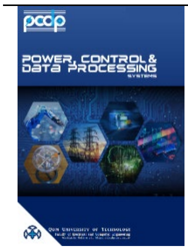
DOI: 10.30511/pcdp.2025.719228 - ISSN: 3060-8376 - Vol 2(1), 2025



POWER, CONTROL AND DATA PROCESSING SYSTEMS

Available Online at: https://pcdp.qut.ac.ir/

Smart Homes Energy Management System Integrated with Renewable Energy Sources and Demand Response Programs

ARTICLE INFO

Article Type
Original Research

Authors
Mehran Haghighi[1]
Mohammad Reza Masoudi[1, *]
Milad Rahimipour Behbahani[2]

[1] Department of Power and Control Engineering, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran
mehranhaghighi@hafez.shirazu.ac.ir
mohammadreza.masoudi@hafez.shirazu.ac.ir
[2] Department of Electrical Engineering and Information Technology, Ilmenau University of Technology, Germany
milad.rahimipour-behbahani@tu-ilmenau.de

**** Correspondence***
Address: Department of Power and Control Engineering, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran.
Phone: -
Fax: -
mohammadreza.masoudi@hafez.shirazu.ac.ir

Article History
Received: November 08, 2024
Accepted: December 23, 2024
ePublished: March 01, 2025

ABSTRACT

Home energy management systems (HEMS) play an important role in optimizing energy consumption. These systems manage the electricity consumption of household appliances using demand response programs based on real-time prices. The main goal of these systems is to reduce electricity costs and increase energy efficiency. In this paper, a price-base demand response approach is proposed for a smart home with different types of home appliances, including electric storage and thermal storage systems. In the proposed method, various appliances are considered in the smart home modeled by the energy hub system. An objective function is developed for daily management simultaneously addressing electricity costs to provide comprehensive management for smart homes. The proposed model examines how the smart home energy system responds under various conditions. Additionally, stochastic optimization accounts for the probabilistic nature of demands, photovoltaic (PV), and wind energy. The simulation results indicate that the consumer's payment cost is 79 cents and the emissions cost is 7 cents. The numerical results demonstrate the effectiveness of this approach.

Keywords: Demand Response, Home Energy Management System (HEMS), Thermal Storage Systems, Energy Hub System, Smart Home, Household Appliances.

1 Introduction

As power systems are restructured and modern communication infrastructures are developed, there is an increasing focus on involving consumers in energy management systems. The demand side management program can lower production, transmission, and distribution costs by altering the grid's load profile. By implementing the demand response (DR) program, consumers who are willing to cut back on their usage have helped decrease consumption during peak hours. Consequently, there is no need to invest additional funds in creating production capacity for brief periods each year. The main objective of a demand response program has always been to level out the load profile. Developing incentive programs is crucial to boost consumer participation in demand-side management. Smart home users benefit from reduced electricity bills in the short term and lower tariffs over the long term. However, experience indicates that consumers are typically reluctant to cut their consumption, particularly during peak hours, as they value their comfort and convenience. As smart homes evolve, customers gain the ability to control their electricity usage, leading to lower electricity costs. Smart meters and home energy management systems (HEMS) are crucial in overseeing demand response activities in residential areas [1]. The primary incentive for consumers to use HEMS is to save on costs, which necessitates altering or reducing electricity consumption, often at the expense of daily comfort [2].HEMS facilitates demand response programs for residential customers. Consumers adopt these programs to gain economic advantages and avoid blackouts. While the primary motivation for participation is financial and economic benefits, consumers also contribute to enhancing grid reliability indirectly. In recent years, several research works have been focused on the design and discussion of demand response programs.The importance of energy storage systems has become so significant today that numerous studies are now focused on estimating the charging and discharging profiles of electric vehicles connected to the grid [3].In [4], a risk-constrained bidding strategy was proposed for the smart grid, taking into account plug-in electric vehicles (EV) and demand response (DR) applications. In [5], the authors introduced a method for forecasting household loads. Their model examined how price-based demand response programs influence the load patterns of smart homes. In [6], the authors proposed an energy management system designed to manage distributed energy resources, aiming to lower residential energy consumption and optimize battery usage. In [7], the authors presented an optimal home energy management approach in which consumers reacted to various drivers of demand response (DR) programs. The findings indicated that different motivation levels exerted varied impacts on the consumers' comfort index. In [8], a comprehensive optimization method was developed for utilizing various home appliances, taking into account customer preferences. Additionally, a distinct system was designed for the charging and discharging of storage devices. In [9], the authors developed an integrated home energy management system that engaged in a demand-side management program and utilized smart home computing through a smart home operation platform. In [10], the authors examined the effects of integrating a smart thermostat with a home energy management system. In [11], the authors minimized the total energy cost and thermal discomfort of a sustainable smart home with heating and air conditioning loads over an extended period. In [12], the authors presented a MILP model for an energy management system aimed at reducing electricity consumption costs. The loads were categorized into two groups: thermostat-controlled loads and non-thermostat-controlled loads. The proposed model also integrated battery storage systems and distributed generation systems. In [13], the authors explored the use of second life battery energy storage systems (SL-BESSs) to enhance the home energy management system. Meanwhile, [14] investigated the energy planning of a house equipped with solar heating, air conditioning, and water heating systems under real-time pricing. However, the study did not account for the correlation between electricity prices and ambient temperature. In [15], an energy management system was proposed that incorporated plug-in electric vehicles (PEVs), solar photovoltaic (PV) panels, battery electrical energy storage (BEES), and demand response (DR) programs. The model assessed the effectiveness of various DR programs on smart home performance. Similarly, in [16], the authors introduced a predictive home energy management system for a residential building, integrating a plug-in electric vehicle, a photovoltaic array, and a heat pump. In [17], the performance of a home energy management system under the export rate was compared with one under a time-of-use (TOU) tariff. The energy hub model was excluded in this study. In [18], an advanced satisfaction-based home energy management system using deep reinforcement learning was proposed for planning controllable and removable appliances; however, this model was not structured as an energy hub and did not account for the uncertainty of renewable resources. A joint scheduling model for electric and natural gas utilities in home energy management systems (HEMS) was proposed in [19]. In [20], the authors introduced a smart charging approach for off-range electric vehicle chargers in home energy hub (HEH) applications, utilizing direct current sources such as photovoltaics and battery storage systems. In [21], an integrated approach for optimal planning and operation of energy hubs, considering the effects of wind energy resources, was developed. This study accounted for the stable uncertainties of electricity demand, heating, cooling, and wind power energy. Various scenarios were created using the Monte Carlo simulation method, and these scenarios were then reduced using the K-means method to check the uncertainty parameters in the model. Emission reduction was not included in the proposed model. Table 1 provides a comparison of several related research studies.

