

Modeling of Energy Systems for Smart Homes



Hossein Shayeghi and Masoud Alilou

Abstract In the last years, smart homes have been introduced for improving the lifestyle of people. The energy system of a smart home is similar to the power network because both consumer and producer types of devices exist in the smart home. This complexity causes that manually managing the smart home becomes more difficult than a traditional home. Knowing the energy system of the smart home and automatically managing of its devices are important in increasing the efficiency of the smart home and the welfare of consumers. For this reason, analytical and mathematical modeling of devices of the smart home is investigated in this chapter. Modeling of the producer and consumer devices of the smart home's energy system is presented analytically and mathematically. Moreover, an optimization algorithm is also presented to ponder the proposed model of the power system and select the optimal schedule of devices for having the highest operation of the energy system of smart homes. A technical-economic objective function is considered for finding the best schedule of devices. Ultimately, the proposed method is simulated in a sample smart home for evaluating the model of devices and energy system. Ultimately, the efficiency of the proposed energy system of the smart home is pondered based on the simulation results.

Keywords Analytical and mathematical modeling · Energy system · Renewable distributed generation · Smart appliances · Smart home

Nomenclature

I_i Mode of appliance i at period t
 n_p Number of the time interval during the day

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p_s	Starting time interval of appliance i
p_e	Ending time interval of appliance i
OP_i	Proper number of operating time intervals of appliance i
K	The shape coefficient of Weibull
C	The scale coefficient of Weibull
V	Wind speed
V_{ci}	Cut-in speed of wind
V_{co}	Cut-out speed of wind
V_r	Rated speed of wind
$P_{w-rated}$	Rated output power of the WT
S_i	The solar irradiance
η	Efficiency of PV
A	Total area of PV
I_{EP}	Electricity bill of the smart home
I_{PD}	Peak demand of the smart home
C_{PN}	Cost of purchased energy from the power network
n_a	Number of appliances
pa_i	Consumption of each appliance at each period
P_{AP_i}	Total consumption of appliances at period t
n_{type}	Technology of the DG unit
n_{DG}	Number of considered type of DGs
P_{DG_t}	Total produced power of renewable DGs at period t
Tr_t	Electricity tariff at period t
pr_t	Electricity price of sold back to the grid at period t
pr_{DG_t}	Cost of producing 1 KWh energy by renewable DG unit
P_{App_t}	Total consumption of all appliances of SH at period t
P_t^{APP}	Demand of appliances
P_t^{SH2PN}	Sold energy to the power network
P_t^{PN2SH}	Purchased energy from the distribution system
P_t^{RDG}	Produced power of renewable DG units
P_{RDG}^{min}	Minimum level of producing the power of DG
P_{RDG}^{max}	Maximum level of producing the power of DG

1 Introduction

Nowadays, the imagination of the world without electrical energy is approximately impossible. This dependence causes the power network becomes more complex over time in order to respond to the demand of consumers. On the other side, the progress of technology improves the performance of old devices of the energy system and also adds new devices to this network. All the mentioned issues increase the complexity of energy systems. Analytical and mathematical modeling of devices of the system is one of the useful methods for proper recognizing the devices and better managing the

energy system. Modern homes, which are known as smart homes, are a power network in the small size. For this reason, the energy model of the smart home (SH) is so similar to the model of the energy system according to the consumption and production sides. A smart home has the consumer and producer devices the same as an energy network. In the smart homes, appliances like refrigerator and lights consume electricity while domestic renewable energy sources like wind turbine and photovoltaic panel produce green energy. Renewable units produce electricity based on the variation of their initial energy such as wind speed and solar irradiance; therefore, it is better that a stochastic formulation is considered for modeling renewable distributed generation units due to the stochastic behavior of their initial energy [1–3].

The concept of a smart home is a fundamental combination of different subsystems related to automatically control of home devices through advanced technologies. It can both share generation units and transfer within the home, and the operator can exchange data with your SH external network through your home smart gateway. Its base purpose is to supply people with an efficient, easy, secure, useful and eco-friendly living environment integrating system, service and management. Devices of a smart home are connected with each other and also are controllable through one central point such as home energy management system (HEMS). HEMS of the smart home observes and manages all appliances in real-time, regards to predetermined constraints and user's preferences, for decreasing electricity bill, decrease the dependence of the SH the power network and improve energy utilization efficiency. The sample diagram of a SH is demonstrated in Fig. 1 [4, 5].

As mentioned above, the management of a smart home has an effect on the performance of that. In this regard, some researchers have studied energy sources, appliances and operational schedule of smart homes. For example, In Ref. [6], the alternating current and direct current grid arrangement of smart homes has been proposed for improving the used penetration of distributed generation units and reducing the dependence of the Microgrid on the upper network. In this paper, devices of SHs in a micro grid have been managed. Moreover, both grid-connected and off-grid modes of Microgrid have been evaluated in this study. An energy management framework has been proposed for optimizing the operational schedule of home devices in Ref. [7]. This optimization has been done in two steps. In the first step, each consumer minimizes his pay charge. In the second step, smart distribution company minimizes deviation of distribution system load and the cost of modifying the desired scheduling of consumers. In another study, the demand side management has been done in a SH with photovoltaic panel and battery [8]. In this chapter, management charging and discharging of storage system is the main purpose which is solved by a methodology based on artificial neural network. The availability of solar irradiance and the cost of purchasing power from the power network have been considered for better managing the operational time of battery. In another study, authors have studied the residential load commitment framework for achieving the minimum electricity bill for consumers [9]. The operating schedule of appliances and also the charging time and the discharging time of battery and electric vehicles has been scheduled in this paper.



