Iranica Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

An MILP Formulation for Energy Scheduling of Self-sufficient Smart Home Considering Household Appliances, and Investigating Its Energy Behavior

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P A P E R I N F O

Paper history:
Received 05 August 2023
Accepted in revised form 23 November 2023

Keywords:
Distributed energy resources
Energy management system
Energy scheduling
Self-sufficient smart home

A B S T R A C T

The electric energy demand has been increasing, following digitalization and development of urbanization, which has led to functional enhancement of home energy management system (HEMS) and its subsystems. A great amount of the produced electricity is used for household loads, whereas self-sufficient smart homes can supply all or a large portion of their electricity consumption by using renewable energy resources. In this study, an MILP model is formulated for energy scheduling on a 24-hour time horizon, to achieve the optimal performance of each home appliance for minimizing the smart home energy bill. The studied smart home can exchange electrical energy with the upstream network. A sensitivity analysis has been performed to show the impact of the changes in scheduling and energy prices on the electricity energy bill. The impact of the presence of renewable resources and electrical storage is studied on the electricity energy bill and the electrical energy sales profit of the house in different scenarios. Numerical results show that using the proposed model in the self-sufficient smart home reduces the amount of power purchased from the grid by 45%, transfers energy to the grid at some hours, and the energy bill is reduced by 65%.

doi: *10.5829/ijee.2024.15.03.04*

NOMENCLATURE

h	Index of time periods	θ_{air}^{max}	Maximum desired temperature (°C)
c	Index of controllable appliance	θ_{out}	Outside temperature (°C)
uc	Index of uncontrollable appliance	$\beta.\gamma$	Coefficient related to air conditioner
air	Index of air conditioner	P_{pv}^{use}	Power use to appliances from PV (kW)
π_{buy}	Price of purchased electricity (cent/kwh)	P_{pv}^{sell}	Power injected to grid from PV (kW)
π_{sell}	Sold electricity price (cent/kwh)	P_{wind}^{use}	Power use to appliances from wind turbine (kW)
Δh	Time step (h)	P_{wind}^{sell}	Power injected to grid from wind turbine (kW)
S_c	Start time of the controllable appliance	P_{Ess}^{use}	Power use to appliances from electrical storage
E_c	End time of the controllable appliance	P_{Ess}^{sell}	Power injected to grid from electrical storage
S_{uc}	Start time of the uncontrollable appliance	P_{Ess}^{ch}	Charging power of the electrical storage (kW)
E_{uc}	End time of the uncontrollable appliance	P_{Ess}^{dis}	Discharging power of the electrical storage (kW)
DR_{uc}	Duration of the uncontrollable appliance	η^{ch}	Charging efficiency of the electrical storage
PR_c^{device}	Rated power of controllable appliance	η^{dis}	Discharging efficiency of the electrical storage
PR_{air}^{device}	Rated power of air conditioner	P_c^{device}	Power consumption of controllable appliances
PR_{uc}	Rated power of uncontrollable appliance	P_{uc}^{device}	Power consumption of the uncontrollable app
P_{buy}	Electricity purchased from the grid (kw)	P_{air}^{device}	Power consumption of the air conditioner
P_{sell}	Electricity sold to the grid (kw)	I_c^{device}	Binary variable of controllable appliances
E_c^{device}	Required energy of the controllable devices	I_{uc}^{device}	Binary variable of uncontrollable appliances
θ_{air}^{min}	Minimum desired temperature (°C)		

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Please cite this article as: Hasanlu F, Fallah-Sabet A, Fereidunian A. An MILP Formulation for Energy Scheduling of Self-sufficient Smart Home Considering Household Appliances, and Investigating Its Energy Behavior, Iranica Journal of Energy and Environment, 2024 July, 15(3): 255-64. Doi: 10.5829/ijee.2024.15.03.04

INTRODUCTION

Due to the increase in the world's population, the demand for electrical energy is increasing sharply, so many efforts have been made to develop the use of renewable energy sources (1, 2). A smart home is an important part of the smart grid. Despite being small, it has a substantial potential to perform energy policies. In smart homes, residents can choose how to use energy due to their own needs and interests (3).

Nowadays, integrated operation of different energy infrastructures is taken into account to increase flexibility and reduce operation cost (4–6). Home energy management system is made by the improvement of smart homes, which creates an appropriate interaction for automatic, efficient, and compatible operation between occupants and household appliances. HEMS programs decrease energy energy bills and the amount of peak load (7, 8).

HEMS, as an essential part of smart homes, can use technology and automation to control energy consumption and implement demand response programs in smart homes (9). HEMS program performs day-ahead scheduling for the different controllable home appliances to reduce the electricity energy bill and avoid the waste of energy (10). Carbon emissions can be reduced by improving the energy efficiency in homes. Using renewable energy sources including solar panels in houses, is a helpful solution to reach this goal and reduce the environmental damages of the demand growth (11). To increase renewable energy consumption and improve energy efficiency, occupants participate in demand response programs (12).

Tahiru et al. (1) developed a behavioral HEMS model based on time-driven prospect theory including energy storage systems, renewable energy resources, and flexible home appliances. The non-flexible loads and renewable sources generation uncertainties have been demonstrated by a scenario-based uncertainty modeling approach. The suggested method is a Mixed-Integer Linear Programming model. Yang et al. (12) proposed a dynamic load priority scheduling. The proposed model evaluates some indexes such as user comfort, electricity cost, and task urgency of home appliances.