TABLE 1. Taxonomy of the model used for designing DR-based HEMS.

References	ESUs	DER	Emission reduction	Uncertainty	Wide variety of appliances	Hub
[16], [17]	✓	✓	-	✓	✓	-
[13]	✓	✓	-	-	✓	-
[8]	✓	✓	-	✓	✓	-
[15],[18],[19]	✓	-	-	-	✓	-
[2]	-	-	-	✓	✓	-
[6],[1]	✓	✓	-	-	✓	-
[20]	✓	-	-	✓	✓	✓
[4]	✓	✓	-	✓	-	-
[21]	✓	✓	-	✓	-	✓
[7],[9]	✓	-	-	-	✓	-
Proposed model	✓	✓	✓	✓	✓	✓

Y/N denotes that the subject is/is not considered.

The list of contributions presented in the paper is as follows:

- Innovative Demand Response Framework
- Comprehensive Appliance Integration
- Diverse Distributed Energy Resources (DERs) Utilization
- Strategic Energy Storage Integration
- Facilitation of Energy Trading
- Application of Stochastic Modelling
- Economic Efficiency through Objective Function Optimization
- Practical Validation and Effectiveness

This paper is organized as follows. Section II describes the methodology and mathematical formulation of the proposed model. Section III introduces the case studies and discussion. Finally, conclusion is presented in Section IV.

2 METHODOLOGY

As shown in Fig. 1, the home energy management system modifies the smart home's performance based on signal prices. The proposed model includes a smart home with diverse electrical, heating, and cooling loads. Fig. 2 illustrates the optimization structure, aiming for consumers to engage in the demand response program and manage their energy systems effectively.

The objective function is stated in Eq. (1) that the goal is to pay the lowest cost by the consumer for using the appliances of a smart home.

$$Min(J_1 + J_2 + J_3) \tag{1}$$

J_1, J_2, J_3, in the above equation are respectively expressed as follows. J_1 refers operating cost of HEMS (cents/kWh) and, J_2 is the cost of pollution and J_3 is load shedding.

$$\begin{aligned} J_1 = \sum_{s\in S} Ro(s) * \sum_{t\in T} \big[\lambda_{buy}(t) * P_{buy}(t,s) * \Delta t \\ - \lambda_{sell}(t) * P_{sell}(t,s) * \Delta t\big] \\ + \sum_{t\in T} Lan_G(t) * Gb(t) * \Delta t \end{aligned} \tag{2}$$

$$\begin{aligned} J_2 = \textstyle\sum_{s\in S} Ro(s) * \sum_{t\in T} \big[P_{buy}(t,s) * \big(C_{CO_2} * E_{CO_2} + \\ C_{SO_2} * E_{SO_2} + C_{NO_x} * E_{NO_x}\big)\big] + \textstyle\sum_{t\in T} Hb(t) * \\ \big(C_{CO_2} * Eb_{CO_2} + C_{SO_2} * Eb_{SO_2} + C_{NO_x} * \\ Eb_{NO_x}\big) \end{aligned} \tag{3}$$

