

Chapter 12

Optimal Operation of Renewable-Based Residential Energy Hubs for Minimizing PV Curtailement



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12.1 Introduction

Increasing rate of energy consumption, lack of fossil fuels, reliability, and environmental concerns are the main challenges of the energy systems. These reasons motivate us to use energy sources more efficiently. As a promising solution, cogeneration technologies have been proposed recently to make the energy generation and consumption more efficient. This technology uses a kind of energy carrier such as natural gas, biofuels, or solar energy to produce electricity, heating and cooling energies. Combined heat and power (CHP) units, as the most popular cogeneration technologies, is penetrating drastically in the worldwide energy system. For example, it is forecasted to have more than two million micro-CHP units in Japan by 2030, especially beside the residential consumers [1]. The CHP units are fed with natural gas and generate electricity and heat in the output.

An energy system including cogeneration technologies is named multi-carrier energy system. Energy hub is a usual structure to model the energy transfer, storage, and conversion in a multi-carrier energy system [2]. Because of interactions between different energy carriers, the operation of energy hub is more complex than a single energy carrier system. The main operational questions in a residential energy hub are “how much the energy carrier is consumed at the input port of the energy hub” and “how energy carriers are flowing in the different ways from inputs to outputs of the energy hub.” These questions are usually answered by solving an optimization-based problem.

Since almost 40% of total energy is consumed in residential sectors [3], it seems essential to study residential energy hubs, using CHP units [4]. A boiler is usually

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used next to the CHP unit to guarantee providing the heat demand. In other words, the demanded heat can be provided by the CHP or the boiler. In addition, a share of electrical demand is fed by the CHP unit and remained can be supplied by electrical grid and other electrical resources. Ren et al. [4] developed a mixed integer nonlinear programming (MINLP) optimization and determined the optimal overall energy cost for a test year and the hourly operation schedules of CHP unit.

Recently, many studies focused on the optimal operation of multi-carrier energy systems especially residential energy hubs [5–10]. The main objective functions of proposed optimization problems in the residential energy hub are minimizing customers' costs, such as the energy cost or the emission cost. For example in [2], a general modeling of multi-carrier energy systems is developed and the concept of energy hubs is explained. Then, power flow equations for each energy carrier are used to model the energy hub. Finally, total energy cost is considered as the objective function and is minimized. In [10], a residential energy hub is modeled and a multi-objective optimization is proposed. The authors used weighted sum technique to converting a multi-objective function to a single objective one. The single objective function elements are containing energy costs, energy consumption, CO₂ emission costs, and the peak load of electricity demand. Then, based on the weights set by customers, the optimization is solved and the amount of each energy carrier at inputs of the energy hub and the interaction between different energy carriers are determined.

In addition, renewable resources particularly photovoltaic (PV) panels although have a high installation cost are becoming more widespread in the residential buildings because of low operational and emission costs. In [11], a residential energy hub is proposed and solar panels are providing power for the energy hub. Other components like CHP unit, plug-in hybrid electric vehicle (PHEV), and heat storage as parts of future smart homes are incorporated. The objective function is customer's energy cost. These resources such as PV panels, which have low operational costs, should be utilized maximally to become profitable for their owners [10, 12]. In renewable residential energy hubs that contain a CHP generator and PV panels, high heat demand may have impact on the PV utilization. Because, at hours with high heat demand, CHP units are utilized to meet heat demands, which causes supplying a large portion of the power demand. Thus, the PV generation power is less than what it could potentially produce, that can affect the revenue of PV installation. In other words, when a large portion of power demand is supplied by CHP, a part of the PV generation is left unused, which is called PV curtailment. High heat demand can increase the PV curtailment, especially in sunny hours of the day [13]. In addition, heat and electrical storage systems can be considered in the energy hub [11, 14]. Reference [14] has investigated the effect of energy storage on optimal operation of residential energy hub. The investment payback and benefits of thermal and electrical storage on other component of energy hub is analyzed in [14]. The objective function contains customer's energy costs and penalty for carbon emission. Plug-in Hybrid Electrical Vehicle (PHEV) as one of the new emerging technologies is recently considered in the optimal operation study of residential energy hubs [11, 12]. These vehicles consume electrical energy at charging periods

and can bring the charged energy back to the grid by discharging at the time of availability. In summary, although a number of works have studied the operation of residential energy hubs, a few of them have considered all the emerging components, i.e., PV panels, CHP units, boiler, and storage systems, in the smart home. Among these few works, to the best of authors' knowledge, PV curtailment concern has not been considered in the optimal operation of the renewable-based residential energy hub.

This chapter optimizes the day-ahead operation of a renewable residential energy hub. The energy hub model includes a CHP unit, a PHEV, PV panels, and a gas boiler (GB) to provide the electrical and heat demand. Electricity and natural gas are assumed as the energy hub inputs. In addition, opposing to the most of previous works, the gas to heat and gas to power efficiencies of CHP are considered dependent on the output power. According to the proposed model, an optimization problem is designed for optimal operation of the proposed framework. The objective functions are minimizing customer energy cost and PV curtailment simultaneously. The problem is subjected to different operational constraints of the components and energy and heat balance in the energy hub. Solving the proposed problem determines the amount of each energy carrier and interaction between different types of energy. In addition, it determines the time scheduling of PHEV. The proposed method is applied to a home as a renewable residential energy hub to demonstrate the effectiveness of the proposed method. In addition, the impact of incorporating a heat storage system on the PV curtailment is studied in this chapter. Based on recent contents, the main contributions of this chapter are:

- Integrating new technologies such as PHEV, PV panels, and storage systems in the energy hub model,
- Accurate modeling of CHP units especially in part load operation, and
- Considering PV curtailment in the optimal operation of energy hub.

12.2 Methodology and Problem Formulation

12.2.1 Proposed Renewable-Based Residential Energy Hub Structure

Energy hub concept can be used for every multi-carrier framework that includes different kinds of demands and resources. This chapter models a home as an energy hub with electrical and heat demand, PHEV, PV panels, storage systems, a CHP unit, and a boiler. The structure of the proposed residential energy hub is shown in Fig. 12.1. As shown in Fig. 12.1 the electrical demand can be provided directly from the grid, generation power of PV, and output power of CHP unit. In addition, the PHEV can be discharged to provide a part of electrical demand at the time of availability.

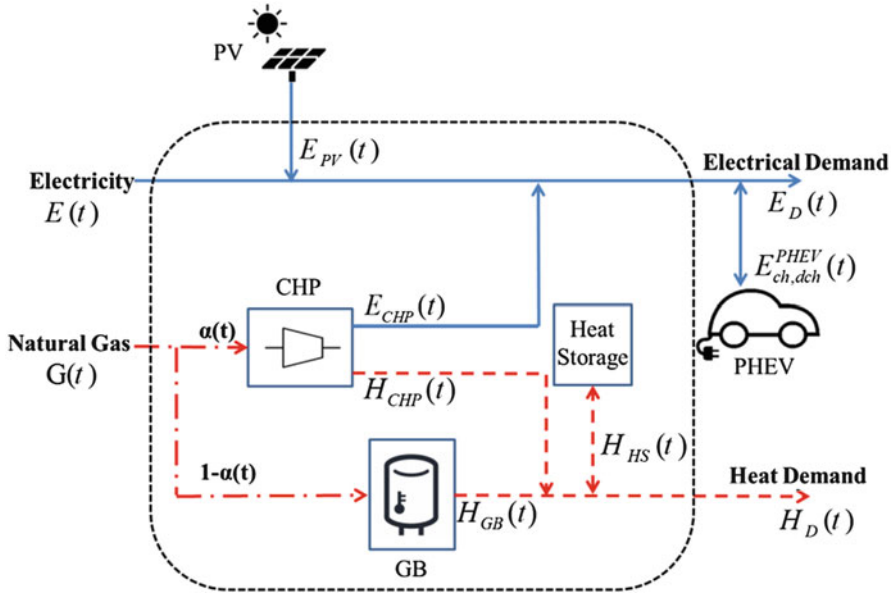


Fig. 12.1 Structure of the renewable residential energy hub

Output heat from CHP unit and gas boiler provides the heat demand. The heat storage can provide a part of the heat demand. In the proposed energy hub structure, the input gas can flow in two paths, i.e., to CHP unit or to gas boiler. Distribution of input gas between components is determined by dispatch factor $\alpha(t)$. The dispatch factor is variable between 0 and 1. This factor determines the amount of natural gas flowing into the CHP unit and gas boiler.