Bagheri et al. (13) considered a nano grid with several different types of devices including renewable energy sources, electrical storage, and an electric vehicle. Also, the difference between considering resilience and not considering it has been taken into account. Mehrabani et al. (14) designed a home energy management system for a smart home. The studied smart home is equipped with renewable energy sources. The optimization of the system is done in the form of seven scenarios in the presence of renewable energy resources, energy storage, electric vehicles, and demand response programs. In this study, different types of incentive-based and time-based demand response programs have been considered.

Yu et al. (15) developed an energy management system framework for a smart home that can perform in vehicle-to-grid and vehicle-to-home modes, to minimize energy costs for consumers. The model has been formulated as a Markov decision process with the objective of household electricity cost minimization.

Shahinzadeh et al. (16) solved an optimization problem for home energy management system in a multi-carrier energy environment. A hybrid optimization algorithm including the gray wolf optimization algorithm and the shark smell optimization. The proposed model aims at increasing energy efficiency and decreasing the operation costs.

Molla et al. (17) developed a framework HEMS has been with novel restricted and multi-restricted scheduling methods for the users. The optimization problem has been developed under the time-of-use pricing scheme. In this study, eight cases have been considered under different time scheduling algorithms.

Essiet et al. (18) suggested an improved differential evolution algorithm for implementing demand response between aggregator and consumer. Responsible and non-responsible loads have been considered for the smart home. The studied smart home is equipped with electrical storage and solar panels. Dinh and Kim (19) investigated the operation of a smart home considering renewable energy resources and energy storage. A multi-objective mixed integer nonlinear programming model, including home appliances and the upstream network, has been suggested to optimize energy cost and user comfort.

Alzahrani et al. (20) considered a smart home including fixed loads, flexible loads, and renewable energy resources in a grid-connected mode. The objective function is minimizing total cost and thermal discomfort cost. Lu et al. (21) suggested a scheduling model of smart home appliances to reduce the amount of peak load and minimize the home's electricity energy bill. Also, a genetic algorithm is suggested for scheduling optimization problems. The simulation results demonstrate the desirable performance of the suggested algorithm in reducing the peak load and electricity energy bill.

Khan et al. (22) also suggested a smart building, connected to a bidirectional upstream network. The smart building includes thermal and electrical loads, solar panels, electrical storage, a boiler, and a combined heat and power unit. A genetic algorithm has been used to solve the building demand response problem and optimal scheduling of sources. Tostado-Véliz et al. (23) developed a home energy management system incorporating three novel demand response strategies. The effectiveness of the suggested strategies has been proved by extensive simulations in a benchmark prosumer environment. Also, a novel scenario-based approach has been developed to manage uncertainties. Duman et al. (24) have suggested a mixed-integer linear programming-based demand response model to increase self-consumption to minimize the daily energy bill.

Mohammad et al. (25) suggested a HEMS framework with the integration of renewable energy sources and an electrical storage system. The grey wolf algorithm is used to solve the multi-objective optimization problem. Mulleriyawage et al. (26) presented a demand-side management strategy to minimize electricity energy bills in a DC residential house. The suggested strategy considers the predictions of load consumption and solar panels.

Huy et al. (27), proposed a multi-objective mixed-integer linear programming model for smart home energy management intending to optimize the electricity cost, and discomfort index. The intended smart home uses vehicle-to-home and home-to-grid capabilities. Ur Rashid et al. (28), have suggested an enhanced energy and cost optimization for consumers to reduce the amount of peak load. Also, they have developed an energy management algorithm with renewable energy sources and electrical storage. Abdalla et al. (29) suggested an energy management approach in a smart home including an electric vehicle and solar panel to reduce electrical energy cost based on time-of-use pricing.

Gonçalves et al. (30) presented a HEMS modeling that includes energy and comfort specifications. The goal of this study is to balance the minimization of energy bill cost and user satisfaction. Arabul et al. (31) have proposed an energy management model for a smart home including fuel cells, batteries, and renewable resources. Also, a controller related to the proposed HEMS has been designed.

According to the review of the past literature, it can be seen that some important issues such as the amount of energy sold from the self-sufficient smart home to the grid and the profit from the sale of energy from the self-sufficient smart home to the grid in different cases, and sensitivity analysis of the impact of HEMS performance on the energy bill cost of the self-sufficient smart home in different modes have not been sufficiently investigated.

This paper presents a scheduling model for the optimal performance of household appliances in an energy-self-sufficient smart home to reduce the electrical energy energy bill and increase the profit from the sale of electricity to the grid. In this study, household appliances are classified into three categories: controllable, uncontrollable, and thermostatically controlled. According to the previous literature review, the contributions of this study are as follows.

- Modeling an energy-self-sufficient smart home including various types of household appliances,
- Providing a framework for HEMS based on MILP, including the optimal performance of all types of household appliances, renewable resources, electrical storage, and price-based demand response,
- Evaluation of the presence of a demand response program, renewable resources, and electrical storage in reducing the electricity energy bill of a self-sufficient smart home and increasing profits from the sale of energy from the smart home to the grid.
- Sensitivity analysis to evolve HEMS performance in different modes.

