home, the maneuverability of charging and discharging the EV battery is increased and the EV can have better performance in reducing the operating costs of the energy hub.

2-4- Results of Case Study 2

In Case Study 2, a solar panel is added to the household energy hub. The problem inputs for optimizing the capacity of the solar panel system are presented in Table (4). The average amount of solar irradiation and ambient temperature are also given in Figure (8).

It is assumed that the selling price of electricity to the grid is equal to 0.27 of the electricity purchase price from the grid. Based on solving the proposed optimization problem, the number of modules is 15 and the optimal capacity of the solar panel system is 2 kW. By adding the solar panel to the optimization problem, the amount of electric power and natural gas received from the grid in the second case study is given in Figure (9).



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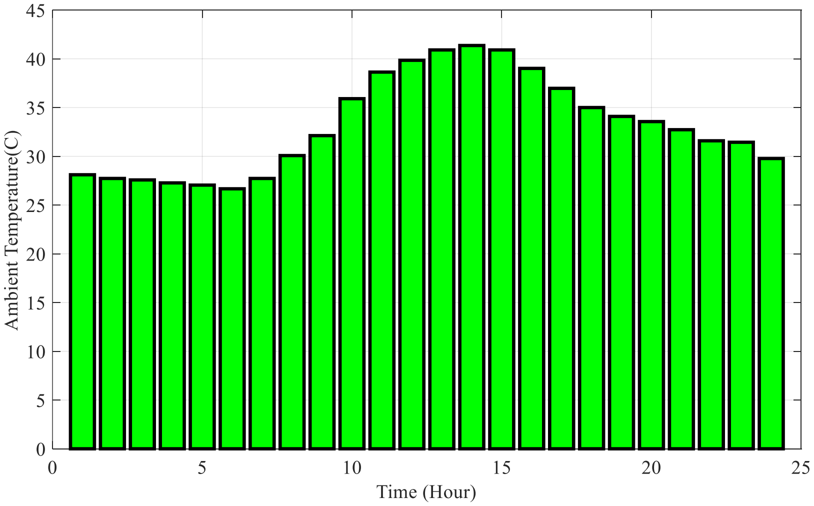


b

Fig. 8. Average solar irradiation and ambient temperature

Table 4. Input data for solar panel system design

Parameter	Value	Unit
Space required for installing each module	1	m²
Effective roof area for installation	50	m²
Module efficiency	16	%
Module price	286/4	$
Module life	25	Year
Inverter cost per kW	310	$
Inverter life	10	Year
Inverter efficiency	90	%
Balance system cost	20	% From total
Cost of operation, repair, and maintenance	10	% From total

System efficiency	98	%
Module temperature correction coefficient	0/4	% 1/°C
Module operational nominal temperature	47	°C
Standard temperature	27	°C
Modulus efficiency reduction linear coefficient	0/75	%
Discount rate	3/2	%

In Figure (9), hours when the electrical power is negative show the sale of electricity to the grid. As shown in the figure, the power received from the grid is zero from 9 to 16:00, and some electrical power is also injected into the grid. Evidently, the use of solar panels has led to a reduction in operating costs and caused daily savings for subscribers.