12.2.2 Problem Formulation

Here, the optimization-based formulations for the operation of the residential energy hub are presented. The goal is determining the optimal value of dispatch factors, i.e., $\alpha(t)$, and the optimal flow of heat and electricity in different paths in Fig. 12.1. The optimization is studied for one-day period with 1-hour time-step. The optimization problem, i.e., objectives and constraints, is presented as follows:

12.2.2.1 Objective Function

The main objective for households is minimizing the energy cost. Hence, the energy cost is assumed as the first criterion in the optimization problem. It is mathematically formulated as follows:

$$EC = \sum_{t=1}^{24} [\lambda_e(t) * E(t) + \lambda_g(t) * G(t)] \quad (12.1)$$

$\lambda_e(t)$ and $\lambda_g(t)$ are the electrical and gas tariffs in hour t . $E(t)$ and $G(t)$ are, respectively, the electrical energy and the natural gas received from the grid in hour t .

In addition, the curtailment of PV panels can be considered as another important criterion in the operation of the energy system. This criterion clearly provides the customer's welfare. PV curtailment is presented as follows:

$$PC = \sum_{t=1}^{24} [E_{PV}^G(t) - E_{PV}(t)] \quad (12.2)$$

where $E_{PV}^G(t)$ is the capability of PV panels for generation and $E_{PV}(t)$ is the energy drawn from the PV panels in hour t .

As a conclusion, we meet a multi-objective optimization problem. The problem can be solved by weighted sum method. This method adds multiple objectives with different weights to make a single objective problem. Here, per unit values of objective functions are added together to develop the objective function, as follows:

$$\min CU = w_1 * EC_{pu} + w_2 * PC_{pu} \quad (12.3)$$

where CU is the customer utilization, EC_{pu} is equal to $\frac{EC}{EC_{base}}$ and, PC_{pu} is $\frac{PC}{PC_{base}}$. The base values of EC and PC, i.e., EC_{base} and PC_{base} , are the energy cost and PV curtailment in a non-optimal case, in which CHP units are used to provide the electrical demand at its rated value.

w_1 and w_2 are importance factors of objectives i.e., weights for EC_{pu} and PC_{pu} . The procedure of determining w_1 and w_2 to consider the preferences of the customer is performed by a fuzzy decision making (FDM) method. The detailed descriptions of this method are presented in [15]. In this chapter, based on the importance of the objectives from the customer's viewpoint the w_1 and w_2 are determined in the Numerical Studies Section, using the FDM method.

12.2.2.2 Optimization Constraints

The proposed objective function is subjected to different constraints, including power and heat flow equations and different technical constraint of the different components in the proposed structure of Fig. 12.1.

- *Power and heat flow equations*

According to Fig. 12.1, power and heat flow equations can be presented as follows:

$$E(t) + E_{PV}(t) + E_{CHP}(t) + \eta_{PHEV}^{dch} * E_{PHEV}^{dch}(t) - \frac{E_{PHEV}^{ch}(t)}{\eta_{PHEV}^{ch}} = E_D(t) \quad (12.4)$$

$$H_{GB}(t) + H_{CHP}(t) + \eta_{HS}^{dch} * H_{HS}^{dch}(t) - \frac{H_{HS}^{ch}(t)}{\eta_{HS}^{ch}} = H_D(t) \quad (12.5)$$

$$E_{CHP}(t) = \alpha(t) * G(t) * \eta_{CHP}^{g-e}(t) \quad (12.6)$$

$$H_{GB}(t) = (1 - \alpha(t)) * G(t) * \eta_{GB} \quad (12.7)$$

$$H_{CHP}(t) = \frac{E_{CHP}(t)}{\beta_{CHP}^{e-h}(t)} \quad (12.8)$$

where $E_{CHP}(t)$ is the output power of CHP in hour t and $\eta_{CHP}^{g-e}(t)$ is gas to power efficiency in hour t , $E_{PHEV}^{ch}(t)$ and $E_{PHEV}^{dch}(t)$ are the PHEV charging and discharging power of PHEV, respectively, in hour t , η_{PHEV}^{ch} and η_{PHEV}^{dch} are the charging and discharging efficiency of PHEV, respectively, and $E_D(t)$ is the demanded power of electrical appliances in hour t .

In addition, $H_{CHP}(t)$ is the heat generation of CHP unit in hour t and $\beta_{CHP}^{e-h}(t)$ is the power to heat ratio of CHP unit in hour t , $H_{GB}(t)$ is the output heat of gas boiler in hour t and η_{GB} is the efficiency of gas boiler. $H_D(t)$ is the heat demand of energy hub in hour t . $H_{HS}^{ch}(t)$ and $H_{HS}^{dch}(t)$ are the charging and discharging heat of heat storage, respectively, in hour t . η_{HS}^{ch} and η_{HS}^{dch} are the charging and discharging efficiency of heat storage.

Equations (12.4) and (12.5) show that the demanded power and heat is provided by grid, CHP unit, and storage. Note that selling the energy to the grid is not possible. Equation (12.6) presents the electrical generation from CHP unit considering the gas to power efficiency, i.e., $\eta_{CHP}^{g-e}(t)$. The gas to power efficiency of CHP depends on the electricity generation of the CHP, i.e., $E_{CHP}(t)$. It is mathematically modeled later. Equation (12.7) calculates the share of heat demand that is provided by the gas boiler. In (12.8), the heat generation of CHP is calculated based on the output power of CHP and power to heat ratio of CHP unit. This efficiency is also a function of output power of CHP.

- *CHP*

Cogeneration system is one of the essential parts of future homes. CHP units are the most popular kinds of cogeneration technologies because of its high efficiency. As the main constraint of CHP unit, output power of CHP cannot go beyond from CHP capacity that presented as follows:

$$E_{CHP}(t) \leq E_{CHP}^{max} \quad (12.9)$$

where E_{CHP}^{\max} is the nominal output power of CHP. The output power and heat of CHP units can be either calculated by gas to heat and gas to power efficiencies or gas to power efficiency and power to heat ratio. These factors are changing versus the electrical load of CHP, which is called CHP part load ratio [16]. Thus, Eqs. (12.10) and (12.11) can mathematically present $\eta_{\text{CHP}}^{g-e}(t)$ and $\beta_{\text{CHP}}^{e-h}(t)$, respectively. This is in line with the presented models in the literature [16].

$$\eta_{\text{CHP}}^{g-e}(t) = 0.9033\text{PL}(t)^5 - 2.9996\text{PL}(t)^4 + 3.6503\text{PL}(t)^3 - 2.0704\text{PL}(t)^2 + 0.4623\text{PL}(t) + 0.3747 \quad (12.10)$$

$$\beta_{\text{CHP}}^{e-h}(t) = 1.0785\text{PL}(t)^4 - 1.9739\text{PL}(t)^3 + 1.5005\text{PL}(t)^2 - 0.2817\text{PL}(t) + 0.6838 \quad (12.11)$$

where PL is the part load ratio of CHP calculated as follows:

$$\text{PL}(t) = \frac{E_{\text{CHP}}(t)}{E_{\text{CHP}}^{\max}} \quad (12.12)$$

Equations (12.10) and (12.11) are valid for $\text{PL}(t) \geq 0.05$. For $\text{PL}(t) \leq 0.05$, mentioned factors are $\eta_{\text{CHP}}^{g-e}(t) = 0.2716$ and $\beta_{\text{CHP}}^{e-h}(t) = 0.6816$.

- *PHEV*

PHEVs, as a part of future smart homes, have a storage capability. Charging and discharging rates are limited to a definite value as follows:

$$E_{\text{PHEV}}^{\text{ch}}(t) \leq E_{\text{max}}^{\text{ch}} \quad (12.13)$$

$$E_{\text{PHEV}}^{\text{dch}}(t) \leq E_{\text{max}}^{\text{dch}} \quad (12.14)$$

where $E_{\text{max}}^{\text{ch}}$ and $E_{\text{max}}^{\text{dch}}$ are the maximum charging and discharging rate, respectively.