$$J_3 = \sum_{s\in S} Ro(s) * \sum_{t\in T} Pns(t,s) * Lan_{NS}(t) \tag{4}$$

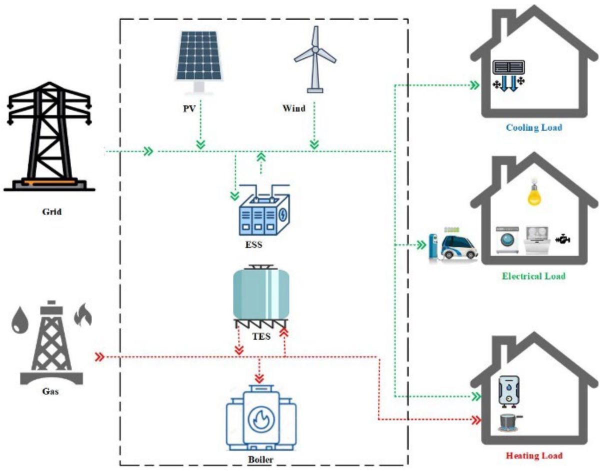


Fig. 1 Proposed smart home structure

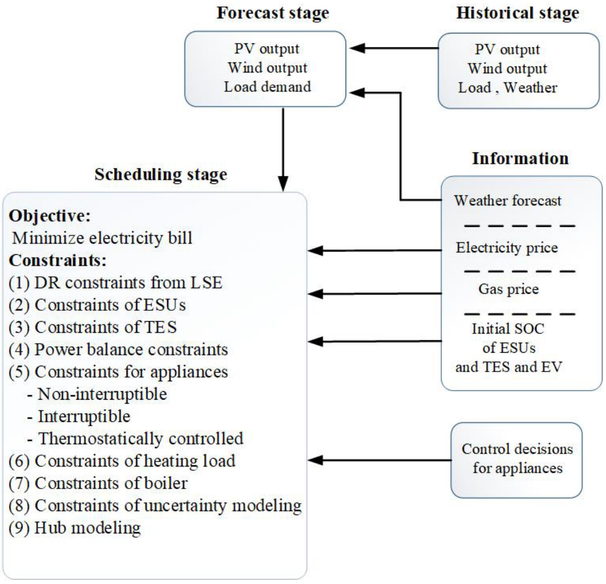


Fig. 2. HEMS optimization framework.

P_{buy} and P_{sell} are the power that is exchanged with the grid (kW).λ_{buy} is Electricity buying prices (cents/kWh) and λ_{sell} is Electricity selling prices (cents/kWh). Lan_G is gas price and Gb is amount of gas purchased for the boiler. Power generated by boiler shown with Hb. Pns is the amount of energy not supplied and Lan_{NS} is Unsupplied energy costs. Different types of devices have several advantages and disadvantages in terms of HEMS-based operational strategy. According to the ability of control, household devices can be divided into controllable and uncontrollable appliances. Based on operational characteristics, controllable appliances are classified into:

1) Non-interruptible appliances (NIA) modeling

For non-interruptible appliances, when a device is turned on, it must operate continuously for the duration of its designated runtime and should be turned off upon completion. In this paper, three NIAs are included such as a washing machine and two dishwashers. The constraints related to NIA during the planning horizon are defined as Eq. (5) to (7):

$$u_i^{APP}(t) = 0 \quad \forall t \in [1, L_i) \cup (U_i, N_T] \quad , \forall i \in A_{non} \tag{5}$$

$$P_i^{APP}(t) = u_i^{APP}(t) * P_{R'i}^{APP} \quad \forall t \in [L_i, U_i] \, , \ \forall i \in A_{non} \tag{6}$$

$$\sum_{t=j}^{j+T_{L,i}-1} u_i^{APP}(t) \ \geq \ T_{L'i} * (u_i^{APP}(j) - u_i^{APP}(j-1)) \quad \forall j \in \left(L_i, U_i - T_{L,i} + 1 \right) \ \forall i \in A_{non} \tag{7}$$

Equation (5) shows the time when the devices are off. u_i^{APP} is a binary variable for equipment, if it is 1, it means that the device is on, and if it is zero, it means that it is off. Equation (6) shows the power consumption of the device during operation. P_i^{APP} is power consumption of the appliance i and. $P_{R,i}^{APP}$ is appliance nominal power Equation (7) shows the minimum time the device stays on.

2) Interruptible appliances (IA) modeling

In interruptible appliances, when the equipment is turned on, it can be turned off during operation, or even its power can increase or decrease. In this paper, one pool pump and two electric vehicles are considered. Constraints related to interruptible appliances are defined as Eq. (8) to (10):

$$P_i^{APP}(t) = 0 \quad \forall t \in [1, Li\ ) \cup (Ui, N_T] \qquad \forall i \in A_{in} \tag{8}$$

$$\sum_{t=Li}^{Ui} P_i^{APP}(t) * \Delta t \ \geq \ E_i^{APP} \qquad \forall i \in A_{in}\ , \forall t \in T \tag{9}$$

$$0 \leq P_i^{APP}(t) \leq P_{R,i}^{APP} \qquad \forall t \in \ T\ , \forall i \in A_{in} \tag{10}$$

Equation (8) shows that if the interruptible appliances are outside of the operating range, the device must be turned off. Equation (9) states that the total power consumption of the interruptible appliances must be at least equal to the energy that the user specifies, in other words, the amount of energy required for the appliances. E_i^{APP} is Energy consumption of appliance i.Eq. (10) specifies the power consumption limits.