Fig. 1 Overall diagram of a smart home

Therefore, the advantages of properly managing smart homes have been shown in some papers. For completing the previous studies, this chapter focuses on the analytical and mathematical modeling of the energy system of a smart home. An optimization algorithm is also utilized to ponder the proposed model of the energy system and find the highest efficiency of devices for having the best operation of the energy system of SH. Firstly, the total introduction of energy systems is presented and then modern smart homes are introduced and their energy system is described. Later, modeling of the producer and consumer devices of the smart home’s energy system is presented analytically and mathematically. Then, a new method based on intelligent algorithms is introduced for optimizing the hourly performance of home appliances and renewable energy sources with regard to stochastic behavior of renewable units for decreasing the electrical cost of the SH and improve the efficiency of the energy system. Ultimately, the proposed method is simulated in a sample smart home for

evaluating the model of devices and energy system. Ultimately, the efficiency of the proposed energy system of the smart home is pondered based on the simulation results.

2 Energy Systems

A system is a group of interrelated or interacting entities which work together for getting common purposes. This feature can be seen clearly in energy systems. An energy system, which consists of many parts and devices, is utilized to deliver the electricity to the consumers. The energy system of electrical energy is the combination of generation, transmission and distribution systems so that each of these systems also consists of some subsystems for better delivering the electrical power to the costumers of the energy system.

2.1 *Smart Homes*

A smart home has the energy system in a small size. Of course, the transmission system doesn't exist in the energy system of smart homes. In other words, both types of producer and consumer devices are in a smart home while only consumer appliances were in traditional homes. In smart homes, the demand of controllable and non-controllable appliances is supplied using the produced power of renewable energy sources and the bought power from the upstream power system.

The optimal management of the operating schedule of appliances and renewable energy sources of smart homes has high effect on the technical and economic parameters of homes. Moreover, the environmental indices are also improved by reducing the dependence of the smart home on the produced power of non-renewable sources.

The HEMS has the responsibility to optimal manage the devices of smart home based on the predetermined constraints and user's preferences. The HEMS finds the best schedule of energy sources and appliances of the smart home so that for improving the efficiency, economics, reliability, and energy conservation of both the smart home and the distribution system.

The HEMS optimizes the best schedule of devices using the predetermined parameters, the condition of market price and the situation of the produced power of wind turbine and photovoltaic panel. The modeling of domestic energy sources and home appliances of the smart home are defined in the HEMS. Moreover, main purposes, constraints and the optimization method are also predetermined in the HEMS based on the user's preferences. The required modeling, objective functions, constraints and optimization algorithm for better managing the energy system of the smart home are explained completely in the next sections.

3 Modeling of Smart Home Energy Devices

In this section, the modeling of home appliances and renewable energy sources are explained analytically and mathematically.

3.1 Home Appliances

One of the main differences between a smart home and a traditional home is the ability to control the appliances of the smart home in order to decrease the consumer's costs and improve the performance of the home's energy system. Appliances are connected to the HEMS of the smart home using the internal technology or another external device.

Smart appliances can be divided into controllable and non-controllable devices. The controllable appliances are the devices which can participate in the demand-side management program and can be scheduled in 24-hour based on the situation of market price and domestic energy sources. On the other side, non-controllable appliances are non-schedulable devices so that their operational time is constantly based on the user's predetermined schedule.

- **Non-controllable appliances**

In the smart home, some appliances cannot participate in the energy management program because their operating schedule is predetermined by the user's preference and lifestyle. This type of devices is called non-controllable or non-schedulable appliances. Samples of this type of appliances can be shown in Fig. 2.

- **Controllable appliances**

Unlike non-controllable devices, some appliances of the smart home participate in the home energy management program for improving the performance of electricity and decrease the electricity bill of the consumer. This type of appliances is called controllable or schedulable devices. The operating time of manageable devices is managed based on the situation of the electricity cost, weather and other predetermined constraints. Figure 3 shows samples of controllable appliances in smart homes.

- **Modeling**

In this chapter, the time-varying model of appliances is considered. In other words, the starting time of appliances is only optimized by the proposed method while the consumption power of devices is constant at each time interval of the operating period. It means that the demand profile of appliances should not be changed by the HEMS; otherwise the considered device operates incorrectly. For instance, if the power of the oven at period t is reduced by the energy management program, the



Fig. 2 Samples of non-schedulable appliances

temperature of the oven doesn't reach the proper degree for baking a delicious Apple pie. Hence, only the starting time of the appliances is optimized by the HEMS.