It is assumed that PHEV is going out in hour g and coming back home at hour c . During $[g,c]$, PHEV is not available at home and charging and discharging is impossible. Therefore, charge level of PHEV battery in hour t ($E_{\text{PHEV}}(t)$) is determined as follows:

$$E_{\text{PHEV}}(t) = \begin{cases} E_{\text{PHEV}}^0 + \sum_{h=1}^t E_{\text{PHEV}}^{\text{ch}}(h) - E_{\text{PHEV}}^{\text{dch}}(h) & \forall t \leq g - 1 \\ E_{\text{PHEV}}^0 + \left[\sum_{h=1}^t E_{\text{PHEV}}^{\text{ch}}(h) - E_{\text{PHEV}}^{\text{dch}}(h) \right] - E_{\text{PHEV}}^{\text{out}} & \forall t \geq c + 1 \end{cases} \quad (12.15)$$

Equation (12.15) defines the charge level of PHEV in hour t , where E_{PHEV}^0 is the charge level of the PHEV at the beginning of the day called initial charge value and $E_{\text{PHEV}}^{\text{out}}$ is the consumed energy of PHEV in out of home hours, i.e., $[g, c]$.

PHEV battery package has a capacity and cannot be charged more than nominal battery capacity. This constraint is modeled as follows:

$$\begin{cases} E_{\text{PHEV}}(t) \geq 0 \\ E_{\text{PHEV}}(t) \leq \text{cap}_{\text{PHEV}} \end{cases} \quad (12.16)$$

where cap_{PHEV} is the PHEV battery capacity.

In addition, customer tends to go out with fully charged battery, as follows:

$$E_{\text{PHEV}}(g - 1) = \text{cap}_{\text{PHEV}} \quad (12.17)$$

PHEV charge level at the end of the day should be more than or equal to its initial charge value. This constraint is presented as follows:

$$E_{\text{PHEV}}(24) \geq E_{\text{PHEV}}^0 \quad (12.18)$$

- *PV panels*

PV generation is dependent on daily sunlight, thus the output power depends on the radiation. Equation (12.19) shows the relation between the output power of PV and the daily radiation as follows:

$$E_{\text{PV}}^G = \begin{cases} (\eta_s/K_s) * R^2 & R \leq K_s \\ \eta_s * R & K_s \leq R \leq R_n \\ P_n & R \geq R_n \end{cases} \quad (12.19)$$

where R is the solar radiation, η_s is the constant efficiency, K_s is the defined knee point, and P_n is nominal output power of PV.

- *Gas boiler*

Beside cogeneration systems, a gas boiler usually exists to guarantee providing the heat demand. The input natural gas of boiler should be capped to nominal capacity as follows:

$$H_{\text{GB}}(t) \leq H_{\text{GB}}^{\text{max}} \quad (12.20)$$

$H_{\text{GB}}^{\text{max}}$ is the nominal capacity of gas boiler.

- *Heat storage*

Previous studies [11, 14] show that the heat storage devices can have an effective role in improving system operation. Thus, a heat storage unit is considered in the proposed structure for better operation of the energy hub. In addition, the heat storage may have impacts on decreasing the PV curtailment. The constraints of heat storage unit are mathematically modeled as follows:

$$\text{SOH}_{\text{HS}}(t) = H_{\text{HS}}^0 + \sum_{h=1}^t H_{\text{HS}}^{\text{ch}}(h) - H_{\text{HS}}^{\text{dch}}(h) \quad (12.21)$$

The state of the stored heat in the heat storage in hour t is calculated in Eq. (12.21). H_{HS}^0 is the stored heat in the storage at the beginning of the day.

Charging and discharging rates of heat storage are limited to their predetermined values, as follows:

$$H_{\text{HS}}^{\text{ch}}(t) \leq H_{\text{HS}}^{\text{max, ch}} \quad (12.22)$$

$$H_{\text{HS}}^{\text{dch}}(t) \leq H_{\text{HS}}^{\text{max, dch}} \quad (12.23)$$

Heat storage charge level at the end of the day is assumed to be more than or equal to its initial value at the beginning of the day. This is shown in Eq. (12.24):

$$\text{SOH}_{\text{HS}}(24) \geq H_{\text{HS}}^0 \quad (12.24)$$

The state of heat in heat storage cannot be negative. On the other hand, the state of heat is always less than heat storage capacity. Equation (12.25) shows this as follows:

$$\begin{cases} \text{SOH}(t) \geq 0 \\ \text{SOH}(t) \leq \text{CAP}_{\text{HS}} \end{cases} \quad (12.25)$$

where CAP_{HS} is the capacity of heat storage.

12.3 Numerical Studies

In this section, a sample home is assumed as the proposed renewable-based residential energy hub and the proposed optimization problem is applied to the home. The purpose of this study is to investigate the effect of emerging components

in future smart homes on the proposed objective function and interactions between these components. Four cases are defined here.

- *Case 1:* PHEV and heat storage are omitted from the presented energy hub in Fig. 12.1. In addition, the gas to power efficiency and the power to heat ratio of CHP unit are considered constant. Results reported in this case are the amount of objective function and the dispatch factor of CHP unit at each hour.
- *Case 2:* the gas to power efficiency and power to heat ratio of CHP unit are considered dependent on the output power of CHP. The gas to power efficiency and power to heat ratio of CHP unit at each hour are also reported in case two.
- *Case 3:* a PHEV is added to the proposed energy hub and the effect of PHEV on the operation of energy hub is taken into account, in Case 3. In this case, charging and discharging schedule of PHEV is also presented at each hour. Although PHEV is shown at the output of energy hub, the PHEV battery can be discharge at some hours and provide a part of the household electrical load. This result is deeply presented in the following.
- *Case 4:* the heat storage is added to the proposed energy hub. The impact of heat storage presence on the objective function, especially, the PV curtailment is presented in the next subsections.

Application of the proposed optimization procedure in each case and the results are reported in the following. The proposed optimization problems are solved using a Nonlinear Programming (NLP) solver in the GAMS environment. Computations are performed on a PC with a 2.53 GHz processor and 4 GB RAM, in less than 1 min.

12.3.1 Assumptions

Since a part of objective function is energy cost, energy tariff has an effective role in determining the value of objective function. The gas tariff is a fixed rate in a day and it is assumed to be 0.05 \$/kWh in this study. It is also assumed that the consumer accepted to participate in a price-based demand response program. One of the most commonly used time-varying pricing for residential consumers is time of use (TOU). Based on this pricing method, different price levels, usually two or three levels, are considered for a day and electricity prices are fixed for a specific period of the day. Here, a two-level TOU tariff is assumed for a day as shown in Fig. 12.2. Figure 12.3 shows the variation of gas to power efficiency of CHP unit based on the CHP part load. The nominal output power of CHP is assumed to be 1.8 kW. In addition, capacity of gas boiler is 0.6 kW with the efficiency of 0.9. Table 12.1 shows PHEV parameters, i.e. PHEV battery capacity, maximum charging and discharging rate, initial charge value, the departure and arrival time, out of home energy consumption of PHEV and charging and discharging efficiencies. In Fig. 12.4, the capability of PV panels for power generation is shown. These values are obtained by inserting radiation values for a sample city in the proposed model for PV panels in Eq. (12.19). Table 12.2 summarizes heat storage parameters, i.e.