3) Thermostatically controlled appliances (TCA) modeling

Thermostat-controlled appliances, such as air conditioners and electric water heaters, consume electrical energy to regulate temperature. In this paper, WH and AC, the most important thermostat-controlled appliances in a smart home, are considered. These appliances adjust the temperature through an integrated thermostat within their system. Constraints related to thermostatically controlled appliances are defined as Eqs. (11)- (18):

$$0 \leq P_i^{APP}(t) \leq \ P_{R,i}^{APP} \quad \forall t \in T \, , \forall i \in WH \tag{11}$$

$$\sum_{k=1}^{t} P_T^{WH}\ (k,s) * \Delta t \geq \sum_{k=1}^{t} \rho_{wh}(t) \qquad \forall t \in T \, , \forall i \in WH \tag{12}$$

$$\rho_{wh}(t) = \ \lambda * m(t) * C_w * \left(T_{u,i}(t) - T_{cold}\right) \qquad \forall t \in T \, , \ \forall i \in WH \tag{13}$$

$$\sum_{k=1}^{t} P_T^{WH}\ (k,s) * \Delta t \leq \lambda * M * C_w * \left(\theta_i^{up} - T0\right) + \sum_{k=1}^{t} \rho_{wh}(k) \ \ \forall t \in T \, , \forall i \in WH \tag{14}$$

$$\theta_i^{dn} \leq T_{u,i}(t) \leq \theta_i^{up} \qquad \forall t \in T, \forall i \in WH \tag{15}$$

$$0 \leq P_i^{APP}(t) \leq P_{R'i}^{APP} \qquad \forall t \in T \, , \forall i \in AC \tag{16}$$

$$T_{u,i}(t) = T_{u,i}(t-1) + \eta\left[W_{out}(t) - T_{u,i}(t-1)\right] + \gamma * P_i^{APP}(t) * \Delta t \quad \forall t > 1, t \in T, \forall i \in AC \tag{17}$$

$$\theta_i^{dn} \leq T_{u,i}(t) \leq \theta_i^{up} \qquad \forall t \in T \, , \forall i \in AC \tag{18}$$

Equation (11) shows the power consumption limits. It is clear from Eq. (12) that the power consumption of water heater from hour 1 to *t* must be at least equal to the power required to heat water from hour 1 to *t* time. P_T^{WH} is Thermal from WH, which is generally used for hot water and ρ_{wh} is Hot water drawn demand (kg). Equation (13) shows the amount of required energy for heating. λ, *m*, c_w ,$T_{u,i}$ and T_{cold} are Constant (1/3600000) for unit conversion, The mass of water consumed, Specific heat of water, Determined temperature of appliance i (◦C), and cold water temperature (◦C) respectively. Equation (14) states that the power consumption by the water heater from the first hour to t must be at most equal to the energy that remains in the water heater in addition to the energy needed to heat the water, Also, it is clear from Eq. (15) that the temperature of hot water should always be between the range determined by the user. Equation (16) shows the power consumption limit of air conditioning. Equation (17) shows the relationship between indoor temperature and AC energy consumption. Equation (18) presents that the temperature inside the building should always remain within the range determined by the user that θ_i^{up} and θ_i^{dn} are Maximum and Minimum desired temperature (◦C) respectively.

Here the storage system refers to a set of batteries that can store electrical energy and deliver it to other devices or even to the main grid when needed. Constraints related to the electric energy storage systems are as Eqs. (19)- (24):

$$P_{ESS}^{use}(t,s) + P_{ESS}^{sold}(t,s) = \eta_{ESS}^{d} * P_{ESS}^{d}(t,s) \qquad \forall t \in T \, , \forall s \in S \tag{19}$$

$$0 \leq P_{ESS}^{c}(t,s) \leq R_{ESS}^{c} * \mu_{ESS}(t) \qquad \forall t \in T, \forall s \in S \tag{20}$$

$$0 \leq P_{ESS}^{d}(t,s) \leq R_{ESS}^{d} * (1 - \mu_{ESS}(t)) \qquad \forall t \in T, \forall s \in S \tag{21}$$

$$S_{ESS}(t,s) = S_{ESS}(t-1,s) + \eta_{ESS}^{c} * P_{ESS}^{c}(t,s) * \Delta t - \frac{1}{\eta_{ESS}^{d} * P_{ESS}^{d}(t,s) * \Delta t} \quad \forall t > 1, \in T, \forall s \in S \tag{22}$$

$$S_{ESS}(t,s) = S_{ESS}^{ini} + \eta_{ESS}^{c} * P_{ESS}^{c}(t,s) * \Delta t - \frac{1}{\eta_{ESS}^{d} * P_{ESS}^{d}(t,s) * \Delta t} \forall s \in S, if\ t = 1 \tag{23}$$

$$S_{ESS}^{min} \leq S_{ESS}(t,s) \leq S_{ESS}^{max} \qquad \forall t \in T, \forall s \in S \tag{24}$$