Therefore, the home energy management system selects the best schedule for the operation time vector of appliances. Equation (1) shows the daily state vector of each appliance in the smart home.

$$I_i = [I_1, I_2, \dots, I_t, \dots, I_{T-1}, I_T] \tag{1}$$

Here, I_t is the mode of appliance i at time-interval t ; the amount of this parameter is 1 or 0 that it is equal to on/off of appliance i at time-interval t . All devices should be executed during the day; this constraint is formulated in Eq. (2).

$$\sum_{t=1}^{n_p} I_{it} \geq 1 \tag{2}$$

Moreover, each appliance has the number of operating periods. In other words, each device needs to run for consecutive periods without interruption when it is started. Equation (3) demonstrates this constraint.



Fig. 3 Samples of schedulable appliances

$$\sum_{t=p_s}^{p_e} I_{it} = OP_i \quad (3)$$

As regards to this constraint, the starting time of devices should be selected based on Eq. (4).

$$p_s \leq n_p - OP_i + 1 \quad (4)$$

Therefore, the operating schedule of appliances should be based on Eqs. (1)–(4). Although the starting time of non-controllable appliances is predetermined, the operating time intervals and the ending time of devices are selected using these equations.

3.2 Home Renewable Energy Units

Wind turbines and photovoltaic panels are the most useful technologies of distributed generation units that are used in smart homes. Although renewable energy sources are Eco-friendly, the intermittent nature of the initial energy of those should be considered

for calculating the produced power of renewable DG units. So, the uncertain speeds of wind and illumination intensity of the sun are the main parameters that have effect on the output power of WT and PV, respectively.

In this chapter, a stochastic method is used to compute the amount of uncertain parameters of wind turbine and photovoltaic panel. The hybrid method of Latin hypercube sampling algorithm and K-means clustering algorithm is utilized to find the conserved stochastic data [10].

In the following, the analytical and mathematical modeling of home renewable energy sources is presented [11, 12].

- **Wind turbine unit**

In most countries which are the pioneer in the clean energy, wind turbine (WT) is one of the common and useful renewable DG technologies. WT converts wind energy into electrical energy. In smart homes, the small size of wind turbines is utilized to supply the demand of the home. Figure 4 shows the wind turbines which is used in the residential areas.

Totally, the wind turbine has a stochastic performance. So it is better that a probabilistic model is simulated according to available historical data. The meteorological



Fig. 4 Wind turbines of residential areas

data is the best reference for estimating the wind energy potential of a special site. Regards to wind speed behavior and a large number of experiments, Rayleigh probability density function is utilized to model wind speed. Rayleigh distribution is a particular form of Weibull probability density function in which the shape index is equal to 2 [11].

Mathematically, the Weibull distribution of wind speed is presented by Eq. (5).

$$f(v) = \frac{K}{C^K} v^{(K-1)} e^{-\left(\frac{v}{C}\right)^K} \quad 0 \leq v \leq \infty \tag{5}$$

Thus, the equation between the electrical power of a WT and the wind speed can be formulated by Eq. (6).

$$P_w = \begin{cases} 0 & 0 \leq V \leq V_{ci}, V_{co} \leq V \\ P_{w-rated} \times \frac{V-V_{ci}}{V_r-V_{ci}} & V_{ci} \leq V \leq V_r \\ P_{w-rated} & V_r \leq V \leq V_{co} \end{cases} \tag{6}$$

According to Eq. (6) can be said that a wind turbine can generate energy when the wind speed is more than the minimum wind speed. The wind turbine produces electrical power until the wind speed is lower than the maximum limit.

• **Photovoltaic panel**

Photovoltaic (PV) is one of the popular and useful technologies of renewable DGs. PV panels can be located on the roof, in the yard and in the backyard of smart homes. Samples of utilized PV panels in smart homes are demonstrated in Fig. 5.

Although the area and efficiency of the solar panel have an effect on the produced power of PV panel, the electrical power of a PV unit is predominantly affected by the illumination intensity. So, the PV panel has also a stochastic behavior due to uncertain characteristic of solar power [12].

According to the last studies and experiments, it is shown that the stochastic behavior of solar power can be simulated by the Beta probability distribution function. Therefore, the equation between solar irradiance and the electrical power of a PV unit can be described by Eq. (7) [12].

$$f(Si) = \begin{cases} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \times Si^{(\alpha-1)} \times (1 - Si)^{(\beta-1)} & \text{if } 0 \leq Si \leq 1, \alpha \geq 0, \beta \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Here,

$$\beta = (1 - \mu) \times \left(\frac{\mu \times (1 + \mu)}{\sigma^2} - 1 \right) \tag{8}$$

$$\alpha = \frac{\mu \times \beta}{1 - \mu} \tag{9}$$



Fig. 5 Samples of PV panels in smart homes

where μ and σ are the mean and standard deviation, respectively; they are extracted from the random variable. After calculating the probability distribution function of the solar irradiance, the electrical power of a PV is calculated by Eq. (10).

$$P_S(S_i) = \eta \times A \times S_i \tag{10}$$

4 Optimizing Method of Smart Home Devices

In this section, objective functions, constraints and the optimization algorithm for selecting the optimal schedule of smart home's energy sources and appliances are described completely.