This article is an extended version of the work presented at the ACEC2023 conference by Hasanlu et al. in (8), which includes: investigating the impact of price change in the energy bought and sold, as well as the impact of the time horizon for the home appliance performance. Furthermore, a base case 0 is considered in the extended version as a ground for more tangible comparisons, in which demand response program and renewable resources are not used in the smart home.

The parts of this paper are as follows; In section 2, the modeling of the objective function of the problem, the various components, and the governing constraints of the self-sufficient smart home has been stated. In section 3, the understudy network and the evaluation of the simulation results in three scenarios have been discussed and at the end, the results of this study have been summarized. In section 4, a discussion and analysis of the results have been stated.

MATERIAL AND METHODS

The studied smart home is a self-sufficient low-carbon home whose energy is considered to be scheduled, followed by a sensitivity analysis on prices and time horizons. The components of the smart self-sufficient low-carbon home are demonstrated in Figure 1.

Objective function

The studied smart home, can purchase electrical energy from the network and also sell it to the network. Equation 1, demonstrates the objective function of the problem, which aims at reducing the house energy bill cost. It includes the difference in the cost of power purchased from the network and the cost of power sold to the network.

Minimize: Z

$$Z = \sum_h (\pi_{buy} P_{buy} - \pi_{sell} P_{sell}) \quad [1]$$

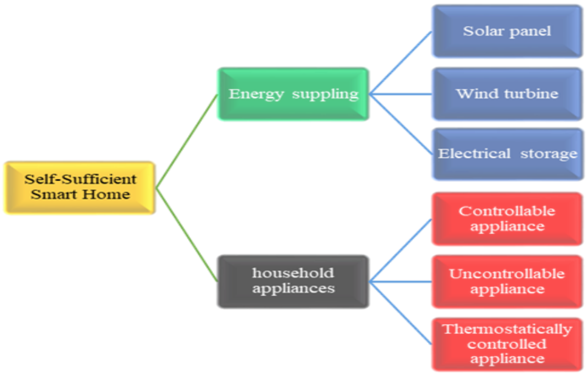

Figure 1. The components of the studied smart home

Constraints

Controllable appliances

Controllable appliances have a time horizon, determined by residents that starts at S and ends at E. These appliances should operate and complete their daily task during the mentioned time horizon. Also, these kinds of household appliances can work with more or less power than their rated power. To reach optimal performance, HEMS can connect and disconnect these appliances during the time horizon. Appliances such as electric vehicle, Water pump, and vacuum cleaner are included in this category. Table 1 summarized the data of controllable appliances. The required energy of this appliance is a certain and fixed amount (32).

$$I_c^{device}(h) = 0 \quad \forall h \in [1. S_c) \cup (E_c. 24] \qquad [2]$$

$$\sum_{h=S_c}^{E_c} P_c^{device}(h)\, \Delta h \geq E_c^{device} \quad \forall h \qquad [3]$$

$$0 \leq P_c^{device}(h) \leq PR_c^{device} \quad \forall h \qquad [4]$$

Uncontrollable appliances

Uncontrollable appliances work continuously and without any interruption during the operation time with their rated power. Several appliances including washing machines and dishwashers are stated in this category (Table 2). Uncontrollable appliances work continuously for DR hours, without interruption in the time horizon that starts from S and ends at E. Figure 2 demonstrates how these appliances perform during one day (32).

$$I_{uc}^{device}(h) = 0 \quad \forall h \in [1. S_{uc}) \cup (E_{uc}. 24] \qquad [5]$$

$$\sum_{h=S_{uc}}^{E_{uc}} I_{uc}^{device}(h) = DR_{uc} \qquad [6]$$

$$P_{uc}^{device}(h) = I_{uc}^{device}(h)\, PR_{uc} \qquad [7]$$

$$\sum_{h=n}^{n+DR_{uc}-1} I_{uc}^{device}(h) \geq DR_{uc}(I_{uc}^{device}(n) - I_{uc}^{device}(n-1)) \qquad [8]$$

$$\forall n \in (S_{uc}. E_{uc} - DR_{uc} + 1]$$

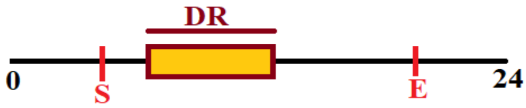

Figure 2. The schematic of uncontrollable appliance scheduling

Table 1. The data of controllable appliances

Controllable Appliances	Start	End	Required energy (kWh)	Rated power (kw)
Vacuum cleaner	1	12	1.6	1.1
Water pump	5	22	1.4	0.9
Electric vehicle	1	8	5.9	2

Table 2. The data of uncontrollable appliances

Uncontrollable Appliances	Duration (hour)	Start	End	Rated power (kW)
Dishwasher	2	10	23	1
Washing machine	2	7	21	1.5
Oven (works two times a day)	1	12	14	1.3
	1	20	22	1.3

Thermostatically controlled appliance

The utilization of thermostatically controlled appliances is the regulation of the domestic temperature of the smart home. As shown in Table 3, air conditioner states in this category and it performs according to the outdoor temperature and regulates the indoor temperature within the resident's desired range. These appliances do not have any operational time horizons (32).

$$0 \leq P_{air}^{device}(h) \leq PR_{air}^{device} \quad \forall h \qquad [9]$$

$$\theta_{air}(h) = \theta_{air} + \beta\, [\theta_{out}(h) - \theta_{air}(h-1)] + \gamma P_{air}^{device}(h) \quad \forall h > 1 \qquad [10]$$

$$\theta_{air}^{min} \leq \theta_{air}(h) \leq \theta_{air}^{max} \qquad [11]$$

The total required power of other household appliances like lighting, television, refrigerator, etc per hour is stated in Figure 3. As shown in Figure 3 the maximum amount of consumption is around dusk. It is also minimal in the middle of the night.

