Technical-economic management of smart home energy system in the presence of stochastic and seasonal behavior of PV and EV

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Smart home energy management is a useful tool to optimally manage the energy devices of a dwelling. A building with renewable units, controllable appliances, and the electric vehicle has the ability to implement home energy management. This study presents a novel multi-objective method for the smart home energy management system during the different seasons. The smart home has controllable and uncontrollable appliances while the rooftop photovoltaic panel can supply part of the demand during the day. The considered private electric vehicle has the vehicle-to-home technology for better participation in the home energy management program. The solar irradiance, state of charge, and availability of the electric vehicle in the parking are the uncertain parameters that are calculated using the combination of Latin hypercube sampling and K-means algorithms. The defined multi-objective technical-economic function is optimized using the dragonfly algorithm and then the best solution is selected using the fuzzy mechanism. The considered multi-objective algorithm is compared with other optimization methods for showing its efficiency. The numerical results, which are the output of implementing the method in a sample smart home, show the proper performance of the proposed method rather than other algorithms by about 10-40 %. Although the proposed method considerably improves the indices of the smart home, the highest efficiency of the smart home is achieved after applying the proposed energy management method on a spring day because of more availability of domestic energy units.

keywords: *Electric vehicle, energy management program, rooftop photovoltaic panel, smart home, uncertainty.*

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NOMENCLATURE

$S_{j,t}$	The situation of appliance j at time-interval t
OP_j	The operational period of appliance j
t_{ST}	The staring time interval of appliances
t_{ET}	The ending time interval of appliances
r_{si}	Value of solar irradiance
μ	Mean value
σ	Standard deviation
η_{panel}	The efficiency of the PV panel
A_{panel}	The area of the PV panel
μ_X	Mean amount of EV stochastic parameter
σ_X^2	Variance amount of EV stochastic parameter
x_{min}^X	Minimum amount of EV stochastic parameter
x_{max}^X	Maximum amount of EV stochastic parameter
S_t^{Ch}	Off or on mode of EV for charging
S_t^{Dis}	Off or on mode of EV for discharging
SOC_{min}	Minimum SOC of EV
SOC_{max}	Maximum SOC of EV
R_{ch}	Maximum charge rate of EV
R_{Dis}	Maximum discharge rate of EV
SOC_t	SOC of EV at time-interval t
SOC_{Ins}	Initial SOC of EV
t_{DT}	Departure time of EV
t_{AT}	Arrival time of EV
SH_D	The daily demand of the SH
SH_{EC}	The energy cost of the SH
Dem_t	The required demand of the SH at the period t

n_{TI}	Number of time intervals in 24-hour
AP_t	The power of all appliances at period t
DP_t	Produced power of domestic energy units at period t
C_{G2H}	The cost of purchased power from the grid
R_{H2G}	The revenue of sold power to the grid
n_{App}	Number of home appliances
$Dem_{App,i}$	Demand of appliances i at time interval t
$Power_{App_t}$	Total hourly energy consumption of all appliances
n_{DG}	Number of PV units
$G_{PV,j}$	The produced power of PV panel j
n_{EV}	Number of EV
$p_{EV,i}$	Power of EV at time interval i
S_i	The situation of EV at time interval i
η	Efficiency
$Power_{SH_t}$	Power of the SH at hour t
Tr_t	The electricity tariff at period t
pr_t	The tariff of bought electricity from SH at period t
E_t^{APP}	The energy of appliances at period t
$E_t^{EV,Ch}$	The charged energy of EV at period t
E_t^{H2G}	The sold energy to grid at period t
E_t^{G2H}	The bought energy from grid at period t
E_t^{PV}	The generated energy of PV at period t
$E_t^{EV,Dis}$	The discharged energy of EV at period t
N	Number of neighboring particles in MODA
P_j	Position of particle j in MODA
V_j	Velocity of particle j in MODA
P	Position of current particle in MODA
P^+	Position of food (the best particle) in MODA
P^-	Position of enemy (the worst particle) in MODA

Abbreviations

SH	Smart home
HEMS	Home energy management system
PV	Photovoltaic panel
EV	Electric vehicle
V2H	Vehicle to home
MODA	Multi-objective dragonfly algorithm
ST	Starting time of appliances
ET	Ending time of appliances
PDF	Probabilistic distribution function
SOC	State of charge of the EV
AT	Arrival time of the EV to the parking
DT	Departure time of the EV from the parking
LHS	Latin hypercube sampling method