4.1 Objective Function

Minimizing the electricity bill and the peak demand of the SH is considered as the main purpose of the home energy management program. Therefore, optimizing the operational schedule of devices is a multi-objective problem. Mathematically, the main purpose of the optimization is presented by Eq. (11).

$$\text{Objective}_{function} = \min\{I_{EB}, I_{PD}\} \quad (11)$$

• The Electricity bill of the smart home

The HEMS provides the electricity power of smart home by using of purchased energy from the power network and home energy sources. Renewable distributed generation units are home energy sources. The produced power of the WT and the PV is variable based on weather and hour.

Therefore, the HEMS of the smart home schedules the hourly performance of appliances and home energy sources so that the total consumer's electricity bill becomes minimal.

The total electricity bill of the smart home is formed from the following items:

1. Cost of bought electricity from the power network
2. Cost of the produced electricity of wind turbine and photovoltaic panel
3. Income from selling the electricity to the power network

Consequently, the electricity bill of the smart home is formulated based on the costs and incomes in Eq. (12).

$$I_{EB} = C_{PN} + C_{RDG} - I_{PN} \quad (12)$$

C_{PN} is the cost of purchased energy from the power network. The consumer purchases his demand from the distribution-company with a variable price. As regards that there are renewable distributed generation units the smart home, a part of electricity demand is supplied by home energy sources and so the extra power is purchased from the distribution system. So, firstly, the total demand of all appliances at time-interval t is calculated by Eq. (13).

$$P_{Ap_t} = \sum_{i=1}^{n_a} pa_i \quad (13)$$

Then, Eq. (14) is utilized for computing the hourly production power of renewable distributed generation units.

$$P_{RDG_t} = \sum_{i=1}^{n_{type}} \sum_{j=1}^{n_{DG}} pd_{ij} \quad (14)$$

Consequently, Eq. (15) is utilized for calculating the hourly extra demand of SH that it is supplied by the power network.

$$P_{PN_t} = P_{Ap_t} - P_{RDG_t} \quad (15)$$

Finally, the daily cost of energy purchased from the distribution system is expressed in Eq. (16).

$$C_{PN} = \sum_{t=1}^{n_p} P_{PN_t} \times Tr_t \quad \text{if } P_{PN_t} > 0 \quad (16)$$

In this equation, Tr_t is the electricity tariff at period t which is predetermined by the independent system operator (ISO). It is worth mentioning that the length of each period is considered one hour; therefore, the total number of time-intervals in the day is 24.

As can be seen in Eq. (16), the smart home purchases energy from the distribution system when the consumption of appliances is more than the generation of home energy sources at the considered period. On the other side, the smart home sells power to the network at some periods when the generation of home energy sources is more than the consumption of appliances. Therefore, the income from selling the electricity to the power network is formulated in Eq. (17).

$$I_{PN} = \sum_{t=1}^{n_p} -1 \times P_{PN_t} \times pr_t \quad \text{if } P_{PN_t} < 0 \quad (17)$$

Here, the amount of pr_t is predetermined between ISO and consumer for various time-intervals.

The cost of the produced energy of renewable distributed generation units is presented in Eq. (18).

$$C_{RDG} = \sum_{t=1}^{n_p} \sum_{i=1}^{n_{type}} \sum_{j=1}^{n_{DG}} pd_{ijt} \times pr_{DG_i} \quad (18)$$

where, pr_{DG_i} is the cost of the produced 1 KWh energy by renewable DG unit; the costs of investment, maintenance and operation of DGs are merged in this parameter.

- **The peak demand of the smart home**

This index shows the peak consumption of the SH. This index, which is a technical index of the smart home, demonstrates the maximum hourly purchasing power of the smart home from the power network during the day. Equation (19) is utilized to calculate the peak demand of the smart home.

$$I_{PD} = \max_t \{ P_{App_t} \} \quad (19)$$

4.2 Constraints

In this chapter, the power balance constraint and renewable distributed generation units' constraint are considered in optimizing of the operational schedule of devices of the smart home.

- **Power balance constraint**

This constraint is presented at period t by Eq. (20).

$$P_t^{PN2SH} + P_t^{RDG} = P_t^{APP} + P_t^{SH2PN} \quad (20)$$

This equation states that the demand of appliances (P_t^{APP}) and the sold energy to the power network (P_t^{SH2PN}) are satisfied by the purchased energy from the distribution system (P_t^{PN2SH}) and the produced power of renewable DG units (P_t^{RDG}).

- **Renewable DG constraint**

Renewable energy resources including wind turbine and photovoltaic can produce electrical energy in the following range:

$$P_{RDG}^{min} \leq P_{RDG} \leq P_{RDG}^{max} \quad (21)$$

4.3 Intelligent Algorithm

In this research, the combination of multi-objective grey wolf optimization (MOGWO) and fuzzy method is utilized to multi-objective optimize the operating

scheme of smart home’s appliances and energy sources. For getting the best result, firstly, the MOGWO is utilized to optimize the multi-objective function and create the optimal Pareto-front. After applying the MOGWO algorithm, the fuzzy method is used to find the optimal particle from the non-dominated particles.

• **Multi-objective grey wolf optimization algorithm**

Intelligent algorithms are usually inspired from existing natural behaviours of nature. The optimization method of MOGWO is inspired from the grey wolves. Grey wolves which belong to Canidae family are considered as apex predators. This means that they are at the top of the food chain. Grey wolves mostly prefer to live in a pack with a group size [13].