Table 3. The data of thermostatically controlled appliances

Thermostatically controlled appliances	Minimum temp (℃)	Maximum temp (℃)	Rated power (kW)
Air conditioner	21	29	2.1

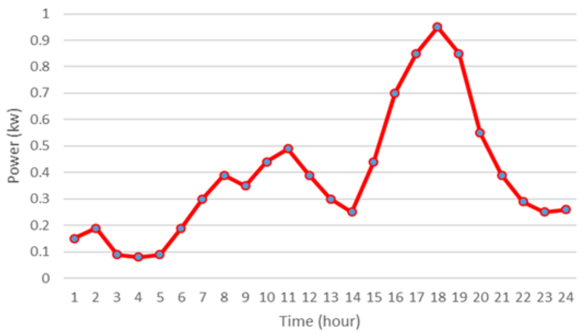

Figure 3. Power consumption of other appliances

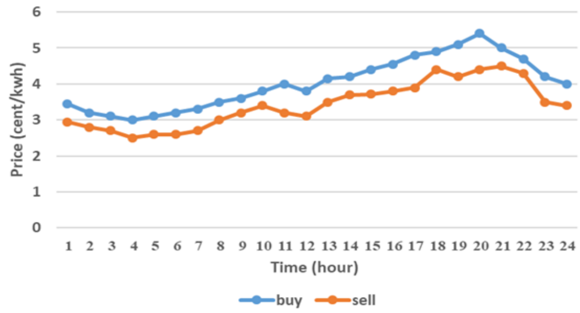

Figure 4. The price of trading electricity between the smart home and upstream network at different hours of a day

The studied smart home has a bidirectional connection with the upstream network. Figure 4 shows The price of purchasing energy from the network and selling energy to the network. As shown in Figure 4, the price of buying energy from the network is a bit higher than the price of selling it to the network.

Renewable energy resources

Equations 12 and 13, express the modeling of wind turbines and photovoltaic generation. HEMS determines how to use the power generated by these resources. The generated power can be used to supply consumption of household appliances or sold to the upstream network (33).

$$P_{wind}^{use}(h) + P_{wind}^{sell}(h) = P_{wind}(h) \qquad \forall h \qquad [12]$$

$$P_{pv}^{use}(h) + P_{pv}^{sell}(h) = P_{pv}(h) \qquad \forall h \qquad [13]$$

Electrical storage

The constraint of the electrical storage is stated in Equations 14 to 18 (33, 34).

$$P_{Ess}^{use}(h) + P_{Ess}^{sell}(h) = \eta^{dis} P_{Ess}^{dis}(\mathrm{h}) \qquad \forall h \qquad [14]$$

$$0 \le P_{Ess}^{ch}(h) \le I_{Ess}(h)\, U_{Ess}^{ch} \qquad \forall h \qquad [15]$$

$$0 \le P_{Ess}^{dis}(h) \le \left(1 - I_{Ess}(h)\right) U_{Ess}^{ch} \qquad \forall h \qquad [16]$$

$$SOC(h) = SOC(h-1) + \eta^{ch} P_{Ess}^{ch} - \eta^{dis} P_{Ess}^{dis} \quad \forall h > 1 \qquad [17]$$

$$SOC_{min} \le SOC(h) \le SOC_{max} \qquad \forall h \qquad [18]$$

Demand and generation balance

The power balance equation is stated in Equation 19 (33).

$$P_{buy}(h) + P_{ess}^{use}(h) + P_{pv}^{use}(h) + P_{wind}^{use}(h) = P_{ess}^{c}(h) + P_{other}^{appliance}(h) + \sum_{app} P_{app}^{appliance}(h) \quad \forall h \qquad [19]$$

IMPLEMENTATION RESULTS

The proposed smart home can trade electrical energy bilaterally with the grid. The objective function and constraints are modeled in the form of mixed-integer linear programming in GAMS software using the CPLEX solver. The proposed smart home consists of uncontrollable, controllable, and thermostatically controlled home appliances, electrical storage, and renewable resources including solar panels and wind turbines.

In this paper, the impact of using a demand response program, renewable sources, and electrical storage on increasing the amount of profit from the electrical energy sold to the grid and also decreasing the cost of the house energy bill, under four different cases were investigated.

Case 0: Absence of the demand response program, renewable energy resources, and electrical storage

Case 1: Presence of the demand response program without using solar panels, wind turbines, and electrical storage

Case 2: Presence of the demand response program, solar panels, and wind turbines

Case 3: Presence of the demand response program, solar panels, wind turbines, and electrical storage

Case 0: “Absence of the demand response program, renewable energy resources, and electrical storage”

In this case, a simple home has been evaluated in which no demand response program has been implemented and the house does not utilize renewable resources and electrical storage. So, the home appliances do not operate optimally and because of the lack of renewable resources and electrical storage, the house is just dependent on the upstream grid to provide its required energy. The simulation results for case 0 are shown in Table 4.