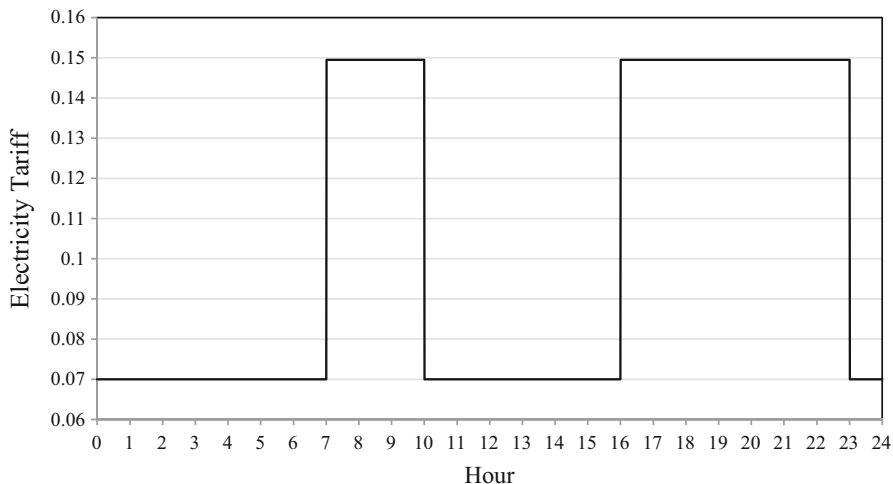


Fig. 12.2 Two-level TOU for a day

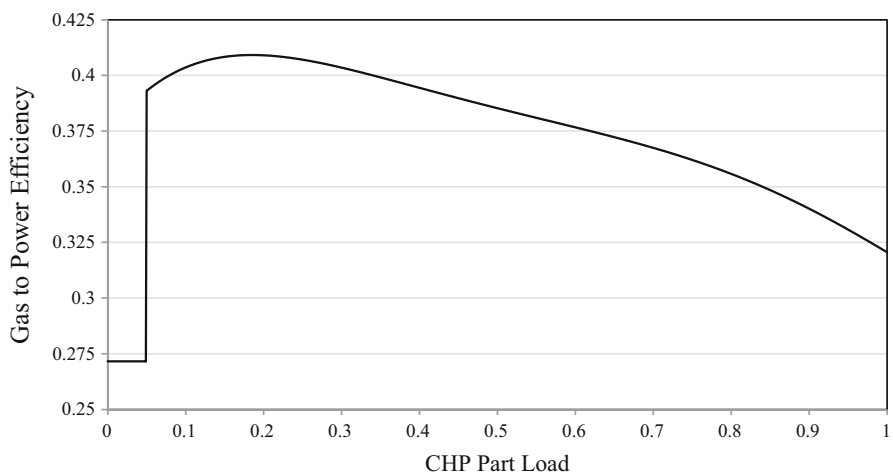


Fig. 12.3 Gas to power efficiency based on the Part Load

Table 12.1 PHEV parameters

cap_{PHEV}	E_{max}^{ch}	E_{max}^{dch}	E_{PHEV}^0	g	c	E_{PHEV}^{out}	η_{PHEV}^{ch}	η_{PHEV}^{dch}
7.8 kW	1.4 kW	1.4 kW	2 kW	8	17	3.9 kW	0.88	0.88

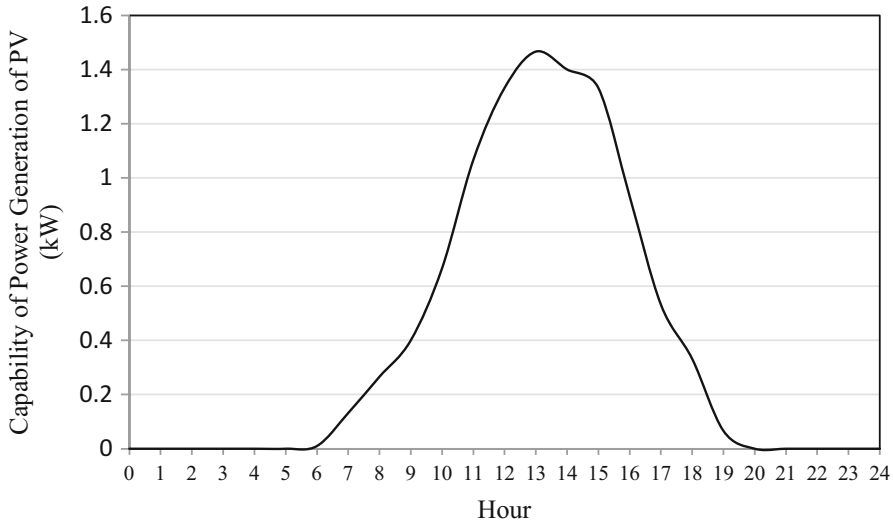


Fig. 12.4 Capability of power generation of PV

Table 12.2 Heat storage parameters

CAP_{HS}	$H_{HS}^{max, ch}$	$H_{HS}^{max, dch}$	H_{HS}^0	η_{HS}^{ch}	η_{HS}^{dch}
0.6 kW	0.2 kW	0.2 kW	0.1 kW	0.9	0.9

heat storage capacity, maximum charging and discharging rate of heat storage, initial charge value and charging and discharging efficiencies. Electrical and heat demands for a sample home is shown in Fig. 12.5 for a day. w_1 and w_2 , which are the weights of the objectives in (12.3), are determined according to the customer’s preferences through the proposed FDM method in [15]. Here, it is assumed that the importance of both objective functions for the customer is similar. In this case, FDM method is applied and the weights, i.e. w_1 and w_2 are also achieved equal to 0.5.

12.3.2 Case 1

This case is simple enough to investigate the impact of the proposed optimization procedure on the operation of the residential energy hub. In this case, according to Fig. 12.1, CHP unit, gas boiler, and PV panels are components of energy hub and electricity grid and natural gas as the inputs of energy hub supply the electrical and heat demands in the output. The gas to power efficiency and power to heat ratio of CHP are assumed to be 0.37 and 0.77, respectively.

Energy hub operation is optimized by Eq. (12.3) subjected to (12.4)–(12.25). The results show that the value of objective function is 3.024. Natural gas and electricity purchased from the grid are determined as the outcome of the problem and are shown in Figs. 12.6 and 12.7, respectively. Total input gas for whole day

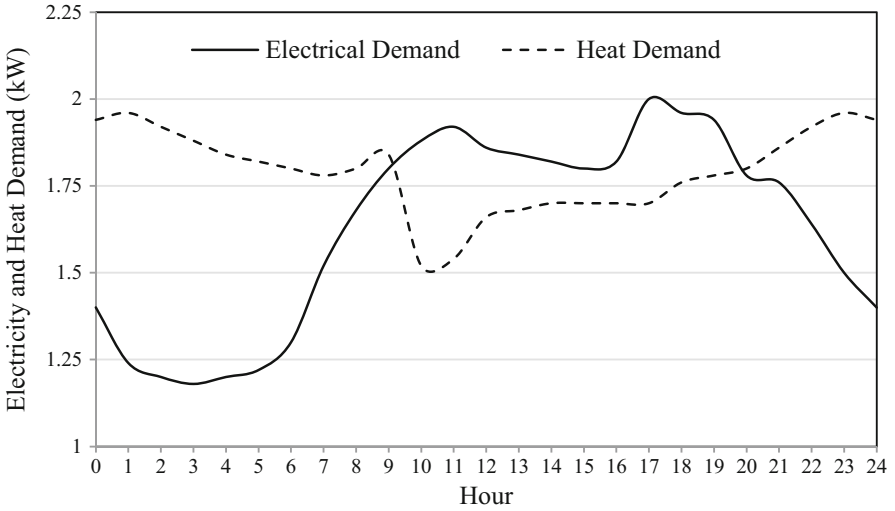


Fig. 12.5 Electrical and heat demand in a sample day

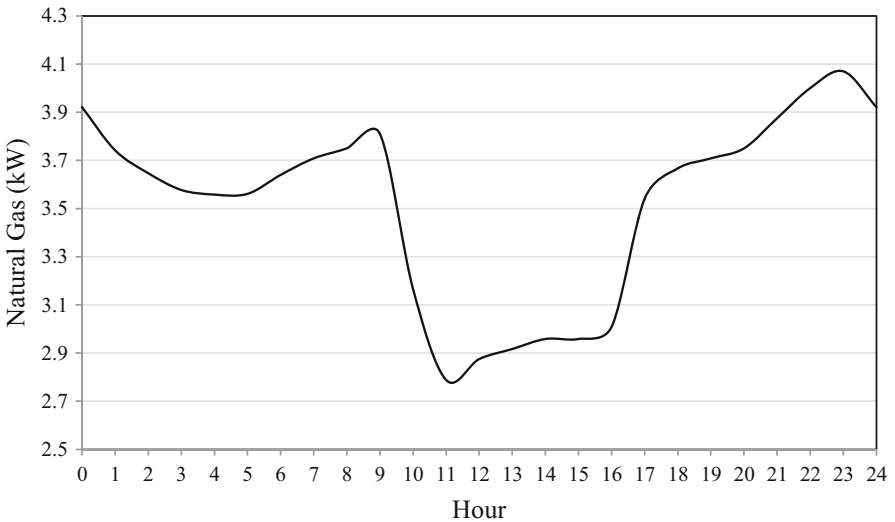


Fig. 12.6 Natural gas purchased from the grid in case 1

is 84.19 kWh and total purchased electricity from the grid is 1.89 kWh. Dispatch factor $\alpha(t)$ is another outcome of the problem and its value at each hour is shown in Table 12.3. At hours (17–23), dispatch factors are equal to one and all the input gas enters the CHP unit. The reason for this is that these hours are high-peak tariff hours and electrical demand is high. Therefore, it is profitable to use CHP unit with maximum output power and supply the remained electrical demand through the grid.