The MOGWO is based on social behavior of Wolves. In this meta-heuristic algorithm, the best solution is considered as α wolf. β and δ wolves are the second and third solutions, respectively. The rest of particles are assumed as ω wolves. The optimization method of the MOGWO is managed by alpha, beta and delta so that the omega wolves follow α , β and δ wolves for reaching the best result.

So in this algorithm, the position of each particle is updated by [13]:

$$X(t + 1) = X_p(t) - A.D \tag{22}$$

where,

$$D = |C.X_p(t) - X(t)| \tag{23}$$

$$A = 2a.r_1 - a \tag{24}$$

$$C = 2r_2 \tag{25}$$

Here, X_p and X show the position vector of the prey and the position vector of a grey wolf, respectively. Vectors of A and C are the coefficients. Moreover, a linearly decrease from 2 to 0 over the iterations while vectors of r_1 and r_2 are random in [0 and 1].

The extra detail of the MOGWO algorithm is available in Ref. [13].

• **Fuzzy method**

After optimizing the technical-economic issue of energy management of the smart home, the fuzzy decision-making method run to choose the optimal compromise solution which represents the optimal amount of technical and economical indices equal to the best schedule of smart home energy sources and appliances.

In the fuzzy decision-making method, the best result is selected in two steps. Firstly, membership values of each particle based on various objective functions are calculated by Eq. (26) [14].

$$\mu_i^k = \begin{cases} 1 & F_i^k \leq F_i^{min} \\ \frac{F_i^{max} - F_i^k}{F_i^{max} - F_i^{min}} & F_i^{min} < F_i^k < F_i^{max} \\ 0 & F_i^{max} \leq F_i^k \end{cases} \quad (26)$$

$$\mu^k = \frac{\sum_{i=1}^{NO} \mu_i^k}{\sum_{k=1}^{NK} \sum_{i=1}^{NO} \mu_i^k} \quad (27)$$

Then, Eq. (27) is utilized to calculate the total membership value of each non-dominated particle which is in the Pareto-front. In these equations, F_i^{min} and F_i^{max} demonstrate the lower and upper bound of index i , respectively. F_i^k shows the amount of particle k based on the objective function i .

Finally, each particle which has the highest amount of total membership value is selected as the best compromise solution [14].

Consequently, the complete method for managing the daily energy of the smart home is demonstrated in Fig. 6. This figure presents that firstly, details of home appliances, wind turbine unit, photovoltaic panel and economic parameters are inputted into the HEMS. Then, the HEMS produces initial random particles for utilizing the intelligent algorithm and calculating the stochastic amount of renewable DG units. Particles are improved by applying MOGWO with considering objective functions and constraints. Finally, HEMS utilize the fuzzy decision-making method for selecting the best particle equal to the optimal daily schedule of home appliances, WT and PV.

5 Numerical Results

In the previous sections, the modeling of home's appliances and energy sources are analytically and mathematically described. In this part, the proposed method for energy managing the smart home is pondered using the evaluation of the considered technical and economic objective functions.

It is considered that the smart home purchases energy from the grid with a variable tariff based on the time-of-use demand response program which is defined by the independent system operator. Figure 7 shows the hourly price of the electrical energy. Moreover, the distribution company buys the extra produced energy of the smart home with the tariff of 0.129 \$/KWh. The price of the produced power of the wind turbine and photovoltaic are also determined at 0.075 and 0.063 \$/KWh, respectively. The considered cost of renewable energy units is an overall cost which is the combination of the costs of installation, maintenance and operation of these units.

As mentioned above, the smart home energy management can utilize the wind turbine and photovoltaic for providing the demand of the smart home. The installed renewable sources are the PV of 335 W SolarPower X21 and the WT of 1500 W WINDMILL. The rated illumination intensity of the PV is 1000 W m^{-2} , and the shape and scale indices are 1.8 and 5.5, respectively. Moreover, the cut-in, normal