Case 1: “Presence of the demand response program without using solar panels, wind turbines, and electrical storage”

In this case, the demand response program has been implemented. But, due to the absence of renewable energy resources and electrical storage, the total cost is high, the house is dependent on the upstream network and

Table 4. Simulation results for case 0

170.07	Smart home electricity energy bill cost (cents)
0	The sale of electrical energy to the grid (cents)
39.60	Amount of purchased power (kw)
0	Amount of sold power (kw)

buys whole the required energy from the grid. Also, the smart home cannot sell energy to the grid. The simulation results for case 1 are stated in Table 5.

Case 2: "Presence of the demand response program, solar panels, and wind turbines"

The presence of the demand response program, solar panels, and wind turbines has made the cost of the smart home electricity energy bill reduced. The smart home has sold some power to the grid and the amount of purchased power from the grid has decreased more. The simulation results for case 2 are shown in Table 6.

Case 3: "Presence of the demand response program, solar panels, wind turbines, and electrical storage"

In this case, in addition to renewable energy sources, the smart home includes an electrical storage device. The smart home has sold more power to the grid and the amount of purchased power from the grid has decreased significantly. The simulation results for case 3 are stated in Table 7.

ANALYSES AND DISCUSSIONS

In this part, an analysis of the effect of changing the price of buying and selling energy, as well as changing the time horizon of the operation of household appliances on the objective function is done.

Table 5. Simulation results for case 1

151.16	Smart home electricity energy bill cost (cents)
0	Profit from the sale of electrical energy (cents)
38.90	Amount of purchased power (kw)
0	Amount of sold power (kw)

Table 6. Simulation results for case 2

76.07	Smart home energy billing fee (cents)
1.27	Profit from the sale of electrical energy (cents)
20.67	Amount of purchased power (kw)
0.34	Amount of sold power (kw)
18.29	The amount of power supplied to home appliances by solar panels and wind turbine (kw)
0	The amount of power sold to the grid by solar panels (kw)
0.34	The amount of power sold to the grid by wind turbines (kw)

Table 7. Simulation results for case 3

58.56	Smart home energy billing fee (cents)
8.73	Profit from the sale of electrical energy (cents)
20.44	Amount of purchased power (kw)
2.02	Amount of sold power (kw)
18.23	The amount of power supplied to home appliances by solar panels and wind turbines (kw)
6.89	The amount of power supplied to home appliances by electrical storage (kw)
0.34	The amount of power sold to the grid by solar panels (kw)
0	The amount of power sold to the grid by wind turbines (kw)
1.68	The amount of power sold to the grid by electrical storage (kw)

Renewables contributions to home and grid energy

Figure 5, demonstrates the amount of power supplied to household appliances by renewable energy resources, and electrical energy storage. Figure 6, shows the amount of power sold to the grid by renewable resources and electrical storage.

Economic analysis

Figure 7 shows the amount of smart home energy bill in all studied cases. Figure 8 demonstrates the amount of the

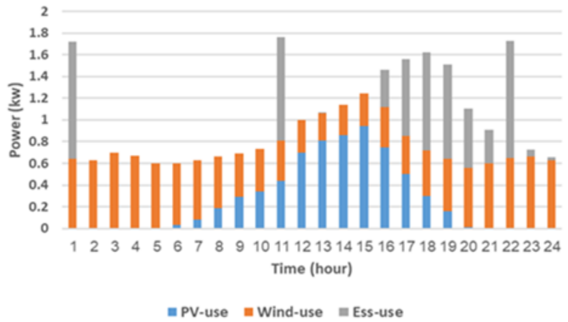

Figure 5. The amount of power supplied to home appliances by solar panels, wind turbines, and energy storage (kw) in Case 3

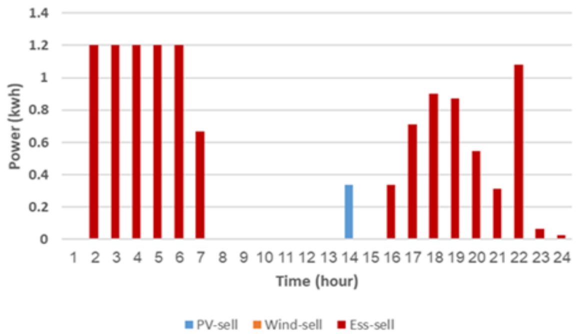

Figure 6. The amount of power sold to the grid by solar panels, wind turbines, and energy storage (kw) in Case 3

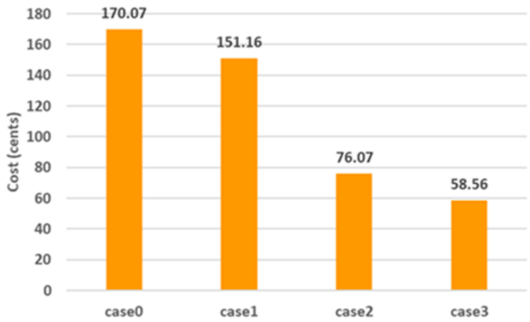

Figure 7. Comparison of the smart home energy bill in all cases

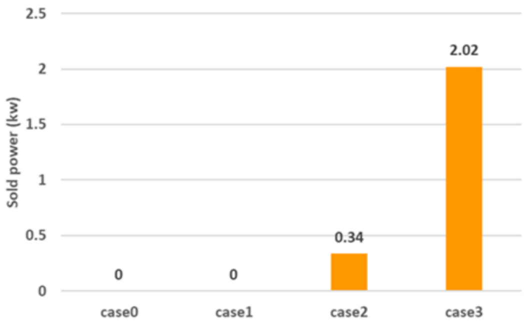

Figure 8. Comparison of the sold power to the grid in four cases

sold power to the grid in studied cases. The comparison of the profit from the sale of electrical energy to the grid in four cases is shown in Figure 9.