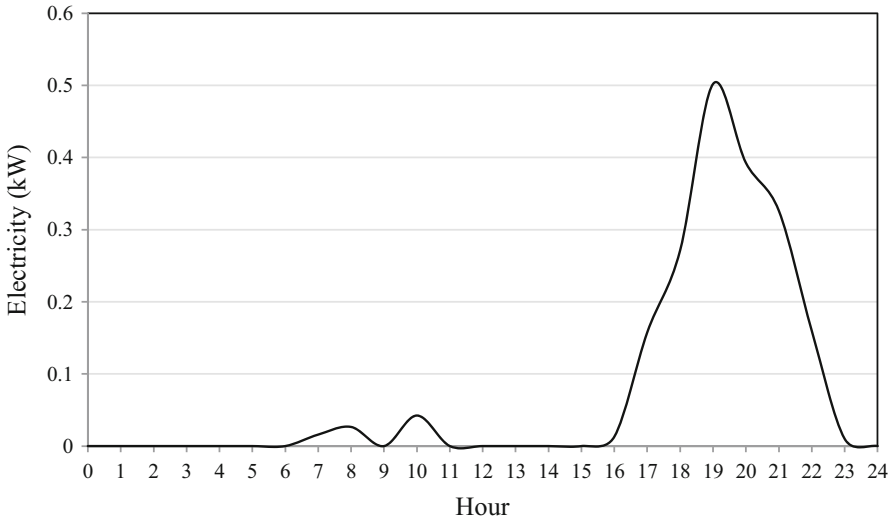


Fig. 12.7 Electricity purchased from the grid in case 1

Table 12.3 Dispatch factor of CHP in case 1

Hour	1	2	3	4	5	6	7	8
Value	0.895	0.889	0.891	0.911	0.925	0.965	1	1
Hour	9	10	11	12	13	14	15	16
Value	0.993	1	0.827	0.768	0.771	0.774	0.774	0.797
Hour	17	18	19	20	21	22	23	24
Value	1	1	1	1	1	1	0.996	0.964

Between hours (11–16), PV panels supply a part of electrical demand. Therefore, the electrical demand at the output of CHP is reduced and CHP can be fed with less natural gas. In the early hours of the day, i.e., hours (1–6), the heat demand is high and the gas boiler cannot provide whole the heat demand. Thus, the CHP supplies the rest of the heat demand. Generated power of CHP at these hours is enough for low electrical demand during these hours and purchased electricity from the grid is zero. As previously discussed, the ratio of output power to rated power is called part load ratio. Figure 12.8 shows the part load ratio of CHP for each hour. This ratio depends on the amount of input natural gas and the dispatch factor $\alpha(t)$. According to Figs. 12.6 and 12.8, the pattern of the input natural gas and part load ratio is similar. Table 12.4 shows the hours in which PV is curtailed. The amount of PV curtailment is also presented in the table. The results show that during hours

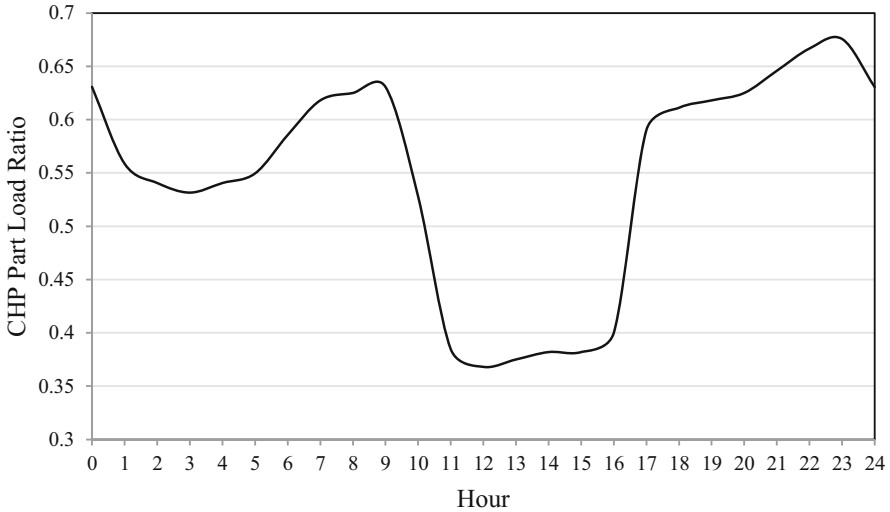


Fig. 12.8 CHP part load ratio in case 1

Table 12.4 PV curtailment in case 1

Hours	12	13	14	15
Value (kW)	0.289	0.458	0.428	0.380

(12–15) a part of capability of PV panels for generating power is unused. Since, the PV generation and the power generation of CHP at these hours are high. Thus, most of the electrical demand is provided by the CHP and the PV is curtailed. In this case, total PV curtailment is 1.555 kWh for whole the day.

12.3.3 Case 2

The gas to power efficiency and power to heat ratio of CHP are varying based on the CHP load according to Eqs. (12.10) and (12.11). As presented in Fig. 12.3, gas to power efficiency of CHP can vary between 0.271 and 0.409. In addition, the power to heat ratio can be between 0.668 and 1.007. In this case, the proposed optimization procedure also determines the optimum values for the CHP efficiency.

The objective function, i.e., the weighted summation of energy cost and the PV curtailment, is minimized subjected to equations (12.4)–(12.25). The resulted value of objective function is 2.925 in this case, which 3.44% is lower than Case 1. Inputted natural gas and electricity are shown in Figs. 12.9 and 12.10, respectively. The daily natural gas and electrical energy purchased from the grid are 81.62 kWh and 4.38 kWh, respectively. However, daily energy of input natural gas is decreased. Although the total received energy is increased a little, decreased PV curtailment

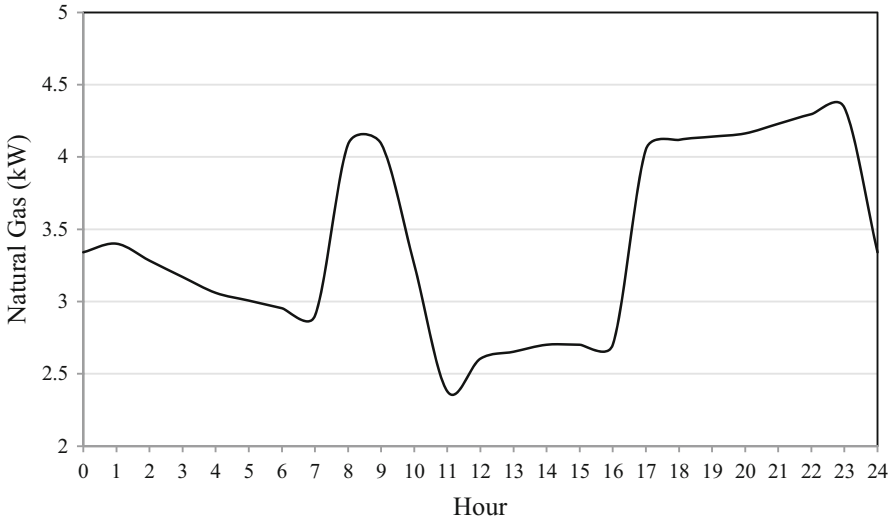


Fig. 12.9 Natural gas purchased from the grid in case 2

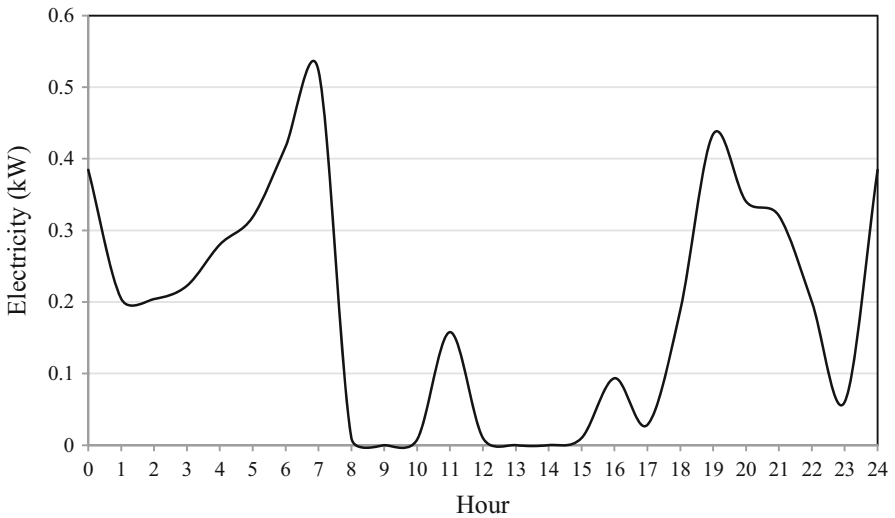


Fig. 12.10 Electricity purchased from the grid in case 2

reduces the objective function. In addition, the peak of natural gas received from the grid is increased in Case 2 in comparison with that of Case 1. In Table 12.5, resulted dispatch factor are shown. According to Fig. 12.9, in Case 2, inputted natural gas is decreased in comparison with case 1 at hours 1–6 and dispatch factor is reduced at these hours. This result causes that the electrical demand at hours 1–6 is not