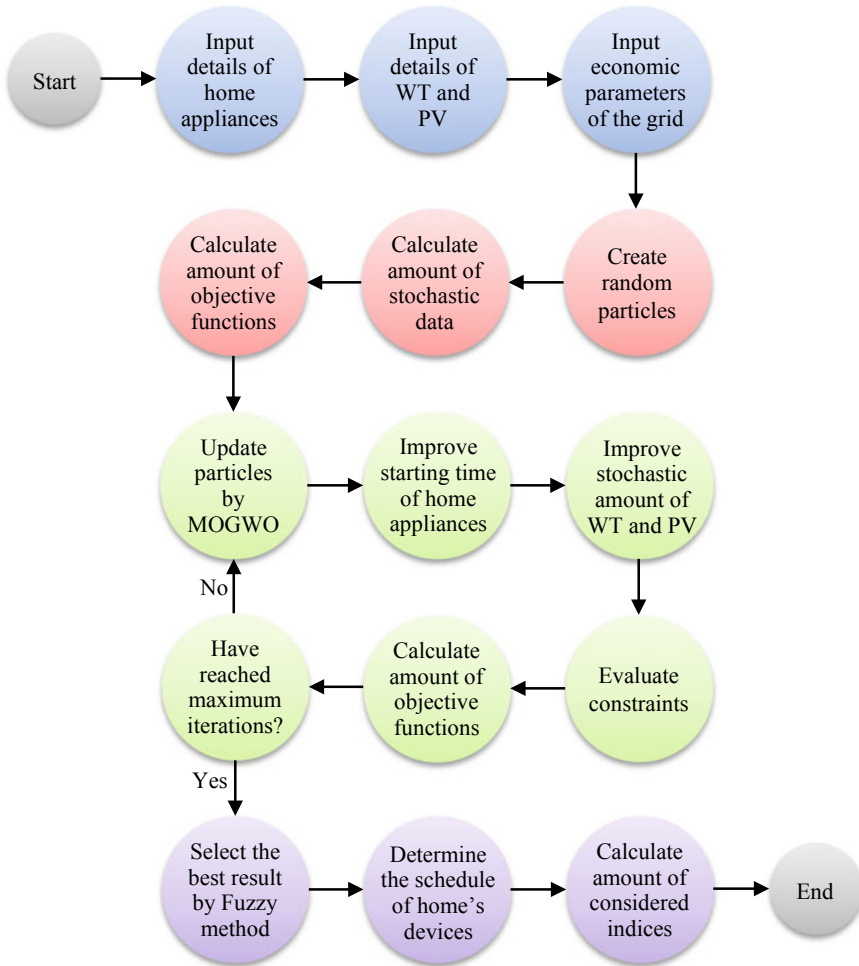


Fig. 6 Flowchart of the energy management of the smart home

and cut-out speeds of the WT are 4, 13 and 20 m/s. The shape and scale indices are 2 and 6.5, respectively. The maximum daily wind speed and solar irradiance in the area, which the sample smart home is located, are 8.5 m/s and 1 kW/m², respectively. The hourly variations of stochastic parameters in Pu are presented in Fig. 8 [15, 16].

The appliances of the smart home are divided into controllable and non-controllable devices. Washing machine, dishwasher, boiler, vacuum cleaner and Iron are considered as controllable appliances while refrigerator, purifier, lights, microwave oven, oven and TV are non-controllable devices of the Home.

The number of time-intervals of the day is considered equal to 24. Figure 9 and Fig. 10 show the demand of controllable and non-controllable appliances in their operational period, respectively [17]. It is worth mentioning that each appliance