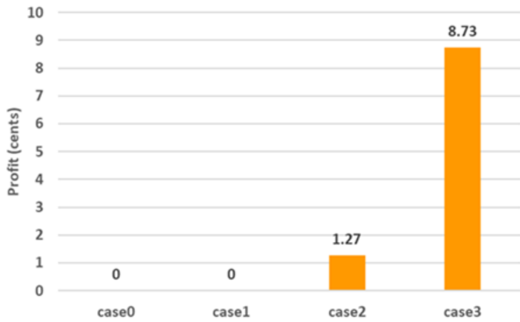

Figure 9. Comparison of the profit from the sale of electrical energy to the grid in four cases

Sensitivity of energy bill to buy and sell price

In this part, to sensitivity analysis and detailed analysis of the HEMS performance and its impact on the energy bill cost of the self-sufficient smart home, the price of electricity purchased from the network and the price of electricity sold to the network in the third case, have been changed by using adjustable coefficients. Table 8 summarizes the smart home energy bill fee, the amount of purchased electricity from the upstream network, the amount of sold electricity to the upstream network, and the amount of power supplied to home appliances by using solar panels, wind turbines, and electrical storage. Table 9 demonstrates the mentioned information after using adjustable coefficients for the price of buying electricity from the grid.

As shown in Table 9 with an increase in the price of buying electricity from the network, the total cost of the smart home energy bill increases. Also, the HEMS uses the energy produced by renewable energy resources to supply the household appliances of the smart home and sells less electricity to the grid. Table 10, shows the mentioned information after using variable coefficients for selling price. According to Table 10, by increasing the price of selling electricity to the grid, the total energy bill cost of the smart home will decrease.

According to Table 10, due to the reduction of energy bill cost the sale of electricity to the grid will become more economical and it will increase. So, the smart home buys more electricity from the grid to supply the electricity needed by its household appliances.

Sensitivity of energy bill to time horizon

In this analysis, the time horizons of the operation of household appliances have been increased to check the performance of the HEMS and its impact on the total cost. The results of this analysis are shown in Table 11.

Table 8. Total operation cost and the amount of exchanged energy between the smart home and the network

Buy price ratio	Sell price ratio	Energy bill cost (cents)	Purchasd power (kw)	Soled power (kw)	Power supplied by PV, wind, and ESS (kw)
1	1	58.56	20.44	2.02	25.13

Table 9. The results after changing the energy purchase prices

Buy price ratio	Sell price ratio	Energy bill cost (cents)	Purchased power (kw)	Soled power (kw)	Power supplied by PV, wind and ESS (kw)
1.1	1	65.186	20.06	1.61	25.86
1.3	1	77.346	18.414	0	27.16
1.6	1	95.195	18.414	0	27.16

Table 10. The results after changing the sell prices of energy

Buy price ratio	Sell price ratio	Energy bill cost (cents)	Purchased power (kw)	Soled power (kw)	Power supplied by PV, wind and ESS (kw)
1	1.1	57.29	22.69	4.28	22.89
1	1.3	53.8	24.75	6.22	22.02
1	1.6	44.33	29.26	10.42	20.52

Table 11. The results of the analysis of changing the time horizon of the operation of household appliances

The average amount of the time horizons	Electricity energy bill (cents)
0 hours	58.56
2 hours	57.09
4 hours	45.23

According to Table 11, with the increase of the time horizons of household appliances, the HEMS will have more maneuver to choose the optimal operation time of household appliances, and as a result, the operation of household appliances will operate at more optimal times, which will ultimately reduce the cost of the home energy bill.

CONCLUSION

The HEMS controls and regulates renewable energy sources and household appliances. In this article, a schedule for the optimal performance of household appliances to decrease the smart home electricity energy bill is used in the form of mixed integer linear programming. In this article, sensitivity analyses have been done to evolve HEMS performance in different modes. The simulation results show the significant effect of the presence of renewable resources in decreasing the cost of electricity energy bills, and increasing the profit from the sale of energy. By using the method proposed in this article, the cost of the smart home energy bill has decreased from $170.07 to $58.56, which means it has decreased by about 65%. Also, the amount of power purchased from the network decreases by about 48%, which shows the effectiveness of the proposed method.