Table 12.5 Dispatch factor of CHP in case 2

Hour	1	2	3	4	5	6	7	8
Value	0.804	0.797	0.790	0.782	0.778	0.774	0.770	0.967
Hour	9	10	11	12	13	14	15	16
Value	0.954	1	0.740	0.744	0.749	0.753	0.753	0.753
Hour	17	18	19	20	21	22	23	24
Value	0.999	0.982	0.977	0.972	0.957	0.942	0.932	0.800

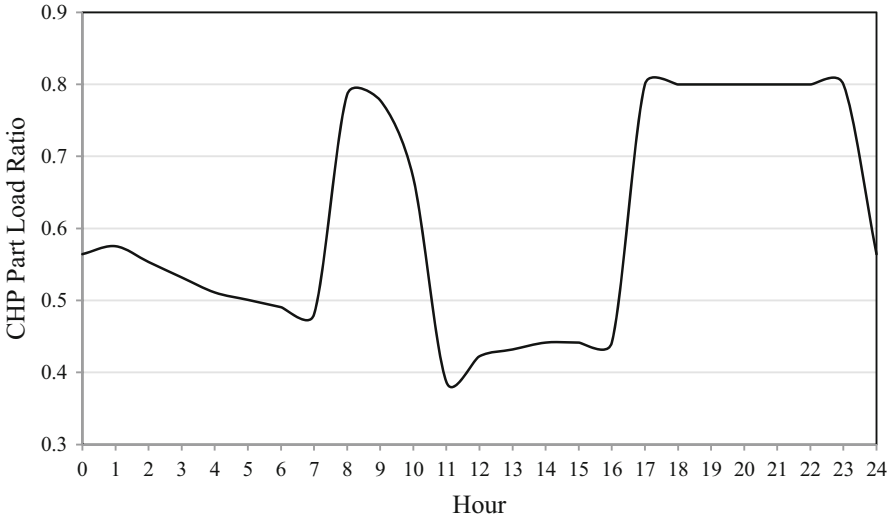


Fig. 12.11 CHP part load ratio in case 2

completely provided by CHP unit. Therefore, the remained electrical demand is supplied from the grid. Figures 12.11 and 12.12 show the CHP part load ratio and gas to power efficiency of CHP, respectively. The pattern of input natural gas and CHP part load is similar. Comparing Figs. 12.9 and 12.12 verifies that operation of CHP at low efficiency leads to high consumption of natural gas at the input to meet the household heat demand. Table 12.6 shows PV curtailment in case 2. Total PV curtailment is 1.337 kWh for whole the day, which is 14% lower than that of Case 1. The reason for this is considering the part load efficiency in Case 2, which is more realistic.

12.3.4 Case 3

In this case, a PHEV is added to the proposed residential energy hub in Case 2. The PHEV is out of home between hours 8 and 17, and its outdoor consumption

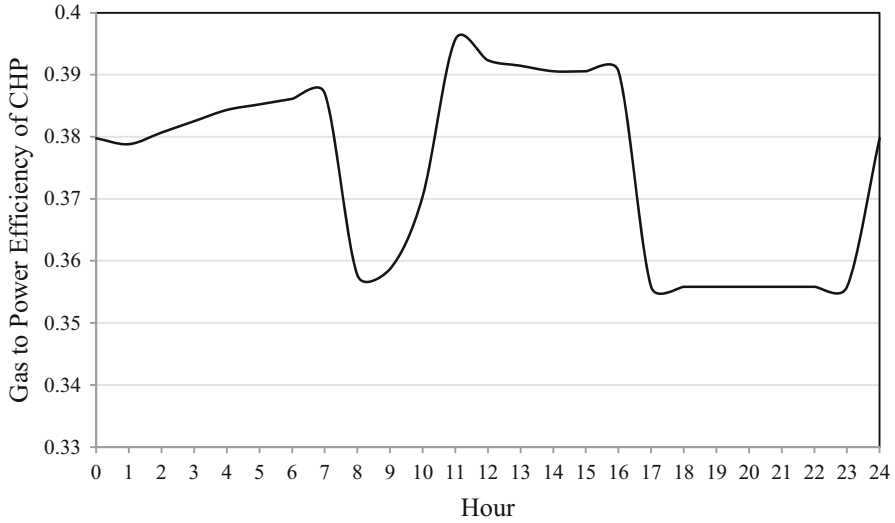


Fig. 12.12 Gas to power efficiency of CHP in case 2

Table 12.6 PV curtailment in case 2

Hours	12	13	14	15
Value (kW)	0.232	0.403	0.375	0.327

is 3.9 kWh. It is assumed that the PHEV goes out with fully charged battery. At available hours at home, PHEV battery package can be charged or discharged with the aim of reducing the objective function according to its constraints. Although the PHEV outdoor consumption is added as an electrical demand, it is worthwhile to note that PHEV battery package acts as electrical energy storage and can improve the objective function at available hours.

The PHEV needs a definite amount of energy to consume out of home. This increases the household electrical demand. Thus, the resulted objective function is 3.009 in this case, which is more than Case 2. In Figs. 12.13 and 12.14, purchased natural gas and electricity is shown, respectively. CHP dispatch factor as another resulted output is shown in Table 12.7 for each hour. CHP part load ratio is represented in Fig. 12.15. Charging and discharging schedule of PHEV is shown in Fig. 12.16. In Fig. 12.16, positive and negative values show, respectively, charging and discharging of PHEV battery.

Total input gas and electricity are, respectively, 78.14 kWh and 11.08 kWh for whole the day. According to Fig. 12.16, during hours (17–23), the PHEV is discharged to supply a part of electrical demand. In addition, PHEV is charged at hours 23, 24, and (1–7). Discharging hours are high-peak tariff hours while PHEV is charged during low-tariff hours. The variation pattern of inputted natural gas in Cases 2 and 3 is similar. Since, the heat demand is the same in both cases. However, between hours 17 and 23, in which the PHEV is discharged, electrical demand of

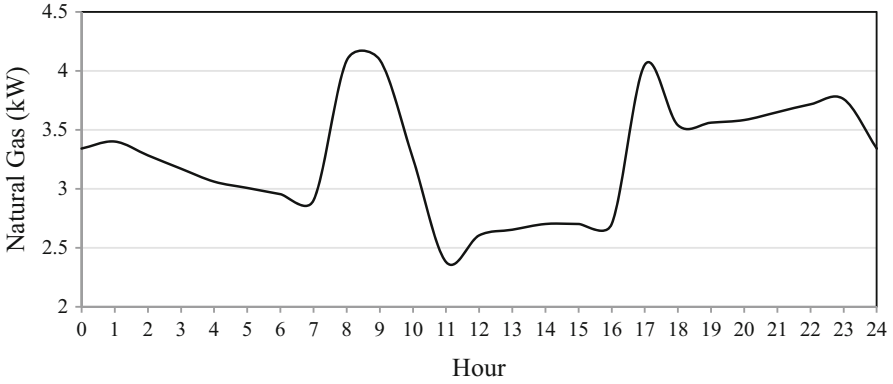


Fig. 12.13 Purchased Natural Gas in Case 3

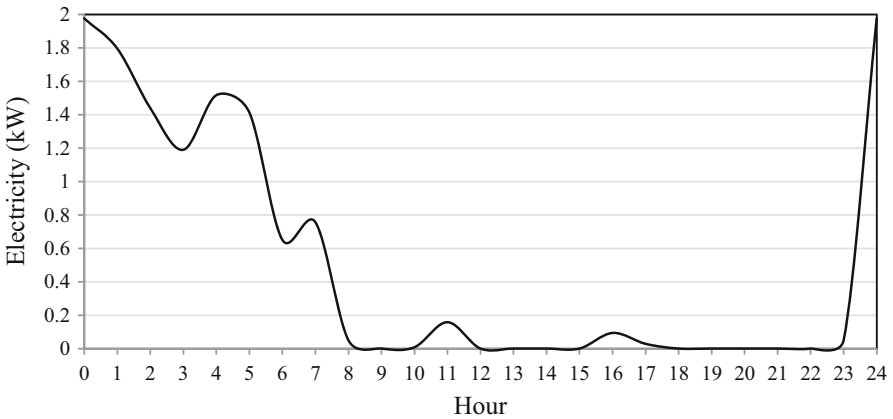


Fig. 12.14 Purchased Electricity in Case 3

Table 12.7 Dispatch factor of CHP in case 3

Hour	1	2	3	4	5	6	7	8
Value	0.804	0.797	0.790	0.782	0.778	0.774	0.770	0.967
Hour	9	10	11	12	13	14	15	16
Value	0.954	1	0.740	0.744	0.749	0.753	0.753	0.753
Hour	17	18	19	20	21	22	23	24
Value	0.999	0.926	0.921	0.915	0.898	0.882	0.872	0.800