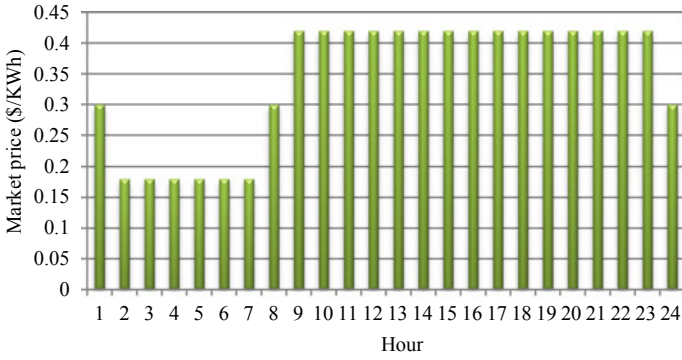


Fig. 7 Hourly market price of the grid

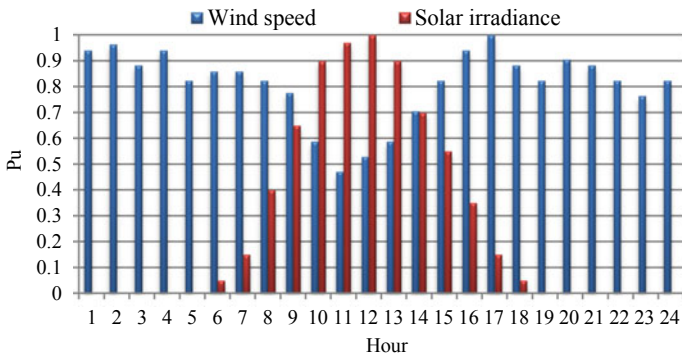


Fig. 8 Hourly variation of wind speed and solar irradiance

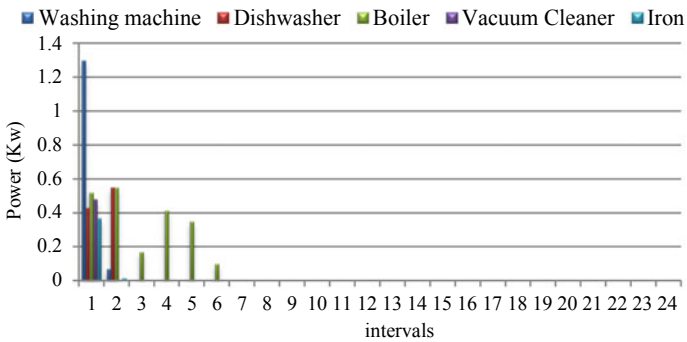


Fig. 9 The demand of controllable appliance in their operational period

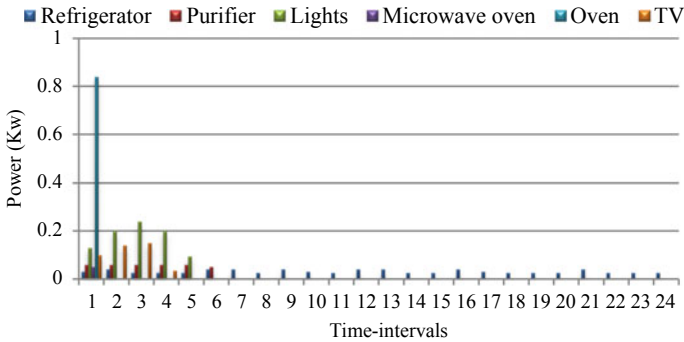


Fig. 10 The demand of non-controllable appliances in their operational period

needs a constant number of time-intervals for properly doing its duty. The number of time-intervals of each device is shown in Figs. 9 and 10.

So, the proposed management method is used to find the optimal schedule of home’s devices and renewable sources. Firstly, the MOGWO algorithm is used to multi-objective optimized the techno-economical objective function. The variations of the economic and technical indices during iterations of MOGWO and also the obtained optimal Pareto-front after applying the meta-heuristic algorithm are demonstrated in Fig. 11.

After finding the optimal Pareto-front, the fuzzy method is applied to non-dominate solutions for selecting the best result. The optimal starting time of appliances is presented in Table 1.

The starting time of appliances is selected so that the load density reduces and also the most part of the demand is provided by the smart home renewable energy sources. This management causes to improve the technical and economic indices of the home.

Figure 12 demonstrates hourly power of all appliances and also the stochastic power of renewable units of the smart home. As can be seen in this figure, wind turbine and photovoltaic can provide the most part of the home’s demand so that these sources supply approximately 97% of daily demand of the smart home. Moreover, the owner of the smart home can sell power to the grid at time-intervals that the produced power of DG units more than the demand of the home. On the other hands, appliances of the smart home are operated at times when home’s energy sources are available or the cost of the market price is low. Totally, the proposed energy management causes to reduce the purchasing power of the smart home from the distribution system. This issue is clearly evident in Table 2.

Table 2 shows the hourly transferred power between the SH and the grid. In this table, the positive number shows that the smart home purchases energy from the grid while the negative number presents that the home sells energy to the grid at time-interval.

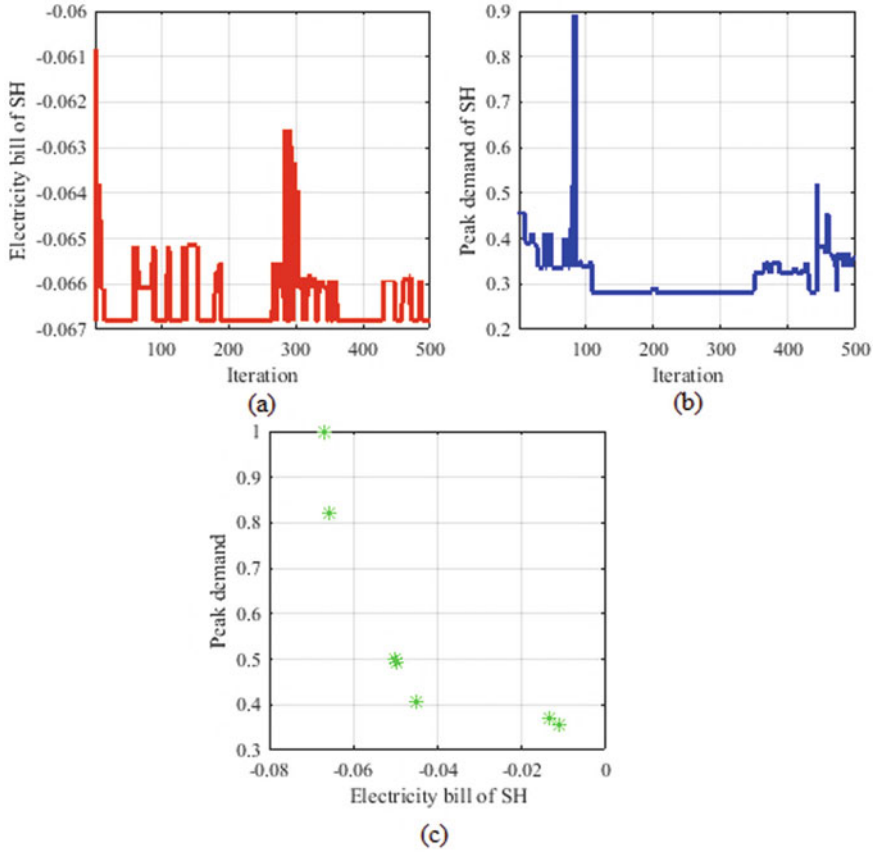


Fig. 11 a The variation of the economic index at each iteration, b the variation of the technical index at each iteration and c the obtained optimal Pareto-front after applying the MOGWO algorithm

Table 1 The optimal starting time of smart home appliances

Controllable	The starting time	Non-controllable	The starting time
Washing machine	13	Refrigerator	1
Dishwasher	3	Purifier	12
Boiler	4	Lights	20
Vacuum cleaner	22	Microwave oven	16
Iron	14	Oven	15
		TV	20