P_{ESS}^{use} and P_{ESS}^{sold} are Energy consumption of appliances from ESUs (kW) and Selling energy to grid by ESUs respectively. η_{ESS}^{c} and η_{ESS}^{d} are Charging efficiency of the ESUs and Selling energy to grid by ESUs discharging efficiency of the ESUs respectively. P_{ESS}^{c} and P_{ESS}^{d} are charging power of the ESUs (kW)and discharging power of the ESUs (kW) respectively. S_{ESS} is charging power of the ESUs (kW)and discharging power of the ESUs (kW) respectively. SoC of ESUs (kWh). Also, thermal energy storage can be used in a smart home. There is a tank in this home where hot water is stored and its loss can be reduced by isolating it. Constraints related to the thermal energy storage unit are in equations 25 to 27:

$$S_{TES}(t,s) = S_{TES}(t-1,s) + \eta_{TES}^{c} * P_{TES}^{c}(t,s) * \Delta t - \frac{1}{\eta_{TES}^{d} * P_{TES}^{d}(t,s) * \Delta t} \forall t > 1, \in T, \forall s \in S \tag{25}$$

$$S_{TES}(t,s) = S_{TES}^{ini} + \eta_{TES}^{c} * P_{TES}^{c}(t,s) * \Delta t - \frac{1}{\eta_{TES}^{d} * P_{TES}^{d}(t,s) * \Delta t} \quad \forall s \in S, if\ t = 1 \tag{26}$$

$$S_{TES}^{min} \leq S_{TES}(t,s) \leq S_{TES}^{max} \qquad \forall t \in T, \forall s \in S \tag{27}$$

P_{TES}^{c} and P_{TES}^{d} are charging power of the TES (kW) and discharging power of the TES (kW) respectively. η_{TES}^{c} and η_{TES}^{d} are charging efficiency of the TES and discharging efficiency of the TES respectively. A small Photovoltaic panel with a 1 kW capacity is also used in this smart home. Equation (28) states that the generating power of PV unit can be used by indoor appliances or injected into the grid. p_{pv} is Generating energy of PV (kW).

$$P_{PV}^{use}(t,s) + P_{PV}^{sell}(t.s) = P_{PV}(t,s) \qquad \forall t \in T, \forall s \in S \tag{28}$$

A small wind turbine with a 1 kW capacity is also used in this smart home. It is clear from Eq. (29) that the actual production power of the wind turbine can be used for two purposes. It can be injected into the grid or consumed by the home appliances:

$$P_{wind}^{use}(t,s) + P_{wind}^{sell}(t,s) = P_{wind}(t,s) \qquad \forall t \in T, \forall s \in S \tag{29}$$

Equation (30) expresses the power balance that ensures the generated energy must be equal to the consumption for each hour. Pns and P$_{must_{run}}$ are amount of energy not supplied and Power of the non-controllable household appliances must run (kW) respectively.

$$P_{buy}(t,s) + P_{PV}^{use}(t,s) + P_{wind}^{use}(t,s) + P_{ESS}^{use}(t,s) + Pns(t,s) = P_{ESS}^{c}(t,s) + \sum_{i \in A} P_{i}^{APP}(t) + P_{must_{run}}(t) \qquad \forall t \in T, \forall s \in S \tag{30}$$

Equation (31) shows the total amount of power sold to the grid:

$$P_{sell}(t,s) = P_{PV}^{sell}(t,s) + P_{ESS}^{sell}(t,s) + P_{wind}^{sell}(t,s) \qquad \forall t \in T, \forall s \in S \tag{31}$$

Equations (32) and (33) ensure that power purchased from the grid and power injected into the grid cannot occur simultaneously. N_1, N_2 and μ_{grid} are defined as the maximum power that can be purchased from the grid, the maximum power that can be purchased from the grid, and a binary variable: 1 if the grid supplies power, 0 otherwise, respectively.

$$P_{buy}(t,s) \leq N_1 * \mu_{grid}(t) \qquad \forall t \in T, \forall s \in S \tag{32}$$

$$P_{sell}(t,s) \leq N_2 * \left(1 - \mu_{grid}(t)\right) \qquad \forall t \in T, \forall s \in S \tag{33}$$

In this paper, wind and solar production sources are used as renewable sources, whose output power is a function of wind speed and solar radiation, respectively. In this study, the uncertainties caused by these sources have been modeled using scenario generation and using the Weibull and Beta distribution functions. An energy hub represents an interface between different energy sub-structures. In this paper, smart home appliances are considered such as dishwashers, washing machines, pool pumps, electric vehicles, uncontrollable loads, heat pumps, water heaters, boilers, thermal loads, electric storage, thermal storage, gas network, electricity grid, and renewable sources to model the smart home by an energy hub system. Constraints related to boiler and hub energy are in the form of Eqs. (36)-(43):

$$P_{TES}^{c}(t,s) = Hb_{TES}(t,s) + P_{TES}^{WH}(t,s) \qquad \forall t \in T, \forall s \in S \tag{36}$$

$$P_{TES}^{d}(t,s) = H_{TES}^{TL}(t,s) + H_{TES}^{WH}(t,s) \qquad \forall t \in T, \forall s \in S \tag{37}$$

$$Hb(t) = Gb(t) * Nb \qquad \forall t \in T \tag{38}$$

$$0 \leq Hb(t) \leq Hb^{max} \qquad \forall t \in T \tag{39}$$

$$Hb(t) = Hb_{WH}(t,s) + Hb_{TL}(t,s) + Hb_{TES}(t,s) \qquad \forall t \in T, \forall s \in S \tag{40}$$

$$P_{i}^{APP}(t) = P_{TES}^{WH}(t,s) + P_{wh}^{WH}(t,s) + P_{TL}^{WH}(t,s) \qquad \forall t \in T, \forall s \in S, \forall i \in WH \tag{41}$$

$$Dh(t) = H_{TES}^{TL}(t,s) + Hb_{TL}(t,s) + P_{TL}^{WH}(t,s) \qquad \forall t \in T, \forall s \in S \tag{42}$$

$$P_T^{WH}(t,s) = H_{TES}^{WH}(t,s) + Hb_{WH}(t,s) + P_{wh}^{WH}(t,s) \qquad \forall t \in T, \forall s \in S \qquad (43)$$