1. INTRODUCTION

Nowadays, the trend of using green and efficient technologies is increasing considerably due to environmental, technical, and economic advantages. One of the practical ways for implementing eco-friendly technologies is the concept of the smart home [1]. In a smart home (SH), the dependence of the building on the electrical energy of the grid, the amount of energy cost, and the rate of environmental pollution are declined using controllable appliances and renewable resources [2]. Of course, the optimal method of operating home devices is managed through a home energy management system (HEMS). It evaluates the situation of renewable units, grid, and user comfort, the condition of controllable and uncontrollable appliances, in order to choose the best operational plan for energy consumers and generators [3]. With the aim of green energy development, it is essential to increase the participation of eco-friendly units in HEMS. The rooftop photovoltaic panel (PV) with eco-friendly technology is a practical choice for householders to decrease their dependence on the energy of the grid [4]. An electric vehicle (EV), as a flexible load, with the vehicle to home (V2H) technology, has a bidirectional operation with the home. The battery of the EV receives energy from the SH and sends energy to it based on the technical or economic conditions [5]. A typical energy connection between different devices of a SH such as smart appliances, rooftop PV panels, and a private electric vehicle is shown in Fig. 1.

In the last years, the home energy management system has received significant attention from researchers. Balakrishnan and Geetha reviewed articles on home energy management systems in Ref. [6]. In this paper, the reviewing method is based on the home energy management systems for various situations and states. The analysis of home energy management on energy consumption has been presented in Ref. [7]. In this study, the authors evaluated the variation of consumption patterns after implementing home energy management systems in ten smart homes. Ref. [8] is one of the articles about the main protocols of smart homes and home energy management systems. In other words, the structure and efficiency of two protocols for wireless communication between sensors and electrical appliances, Zigbee and Z-Wave, have been evaluated in this paper. According to the results, Zigbee has a higher chance to achieve dominance in the market. In Ref. [9], an algorithm has been presented for a home energy management system based on the butterfly algorithm. Reducing the consumption expenses and improving the satisfaction of end-users are the main purposes of home energy management. The authors in Ref. [10] studied home energy management for finding the minimum energy cost. Here, the stochastic optimization approach is utilized to find the supply, demand, and electricity price. Household appliances, battery storage systems, and electric vehicles have been considered in the scheduling problem. Mehrjerdi and Hemmati represented an efficient method for home energy management in the grid-connected smart home [11]. In the considered smart home, electric vehicle, wind turbine, and diesel generator have been scheduled for reducing the daily energy cost of the building. In Ref. [12], a home energy management strategy has been proposed to enable residential smart homes to implement self-power energy during a planned outage period of the upstream network. The domestic photovoltaic panel is considered as a distributed energy. Agbodjan et al. [13] suggested a controller to reformulate the discrete stochastic constraints. This controller, which has been evaluated in the context of the home energy management system, is practical for avoiding the exponential growth of scenario tree. In Ref. [14], the authors developed a framework for the operation of HEMS in a residential distribution network in order to optimal and secure operation of the network. The main purpose of the optimization is to minimize the energy consumption of customers. The house owners are rewarded for their cooperation in the energy management of the grid. The home energy management system has been proposed in Ref. [15] in order to control and schedule home devices and EVs for reducing the energy consumption expenses of the SH. In Ref. [16], a reinforcement learning algorithm has been utilized in order to monitor household electric appliances for minimizing energy consumption using the proper optimization of the energy resources. The HEMS has been investigated in Ref. [17] in the presence of flexible appliances, electric vehicle, and energy storage unit. The proposed management method is optimized to decline the electricity bill of the house. Veliz et al. [18] introduced a developing algorithm for the optimal energy management of the SH. This method is practical for solving multi-objective energy management problem in houses. The proposed framework has the ability to select the best goal for finding the proper operational schedules between the defined various indices of the SH. Ref. [19] is one of the articles about main protocols of smart homes and home energy management systems. In other words, the structure and efficiency of two protocols for wireless communication between sensors and electrical appliances, Zigbee and Z-Wave, have been evaluated in this paper. According to the results, Zigbee has a higher chance to achieve dominance in the market. Balakrishnan and Geetha reviewed articles of home energy management system in Ref. [20]. In this paper, the reviewing method is based on the home energy management systems for various conditions and cases depending on different climate conditions, appliances, controllers, algorithms, home occupants and their living styles. A review of smart home energy management system has been presented in Ref. [21] to identify current trends to smart homes and challenges for future improvement of smart home energy management systems. According to this study, lack of quality attributes such as security, privacy, scalability, interoperability, and difficulty in managing and adapt to the thermal comfort satisfaction of residents are the main challenge of smart homes. The analyzing of home energy management on the energy consumption has been presented in Ref. [22]. In this paper, the authors evaluated the changes in electricity consumption, daily consumption profile and number of low and high consumption hours after implementing home energy management systems in ten smart homes. The authors of Ref. [23] proposed a framework based on building information model to optimize the energy consumption of smart residential buildings. Different materials, equipment, and project locations are considered in the proposed method of this study. In [24], a stochastic method based on the particle swarm optimization algorithm has been investigated for load disaggregation of appliances in a smart home. The proposed method has been evaluated in six different smart homes.