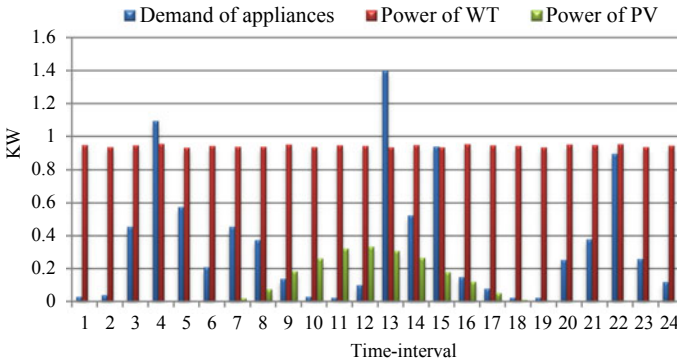


Fig. 12 Hourly demand of appliances and stochastic power of renewable sources

Table 2 Hourly transferred electricity between the smart home and the network

Time-interval	Amount of power	Time-interval	Amount of power
1	-0.9181	13	0.1562
2	-0.8957	14	-0.6904
3	-0.4915	15	-0.1736
4	0.1398	16	-0.9261
5	-0.3579	17	-0.9193
6	-0.7340	18	-0.9302
7	-0.5027	19	-0.9151
8	-0.6381	20	-0.6975
9	-0.9958	21	-0.5688
10	-1.1684	22	-0.0580
11	-1.2441	23	-0.6759
12	-1.1770	24	-0.8246

Therefore, the peak demand of the smart home is improved 88.85% after applying the proposed method so that the peak demand of the home is 0.1562 kW after managing the home’s appliance and energy sources using the proposed method while the initial amount of this index is 1.4 kW.

The hourly economic details of the smart home including of cost of purchasing power from the system, the profit of sold power to the system, the cost of produced power of WT and PV and also the hourly electricity bill are presented in Table 3. According to this table, the proper coordination between the operational time of home’s appliances and the produced power of renewable sources causes that the owner of the smart home has to buy energy from the grid on at 4th and 13th time-intervals. At other time-intervals, the customer earns money by selling energy to the distribution company. The initial electricity bill of the smart home is 2.8635 \$

Table 3 Hourly economic details of the smart home

Time interval	Cost of purchased power	Profit of sold power	Cost of renewable energies	Electricity bill
1	0.0000	-0.1184	0.0711	-0.0473
2	0.0000	-0.1155	0.0702	-0.0454
3	0.0000	-0.0634	0.0710	0.0076
4	0.0252	0.0000	0.0716	0.0968
5	0.0000	-0.0462	0.0700	0.0238
6	0.0000	-0.0947	0.0708	-0.0239
7	0.0000	-0.0649	0.0716	0.0067
8	0.0000	-0.0823	0.0751	-0.0072
9	0.0000	-0.1285	0.0830	-0.0455
10	0.0000	-0.1507	0.0867	-0.0640
11	0.0000	-0.1605	0.0913	-0.0692
12	0.0000	-0.1518	0.0918	-0.0601
13	0.0656	0.0000	0.0896	0.1552
14	0.0000	-0.0891	0.0880	-0.0011
15	0.0000	-0.0224	0.0814	0.0590
16	0.0000	-0.1195	0.0792	-0.0402
17	0.0000	-0.1186	0.0743	-0.0443
18	0.0000	-0.1200	0.0715	-0.0485
19	0.0000	-0.1180	0.0704	-0.0476
20	0.0000	-0.0900	0.0714	-0.0185
21	0.0000	-0.0734	0.0712	-0.0022
22	0.0000	-0.0075	0.0715	0.0640
23	0.0000	-0.0872	0.0702	-0.0170
24	0.0000	-0.1064	0.0708	-0.0355

while the daily electricity bill of the home is -0.2046 after applying the proposed management method. It means that the owner of the smart home earns money after operating the appliances and renewable sources of the smart home by the HEMS.

6 Conclusion

The proper management of appliance and energy sources of a smart home has a high effect on the performance of the smart home. Manually controlling the home's devices is difficult for the consumer due to the number of devices and their load profile, the variation of market price and the situation of renewable units. For this reason, automatically managing the smart home's appliances and renewable energy resources

was investigated in this chapter. Firstly, analytical and mathematical modeling of devices was presented and then the optimal hourly schedule of appliances, WT and PV was selected by applying the combination of MOWOA and fuzzy method to the techno-economic objective function.

The numerical results demonstrate that the home energy management system can properly schedule the operational time of home's devices in order to improve the considered indices. Appliances are operated at times when the market price is low or the produced electricity of the WT and the photovoltaic panel is high. On the other hands, renewable sources reduce the dependence of the smart home on the power of the grid so that sources can supply about 97% of the home's demand. The effect of the WT is higher than the PV because the power of WT is available approximately all hours of the day while the operational time of the PV panel is limit based on solar irradiance. The considered technical and economic indices of the smart home are improved about 89% and 107% after operating the home's appliances and renewable sources using the proposed energy management method, respectively. Therefore, it can be said that the proposed method improves the efficiency of electrical power and the comfort of the consumer.

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