CHP unit and, in turn, CHP part load ratio is reduced. Part load reduction causes a higher CHP efficiency, presented in Fig. 12.3, which lowers input gas for providing the heat demand. According to Fig. 12.14, purchased electricity during hours (17–23) becomes zero because PHEV is discharged and beside the output power of the

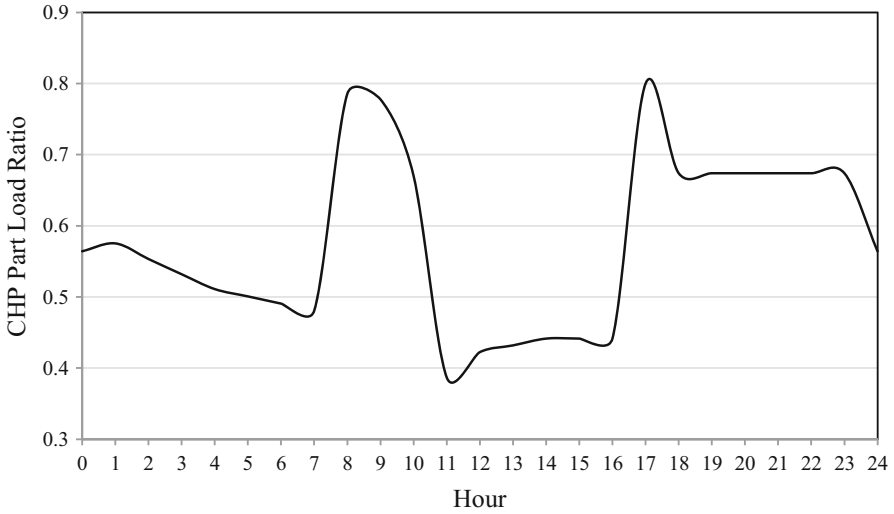


Fig. 12.15 CHP Part Load Ratio in Case 3

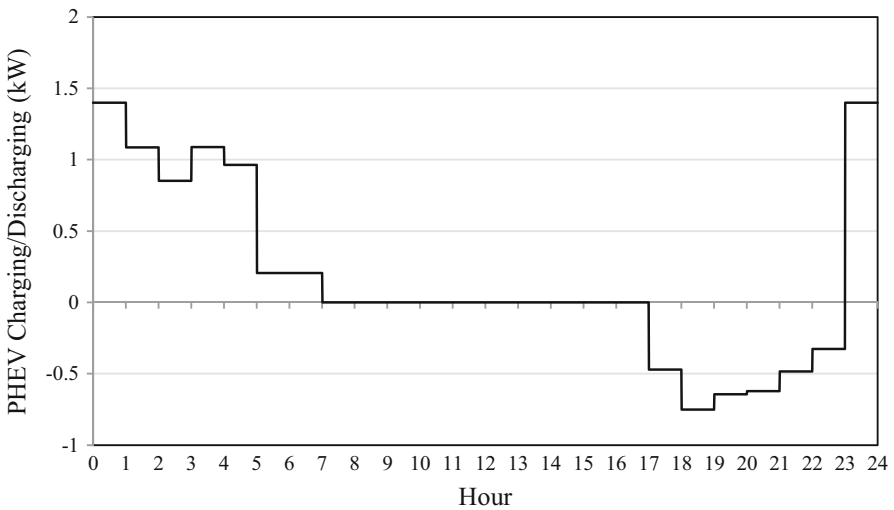


Fig. 12.16 PHEV charging and discharging schedule in Case 3

CHP, it provides the electrical demand. On the other hand, at hours 23, 24, and (1–7), in which PHEV is charged, purchased electricity is increased in comparison with Case 2, and its peak reached 1.975 kW, which is more than that of Case 2. In Case 3, during hours (12–15), PHEV is out of home and there is no change in electrical and heat demand in comparison with Case 2. Therefore, the PV curtailment in this case is the same as Case 2.

12.3.5 Case 4

It was previously discussed that in the proposed energy hub, high heat demand of CHP unit leads to more CHP output power and less using output power of PV panels, which leads to PV curtailment. In this case, the heat storage unit is added to the proposed energy hub. The heat storage can be discharged when needed and provide a part of heat demand. Therefore, the heat drawn from CHP unit is reduced. As a result, output power of CHP is reduced and PV panels can provide more part of electrical demand. The heat storage specifications were presented in Table 12.2.

The objective function is minimized subjected to Equations (12.4)–(12.25). The amount of objective function is 2.772 and it is 7.87% lower than Case 3. In Figs. 12.17 and 12.18, purchased natural gas and electricity from the grid are shown, respectively. Total consumed natural gas is 7.35 kWh and total purchased electricity is 11.21 kWh for the day. CHP dispatch factors are shown in Table 12.8 for each hour. CHP part load ratio for each hour is shown in Fig. 12.19. Charging and discharging schedule of PHEV and heat storage are concluded in Figs. 12.20 and 12.21, respectively.

According to Fig. 12.21, during hours (11–15), the heat storage is discharged to provide a part of the heat demand. Therefore, inputted natural gas, CHP dispatch factors, and CHP part load ratio are decreased at these hours. Thus, more PV generation is used to provide the electrical load and the PV curtailment is decreased in comparison with previous cases.

The presented results in Fig. 12.21 show that discharging/charging the heat storage is occurred at low-tariff/high-tariff hours of electricity. Since, at high-tariff hours of electricity, it is profitable to provide more electricity demand by CHP. Hence, the heat demand of CHP is forced to be increased by charging the storage.

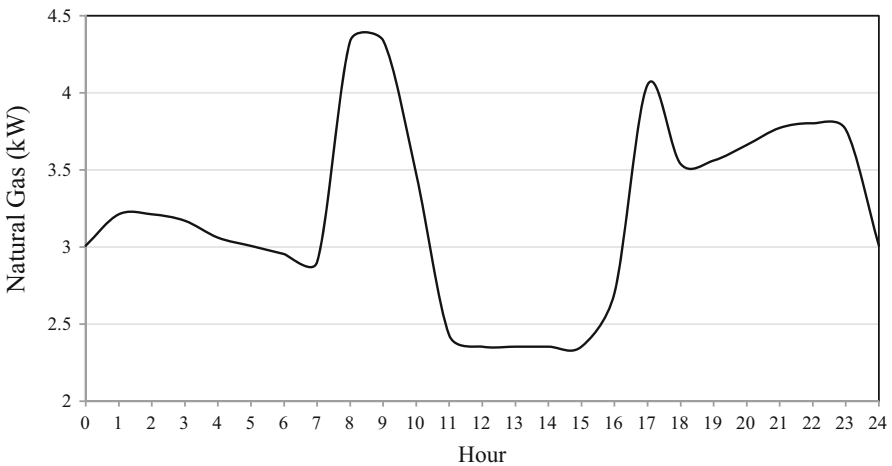


Fig. 12.17 Purchased natural gas in Case 4

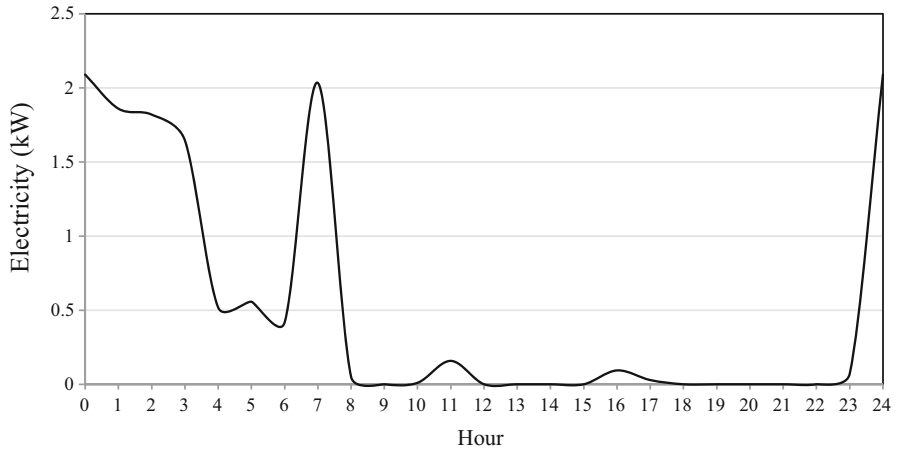


Fig. 12.18 Purchased electricity in Case 4

Table 12.8 Dispatch factor of CHP in case 4

Hour	1	2	3	4	5	6	7	8
Value	0.792	0.792	0.790	0.782	0.778	0.774	0.770	0.912
Hour	9	10	11	12	13	14	15	16
Value	0.900	0.945	0.725	0.717	0.717	0.717	0.717	0.753
Hour	17	18	19	20	21	22	23	24
Value	0.999	0.926	0.921	0.895	0.869	0.862	0.872	0.778