REFERENCES

1. Tahiru AW, Takal SU, Sunkari ED, Ampofo S. A Review on Renewable Energy Scenario in Ethiopia. Iranian Journal of Energy and Environment. 2023;14(4):372–84. Doi: 10.5829/ijee.2023.14.04.07.
2. Nozarian M, Fereidunian A, Barati M. Reliability-Oriented Planning Framework for Smart Cities: From Interconnected Micro Energy Hubs to Macro Energy Hub Scale. IEEE Systems Journal. 2023;17(3):3798–809. Doi: 10.1109/jsyst.2023.3244498.
3. Dorahaki S, Rashidinejad M, Fatemi Ardestani SF, Abdollahi A, Salehizadeh MR. A home energy management model considering energy storage and smart flexible appliances: A modified time-driven prospect theory approach. Journal of Energy Storage. 2022;48. Doi: 10.1016/j.est.2022.104049.
4. Nozarian M, Hajizadeh A, Fereidunian A. Data-Driven Flexibility-oriented Energy Management Strategy for Building Cluster Meso Energy Hubs. 11th International Conference on Smart Grid, icSmartGrid 2023. 2023; Doi: 10.1109/icsmartgrid58556.2023.10170914.
5. Fallahsabet A, Nozarian M, Fereidunian A. Resiliency-Oriented Planning of Smart City Energy Infrastructure, Considering Energy Hubs, Based on Prioritized Critical Loads. 2023 8th International Conference on Technology and Energy Management, ICTEM 2023. 2023; Doi: 10.1109/ictem56862.2023.10084210.
6. Jobran H, Manoochehri H, Fereidunian A. Reinforced Restoration of Smart Distribution Systems Utilizing Transactive Flexibility of Prosumers. 2022 12th Smart Grid Conference, SGC 2022. 2022; Doi: 10.1109/sgc58052.2022.9998951.
7. Alizadeh A, Fereidunian A, Moghimi M, Lesani H. Reliability-Centered Maintenance Scheduling Considering Failure Rates Uncertainty: A Two-Stage Robust Model. IEEE Transactions on Power Delivery. 2022;37(3):1941–51. Doi: 10.1109/tpwrd.2021.3101458.
8. Hasanlu F, Fallah-Sabet A, Fereidunian A. Energy Scheduling of Low-Carbon Self-sufficient Smart Home. In: 8Th Annual Clean Energy Conference (ACEC2023), Babol, Iran. 2023.
9. Tostado-Véliz M, Gurung S, Jurado F. Efficient solution of many-objective Home Energy Management systems. International Journal of Electrical Power and Energy Systems. 2022;136. Doi: 10.1016/j.ijepes.2021.107666.
10. Mansouri SA, Ahmarinejad A, Nematbakhsh E, Javadi MS, Jordehi AR, Catalão JPS. Energy management in microgrids including smart homes: A multi-objective approach. Sustainable Cities and Society. 2021;69. Doi: 10.1016/j.scs.2021.102852.
11. Simões N, Manaia M, Simões I. Energy performance of solar and Trombe walls in Mediterranean climates. Energy. 2021;234. Doi: 10.1016/j.energy.2021.121197.
12. Yang J, Sun Q, Yao L, Liu Y, Yang T, Chu C, Fang L, Zhu L. A novel dynamic load-priority-based scheduling strategy for home energy management system. Journal of Cleaner Production. 2023;389. Doi: 10.1016/j.jclepro.2023.135978.
13. Bagheri S, Talebi H, Fereidunian A. Resilient, Comfort and Economic Operation of Smart Nanogrid. Journal of Control. 2018;12(3):1–12. Doi: 10.29252/joc.12.3.1.
14. Mehrabani A, Mardani H, Ghazizadeh MS. Optimal Energy Management in Smart Home Considering Renewable Energies, Electric Vehicle, and Demand-Side Management. 2022 9th Iranian Conference on Renewable Energy and Distributed Generation, ICREDG 2022. 2022; Doi: 10.1109/icredg54199.2022.9804525.
15. Yi Y, Verbic G, Chapman AC. Optimal Energy Management Strategy for Smart Home with Electric Vehicle. 2021 IEEE Madrid PowerTech, PowerTech 2021 - Conference Proceedings. 2021; Doi: 10.1109/powertech46648.2021.9494787.

16. Shahinzadeh H, Moradi J, Yaici W, Roscia M, Ebrahimi F, Nafisi H. The Appraisal of an Innovative Residential Energy Hub Framework for a Home Energy Management Paradigm Using Two-Point Estimation Technique. Proceedings - 2023 IEEE 5th Global Power, Energy and Communication Conference, GPECOM 2023. 2023;501–7. Doi: 10.1109/gpecom58364.2023.10175834.

17. Molla T, Khan B, Moges B, Alhelou HH, Zamani R, Siano P. Integrated energy optimization of smart home appliances with cost-effective energy management system. CSEE Journal of Power and Energy Systems. 2019; Doi: 10.17775/cseejpes.2019.00340.

18. Essiet IO, Sun Y, Wang Z. Optimized energy consumption model for smart home using improved differential evolution algorithm. Energy. 2019;172:354–65. Doi: 10.1016/j.energy.2019.01.137.

19. Dinh HT, Kim D. An Optimal Energy-Saving Home Energy Management Supporting User Comfort and Electricity Selling with Different Prices. IEEE Access. 2021;9:9235–49. Doi: 10.1109/access.2021.3050757.

20. Alzahrani A, Sajjad K, Hafeez G, Murawwat S, Khan S, Khan FA. Real-time energy optimization and scheduling of buildings integrated with renewable microgrid. Applied Energy. 2023;335. Doi: 10.1016/j.apenergy.2023.120640.

21. Lu Q, Guo Q, Zeng W. Optimization scheduling of home appliances in smart home: A model based on a niche technology with sharing mechanism. International Journal of Electrical Power and Energy Systems. 2022;141. Doi: 10.1016/j.ijepes.2022.108126.