It is clear from Eq. (36) that the charging power of the thermal storage must either be supplied by the boiler or WH. Equation (37) states that the power discharged by the thermal storage is consumed by the thermal loads or heats water. Equation (38) shows the production power of the boiler. Equation (39) presents the production limit of the boiler. It is clear from Eq. (40) that the generated heat of the boiler is used for heating water, and thermal loads stored in the storage tank. From Eq. (41) it is understood that the power produced by WH can be stored in a storage tank, used for heat water or thermal loads. Also, Eq. (42) states that the thermal loads must either be supplied by the storage device, supplied by the boiler, or supplied by WH. Finally, Eq. (43) determines the total power consumption of heat water. Hb_{TES}, P_{TES}^{WH}, P_{wh}^{WH}, P_{TL}^{WH}, H_{TES}^{TL}, H_{TES}^{WH}, P_T^{WH} and Dh are defined as follows: the heat that the boiler supplies to the thermal storage, the WH power used to heat water for storage, the WH power used to heat hot water, the WH power used for thermal loads, the heat that the storage provides for thermal loads, the stored energy used for hot water consumption, the thermal energy from WH, which is generally used for hot water, and the thermal load, respectively.

3 CASE STUDY

A home equipped with various appliances connected to the HEMS is used as a test system. Fig. 3 displays the price of energy exchanged with the grid. Additionally, the smart home includes uncontrollable loads, such as lighting, as depicted in Fig. 4.

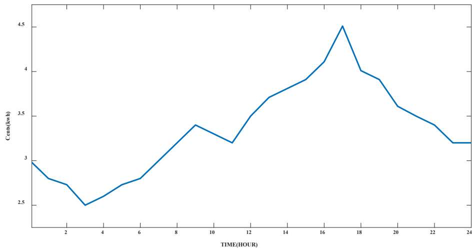


Fig 3. Information on the price of buying and selling electricity from the grid.

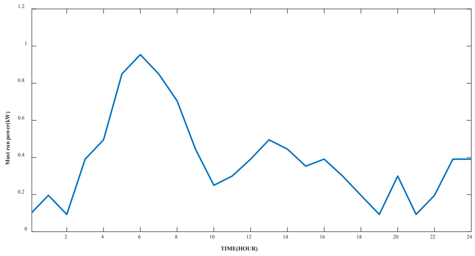


Fig. 4 Must-run power over a day.

The primary objective of this case study is to minimize payment costs. The simulation results indicate that the consumer's payment cost is 79 cents and the emissions cost is 7 cents. Due to the uncertainty in power generation from renewable sources, 10 scenarios were considered in the proposed model. The amount of power produced by solar energy and wind energy for 10 scenarios is shown in Fig 5 and Fig 6, respectively.

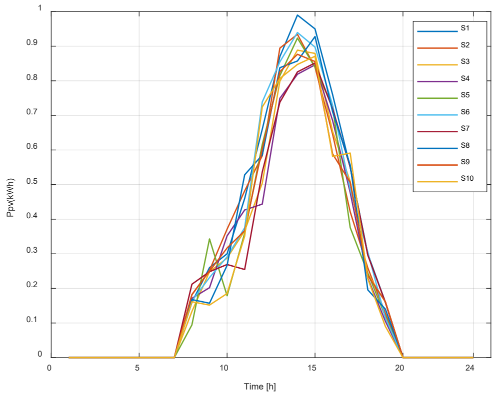


Fig. 5 Amount of power produced by solar energy for 10 scenarios.

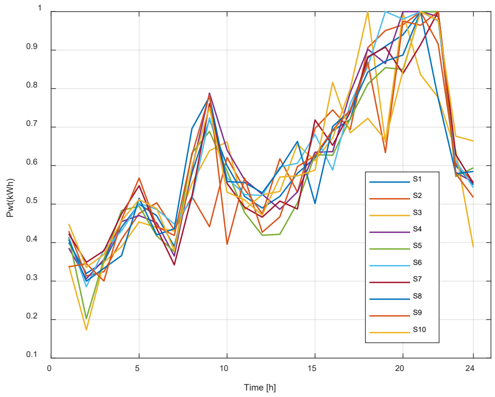


Fig. 6 Amount of power produced by wind energy for 10 scenarios.

Fig. 7 illustrates the amount of energy purchased from and sold to the grid.

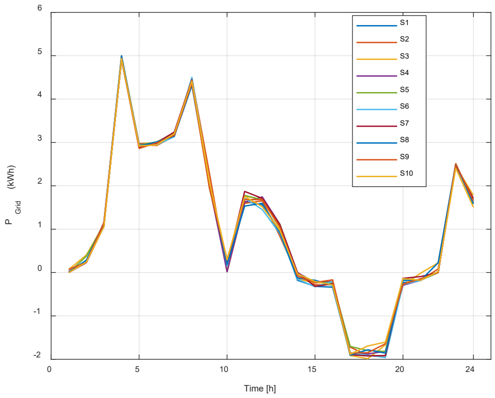


Fig. 7 Hourly purchase of energy from the grid or sale of energy to the grid.