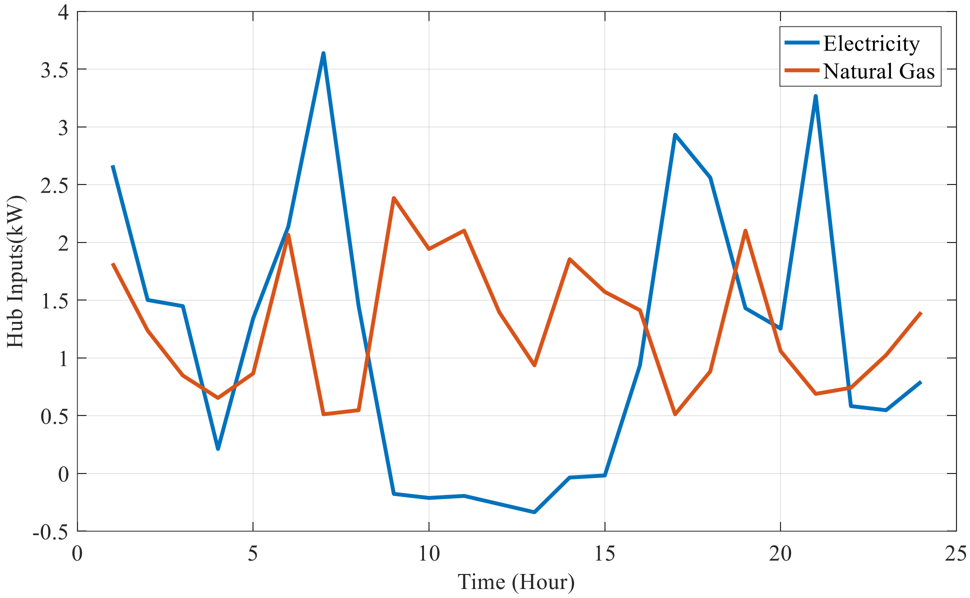
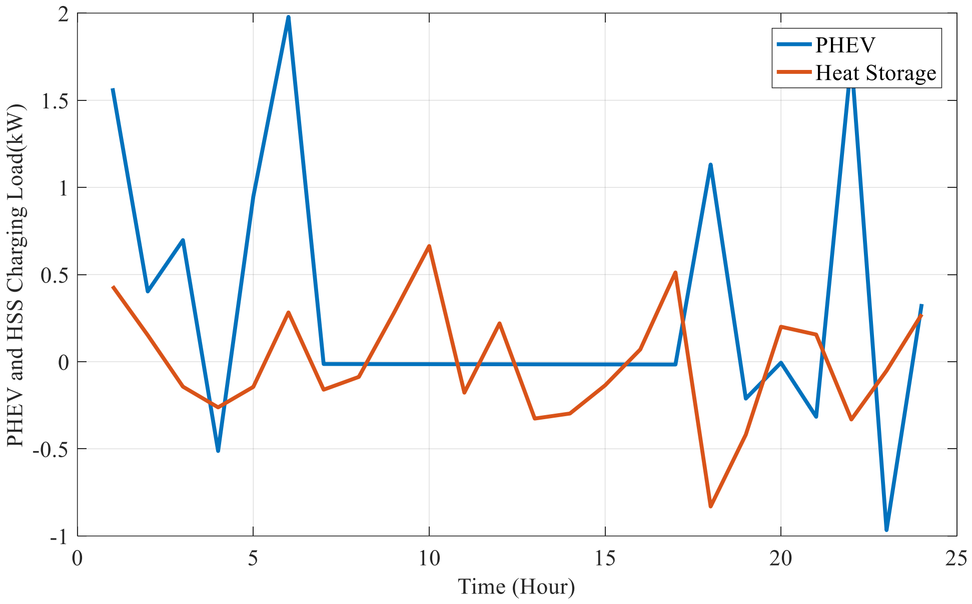


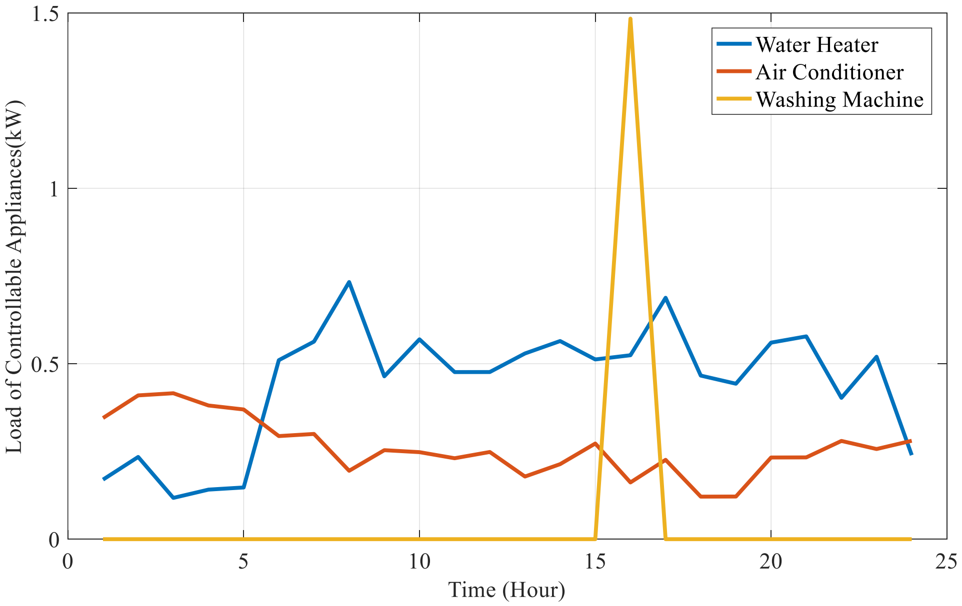
Fig. 9. Electric power and natural gas received from the grid in case study 2

Figure (10) displays the heat storage unit and EV charge/discharge programming, operation of controllable devices and distribution factor values in Case Study 2.