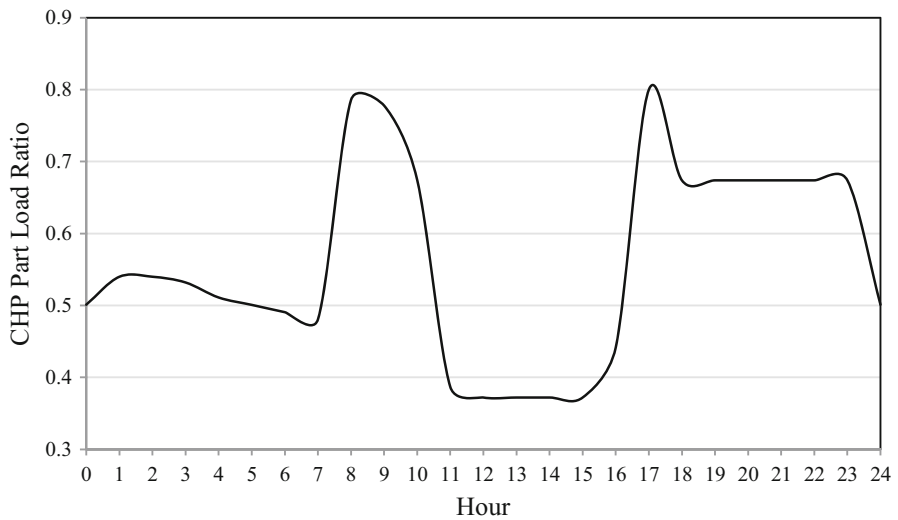


Fig. 12.19 CHP Part load in Case 4

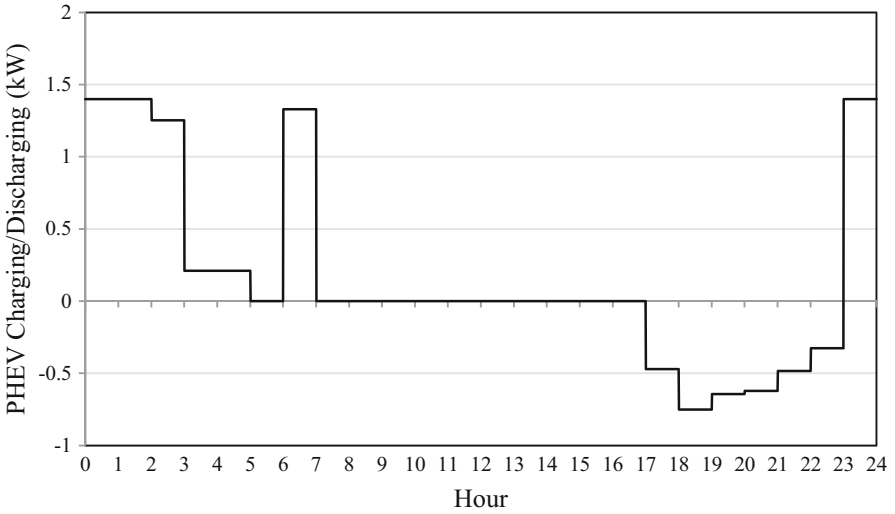


Fig. 12.20 PHEV charging and discharging schedule in Case 4

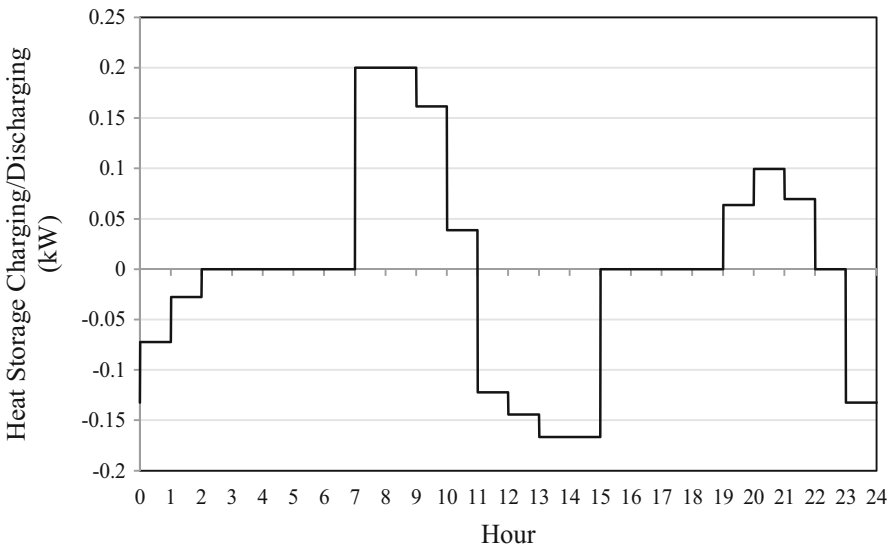


Fig. 12.21 Heat storage charging and discharging schedule in Case 4

This raises the CHP output power, subsequently. This leads to lower need for purchasing the electricity from the grid at high-tariff hours.

According to Fig. 12.20, PHEV provides a part of electrical demand during hours (17–23). This makes the purchased electrical from the grid zero. PHEV battery is charged in low-tariff hours, i.e., (23–24) and (1–7), which causes an increment

Table 12.9 PV curtailment in Case 4

Hours	12	13	14	15
Value (kW)	0.141	0.295	0.249	0.201

in the required electricity from the grid. This leads to 2.08 kW peak load at hour 24. In addition, between hours 12 and 15, output power of CHP along with PV panels can provide electrical demand completely and the purchased electricity from the grid becomes zero. Because of PHEV discharging between hours 17 and 23, output power and part load ratio of CHP are reduced. In Case 4, the amount of PV curtailment is shown in Table 12.9. Total PV curtailment is 0.886 kWh for whole the day. The heat storage unit descends the PV curtailment. As previously discussed, heat storage is discharged between hours (12–15) and reduces the heat demand of CHP unit. Therefore, the inputted natural gas and output power of CHP are reduced. Thus, PV panels can provide more part of electrical demand and PV curtailment is reduced. In Case 4, PV curtailment is reduced about 33% in comparison with Case 2.

12.4 Conclusion

This chapter optimizes the operation of a residential energy hub, including a CHP, a boiler, a PHEV, PV panels, and a heat storage to provide the electrical and heat demand of a home. The objective function is the weighted summation of minimizing the energy cost and PV curtailment. The outputs of the objective function were the dispatch factor of the energy hub at different hours, the amount of purchased electricity and natural gas from the grid, the charge/discharge scheduling of PHEV battery and the heat storage, and the manner of energy flow in the energy hub. Different cases were designed to investigate the impact of PHEV and the heat storage on the results. In addition, the impact of CHP part load efficiency was studied on the results. This makes the results more realistic.

The results show that PV curtailment is occurred at midday, which are the high-generation hours of the PV panels. Thus, a PHEV, which is not usually available at these hours, cannot reduce the PV curtailment significantly. Because of the charge/discharge efficiency of PHEV battery, the average electricity demand of PHEV is positive. Thus, PHEV presence may increase the energy cost in comparison with the case, in which there is no PHEV. However, the heat storage presence not only reduces the energy cost but also decreases the PV curtailment. The results show a 33% decrement in the PV curtailment by using the heat storage system.

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