Fig. 8 illustrates the charge and discharge power diagram of the electric storage, along with its charging level. It is evident that the electric storage charges during off-peak periods and discharges during peak hours when prices are high.

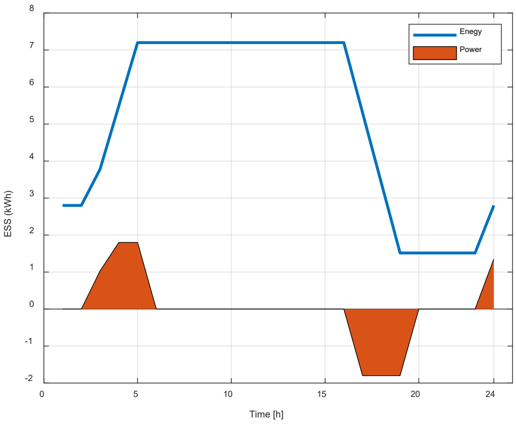


Fig. 8 Energy change of ESUs in one day.

The power consumption of home appliances is shown in Fig. 9. The types of equipment used in the smart home include washing machine, dishwasher 1 and 2, pool pump, electric vehicle 1 and 2, air conditioner, water heater, and boiler. The amount of energy consumption of each device is given along with the scheduled hours of operation.

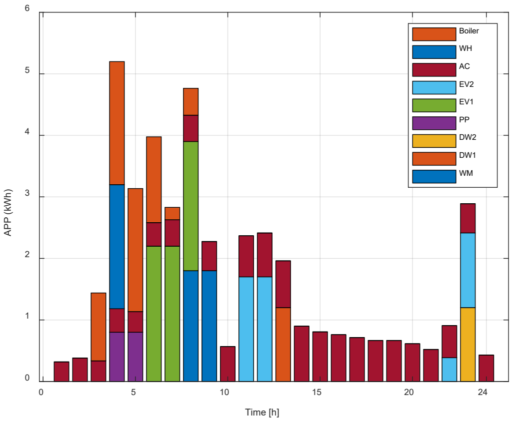


Fig. 9 Schedule of household appliances.

The proposed model aims to minimize the electricity bill by purchasing electricity from the grid during low-price periods and charging the energy storage units (ESUs). It then discharges the ESUs and sells electricity back to the grid during high-price periods. As shown in Fig. 9, the boiler is operated in the early hours when gas prices are low. Fig. 10 indicates that during the same period, the thermal storage is charged and used to meet thermal loads. When gas prices rise, thermal storage can fulfill the thermal demand.

It is known that during hours when the gas price is lower, gas is utilized to produce heat with the boiler, which is then stored for use during hours when the price is high.

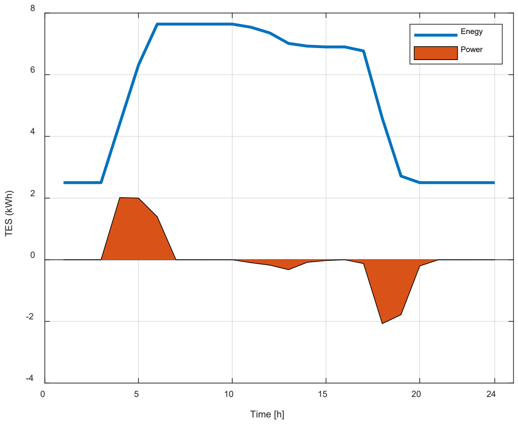


Fig. 10 Energy change of thermal storage in one day.

4 CONCLUSION

In this paper, a new price-based home energy management system is introduced aimed at reducing costs. The proposed model considers various studies and includes all types of smart home appliances with different characteristics. It presents a demand response model based on precise pricing for smart homes with diverse appliances. The energy exchange between the smart home and the grid is calculated, and the optimal times for operating household appliances to minimize consumer costs are identified. According to the results of the paper, the consumer can use her smart home appliances such as washing machines, dishwashers, pool pumps, electric vehicles, air conditioners, water heaters, and boilers in the most optimal mode. Future work will explore peer-to-peer energy trading among multiple HEMS and consider a satisfaction model to offer flexible solutions with varying levels of user satisfaction for residents, because, in addition to the cost paid by the consumer, the level of customer satisfaction with the use of their smart home appliances is considered one of the important factors. The integration with the Internet of Things (IoT) can also contribute to improving communication between devices and enhancing the efficiency of energy management. Ultimately, user interface improvements can assist consumers in engaging more effectively with their home energy management systems, making it easier to monitor and control their energy consumption. These topics represent important directions for future research and development in the field of smart home energy management systems and can lead to significant advancements in this area.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

Reference

[1] Jafarpour, Pourya, Mehrdad Setayesh Nazar, Miadreza Shafie-khah, and Joao PS Catalao. "Resiliency assessment of the distribution system considering smart homes equipped with

electrical energy storage, distributed generation and plug-in hybrid electric vehicles." Journal of Energy Storage, Vol. 55, 2022, 105516.