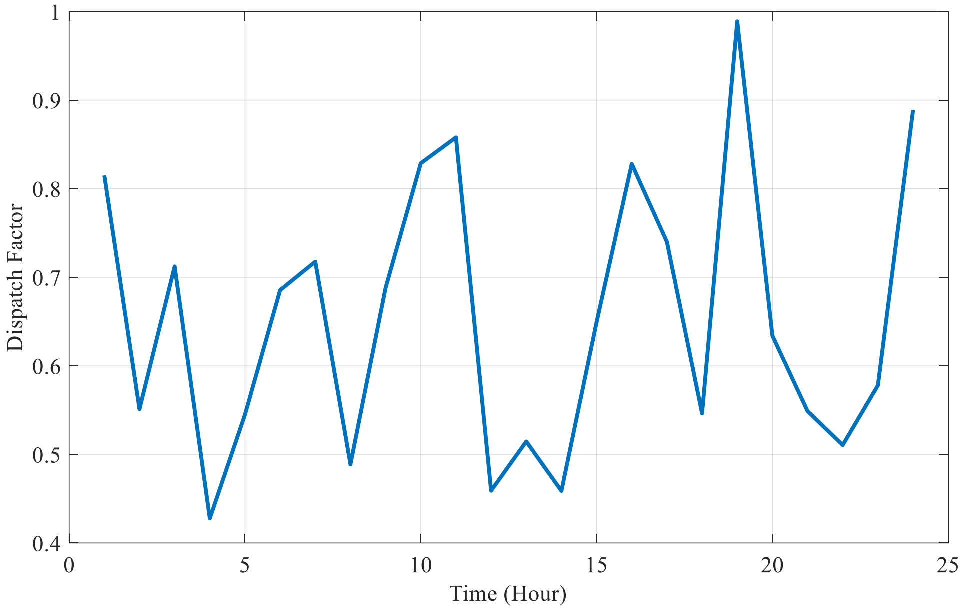
Parameters such as the selling price of electricity to the grid and discount rate can have a great impact on the optimization problem and the optimal capacity of the solar system. For example, in case study 2, if the selling price of electricity to the grid is equal to or greater than the purchase price of electricity from the grid, the optimal number of modules is 50, which is the maximum amount based on area constraints.


PHEV and HSS Charging Load(kW)
2
1.5
1
0.5
0
-0.5
-1
0
5
10
15
20
25
Time (Hour)
PHEV
Heat Storage

a


Load of Controllable Appliances(kW)
1.5
1
0.5
0
0
5
10
15
20
25
Time (Hour)
Water Heater
Air Conditioner
Washing Machine

b



c

Fig. 10. Optimal household energy hub scheduling in case study 2: (A) heat storage unit and EV charging and discharging program, (B) electric power consumption of electric water heater, air conditioner, and washing machine and (C) gas distribution factor

Figure (11) displays the electrical power received from the grid in two modes of buying and selling electricity from/to the grid with the same or different tariffs

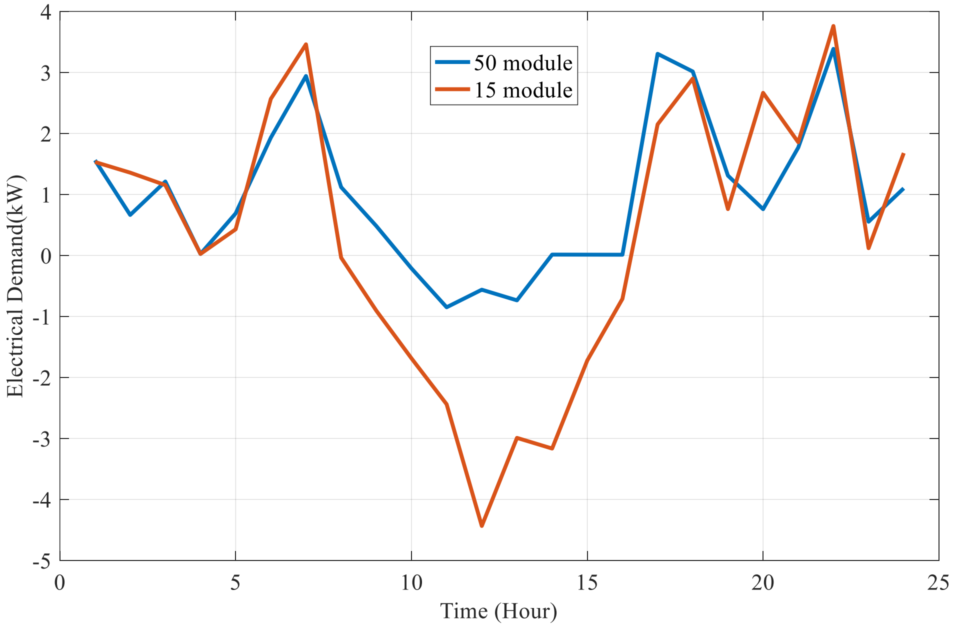


Fig. 11. Electric power received from the grid with different tariffs for electricity purchase from the grid in case study 2

4. Conclusions

The hub comprises a transformer, boiler and simultaneous electricity and heat generator; receives natural gas and electricity from the upstream grid as the input; and supplies the consumers' demanded electricity and heating as the output. Herein, proposed method for optimal operation along with determining the optimal capacity of the solar dispersed generation renewable sources is introduced for a household energy hub. Results of implementing the proposed method in different modes of hub energy management indicate the efficiency of determining the capacity of the solar system and optimal operation of the household energy hub. The results indicate that the cost of operating the energy hub can be reduced by determining the optimal capacity. The use of V2G hybrid EV batteries can also promote system efficiency. The results show that by changing the departure and arrival time of the EV, the optimal scheduling of the components of the energy hub changes. In the second scenario, due to the increase in the time of presence of the EV at home, the maneuverability of charging and discharging the EV battery is increased and the EV can have better performance in reducing the operating costs of the energy hub.

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