22. Khan MH, Asar AU, Ullah N, Albogamy FR, Rafique MK. Modeling and Optimization of Smart Building Energy Management System Considering Both Electrical and Thermal Load. Energies. 2022;15(2). Doi: 10.3390/en15020574.

23. Tostado-Véliz M, Arévalo P, Kamel S, Zawbaa HM, Jurado F. Home energy management system considering effective demand response strategies and uncertainties. Energy Reports. 2022;8:5256–71. Doi: 10.1016/j.egyr.2022.04.006.

24. Duman AC, Erden HS, Gönül Ö, Güler Ö. Optimal sizing of PV-BESS units for home energy management system-equipped households considering day-ahead load scheduling for demand response and self-consumption. Energy and Buildings. 2022;267. Doi: 10.1016/j.enbuild.2022.112164.

25. Mohammad A, Zuhaib M, Ashraf I. An optimal home energy management system with integration of renewable energy and energy storage with home to grid capability. International Journal of Energy Research. 2022;46(6):8352–66. Doi: 10.1002/er.7735.

26. Mulleriyawage UGK, Wang P, Rui T, Zhang K, Hu C, Shen WX. Prosumer-centric demand side management for minimizing electricity bills in a DC residential PV-battery system: An Australian household case study. Renewable Energy. 2023;205:800–12. Doi: 10.1016/j.renene.2023.01.029.

27. Huy THB, Dinh HT, Kim D. Multi-objective framework for a home energy management system with the integration of solar energy and an electric vehicle using an augmented ε-constraint method and lexicographic optimization. Sustainable Cities and Society. 2023;88. Doi: 10.1016/j.scs.2022.104289.

28. Ur Rashid MM, Hossain MA, Shah R, Alam MS, Karmaker AK, Rahman M. An Improved Energy and Cost Minimization Scheme for Home Energy Management (HEM) in the Smart Grid Framework. 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD 2020. 2020; Doi: 10.1109/asemd49065.2020.9276111.

29. Abdalla MAA, Min W, Mohammed OAA. Two-stage energy management strategy of EV and PV integrated smart home to minimize electricity cost and flatten power load profile. Energies. 2020;13(23). Doi: 10.3390/en13236387.

30. Gonçalves I, Gomes Á, Henggeler Antunes C. Optimizing the management of smart home energy resources under different power cost scenarios. Applied Energy. 2019;242:351–63. Doi: 10.1016/j.apenergy.2019.03.108.

31. Keskin Arabul F, Arabul AY, Kumru CF, Boynuegri AR. Providing energy management of a fuel cell–battery–wind turbine–solar panel hybrid off grid smart home system. International Journal of Hydrogen Energy. 2017;42(43):26906–13. Doi: 10.1016/j.ijhydene.2017.02.204.

32. Liu Y, Xiao L, Yao G, Bu S. Pricing-Based Demand Response for a Smart Home with Various Types of Household Appliances Considering Customer Satisfaction. IEEE Access. 2019;7:86463–72. Doi: 10.1109/access.2019.2924110.

33. Safdarian A, Fotuhi-Firuzabad M, Lehtonen M. A distributed algorithm for managing residential demand response in smart grids. IEEE Transactions on Industrial Informatics. 2014;10(4):2385–93. Doi: 10.1109/tii.2014.2316639.

34. Soroudi A. Power system optimization modeling in GAMS. Power System Optimization Modeling in GAMS. 2017;1–295. Doi: 10.1007/978-3-319-62350-4.

Persian Abstract

چکیده

با توسعه شهرنشینی، تقاضای انرژی الکتریکی به شدت افزایش یافته است. از این‌رو، سیستم‌های مدیریت انرژی خانه و زیر سیستم‌های آن به طور گسترده توسعه یافته‌اند. مقدار زیادی از برق تولیدی برای بارهای خانگی استفاده می‌شود، در حالی که خانه‌های هوشمند خودکفا می‌توانند تمام یا مقدار زیادی از برق مصرفی خود را با استفاده از انرژی‌های تجدیدپذیر تامین کنند، حتی برخی از آن‌ها می‌توانند انرژی اضافی را به شبکه دهند. در این مطالعه، یک مدل برنامه‌ریزی انرژی در یک افق زمانی ۲۴ ساعته، جهت دستیابی به عملکرد بهینه هر یک از لوازم خانگی برای به حداقل رساندن صورت‌حساب خانه هوشمند توسعه داده شده است. خانه هوشمند مورد مطالعه می تواند انرژی الکتریکی را با شبکه بالادستی مبادله کند. تحلیل حساسیت برای نشان دادن تاثیر تغییرات در برنامه‌ریزی و قیمت انرژی بر صورت حساب برق انجام شده است. تأثیر حضور منابع تجدیدپذیر و ذخیره‌ساز الکتریکی بر قبض برق خانه و سود فروش انرژی الکتریکی در سناریوهای مختلف مورد بررسی قرار گرفته است. نتایج عددی پس از استفاده از روش پیشنهادی نشان می‌دهد که مقدار توان خریداری شده از شبکه به میزان ۴۵ درصد کاهش یافته است. همچنین، خانه هوشمند خودکفا در برخی ساعات انرژی الکتریکی به شبکه منتقل می‌کند و هزینه صورتحساب الکتریکی خانه هوشمند خودکفا ۶۵ درصد کاهش می‌یابد.