[2] Wang, Huilong, Yongbao Chen, Jing Kang, Zhikun Ding, and Han Zhu. "An XGBoost-Based predictive control strategy for HVAC systems in providing day-ahead demand response." *Building and Environment*, Vol. 238, 2023, 110350.

[3] A. J. Jahromi, M. R. Masoudi, M. Mohammadi, and S. Afrasiabi, "Improving electric vehicle charging forecasting: A hybrid deep learning approach for probabilistic predictions," *IET Generation Transmission & Distribution*, Oct. 2024, doi: 10.1049/gtd2.13276.

[4] P. Afzali, M. Rashidinejad, A. Abdollahi and A. Bakhshai, "Risk-Constrained Bidding Strategy for Demand Response, Green Energy Resources, and Plug-In Electric Vehicle in a Flexible Smart Grid," in *IEEE Systems Journal*, vol. 15, March 2021.

[5] N. G. Paterakis, A. Taşcıkaraoğlu, O. Erdinç, A. G. Bakirtzis, and J. P. S. Catalão, "Assessment of Demand-Response-Driven Load Pattern Elasticity Using a Combined Approach for Smart Households," IEEE Transactions on Industrial Informatics, vol. 12, 2016.

[6] Paramvir Singh, Sandeep Dhundhara, Yajvender Pal Verma, Nisha Tayal,Optimal battery utilization for energy management and load scheduling in smart residence underdemandresponse scheme,Sustainable Energy, Grids and Networks,Volume 26,2021.

[7] X. Lu et al., "Optimal Bidding Strategy of Demand Response Aggregator Based On Customers' Responsiveness Behaviors Modeling Under Different Incentives," in IEEE Transactions on Industry Applications, vol. 57, no. 4, pp. 3329-3340, July-Aug. 2021.

[8] Ubaid ur Rehman, Kamran Yaqoob, Muhammad Adil Khan,Optimal power management framework for smart homes using electric vehicles and energy storage,International Journal of Electrical Power & Energy Systems,Vol 134,2022.

[9] T. Li, Y. Xiao and L. Song, "Integrating Future Smart Home Operation Platform With Demand Side Management via Deep Reinforcement Learning," in IEEE Transactions on Green Communications and Networking, vol. 5, no. 2, pp. 921-933, June 2021.

[10] A. Can Duman, Hamza Salih Erden, Ömer Gönül, Önder Güler,"A home energy management system with an integrated smart thermostat for demand response in smart grids"Sustainable Cities and Society, Vol. 65, 2021.

[11] L. Yu, T. Jiang, and Y. Zhou, ''Online energy management for a sustainable smart home with an HVAC load and random occupancy,'' IEEE Trans. Smart Grid, vol. 10, 2019.

[12] Paterakis, N.G. et al. Optimal household appliances scheduling under day-ahead pricing and load-shaping demand response strategies. IEEE Transactions on Industrial Informatics, 2015.

[13] Y. Deng, Y. Zhang, F. Luo and G. Ranzi, "Many-Objective HEMS Based on Multi-Scale Occupant Satisfaction Modelling and Second-Life BESS Utilization," in IEEE Transactions on Sustainable Energy, vol. 13, April 2022.

[14] H. Nguyen, H. Nguyen and. D. Le "Energy Management for Households with Solar Assisted Thermal Load Considering Renewable Energy and Price Uncertainty," Smart Grid, IEEE Transactions on, vol. 6, 2015.

[15] A. Sangswang and M. Konghirun, "Optimal Strategies in Home Energy Management System Integrating Solar Power, Energy Storage, and Vehicle-to-Grid for Grid Support and Energy Efficiency," in IEEE Transactions on Industry Applications, vol. 56, Oct. 2020.

[16] M. Yousefi, A. Hajizadeh, M. N. Soltani and B. Hredzak, "Predictive Home Energy Management System With Photovoltaic Array, Heat Pump, and Plug-In Electric Vehicle," in IEEE Transactions on Industrial Informatics, vol. 17, Jan. 2021.

[17] P. Munankarmi, H. Wu, A. Pratt, M. Lunacek, S. P. Balamurugan and P. Spitsen, "Home Energy Management System for Price-Responsive Operation of Consumer Technologies Under an Export Rate," in IEEE Access, vol. 10, 2022.

[18] A. Forootani, M. Rastegar and M. Jooshaki, "An Advanced Satisfaction-Based Home Energy Management System Using Deep Reinforcement Learning," in *IEEE Access*, vol. 10, 2022.

[19] K. Li, P. Zhang, G. Li, F. Wang, Z. Mi and H. Chen, "Day-Ahead Optimal Joint Scheduling Model of Electric and Natural Gas Appliances for Home Integrated Energy Management," in IEEE Access, vol. 7, 2019.

[20] H. R. Gholinejad, J. Adabi and M. Marzband, "Hierarchical Energy Management System for Home-Energy-Hubs Considering Plug-In Electric Vehicles," in IEEE Transactions on Industry Applications, vol. 58, Oct. 2022.

[21] S.A. Mansouri, A. Ahmarinejad, M. Ansarian, M.S. Javadi, J.P.S. Catalao,Stochastic planning and operation of energy hubs considering demand response programs using Benders decomposition approach,International Journal of Electrical Power & Energy Systems,Volume 120,2020.