The current paper presents a novel multi-objective method for the home energy management system in a SH in the various seasons. For obtaining the results closer to the real operational condition, the solar irradiance and state of charge, arrival time, and departure time of the EV are formulated as stochastic parameters which are calculated using the Latin hypercube sampling and K-means algorithms. The stochastic method finds the uncertain parameters of PV and EV based on their previous data during each season. The hybrid intelligent algorithm including multi-objective dragonfly algorithm (MODA) and fuzzy mechanism is used to optimize the considered technical-economic indices of the SH. So the main highlights of this manuscript are as follows;

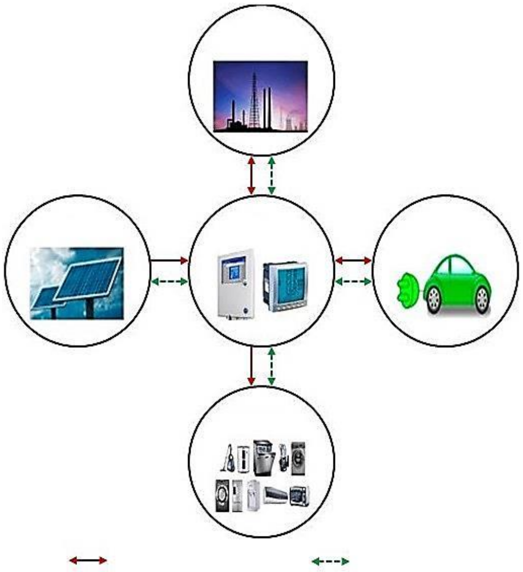


Fig. 1. Communications of a sample smart home

- The home energy management system is addressed by incorporating controllable and uncontrollable appliances, rooftop PV unit, and EV with V2H technology.
- The smart home is able to bidirectional operation with the grid.
- The uncertainty of PV and EV are included and the seasonal pattern is considered for the availability of EV and solar irradiance.
- The minimizing of the daily energy cost and demand of the SH are formulated as the main aims of HEMS.

In Section 2, a model of a smart home including home appliances, a rooftop PV, an EV, and seasonal behavior is formulated. Section 3 shows the proposed energy management method including objective functions, constraints, the intelligent algorithm, and the overall procedure. Section 4 is about the simulation results and discussion on the performance of the proposed method. The ultimate conclusion is presented in section 5.

2. MODELING OF SMART HOME

The HEMS has the responsibility to manage the dwelling's device. In this section, the method of formulating the various devices of the SH in the HEMS is presented.

A. Home appliances

The appliances of a smart home are controllable and uncontrollable. The formulating models of both types are the same. Only, the starting time (ST) of uncontrollable appliances is predetermined and constant during the optimization. Firstly, for each appliance, a vector is defined by Eq. (1) for showing its situation at time intervals.

$$App_j = \left[S_{j,1}, S_{j,2}, \ldots, S_{j,t}, \ldots S_{j,T-1}, S_{j,T}\right] \tag{1}$$

Here, $S_{j,t}$ shows the situation of appliance j at time-interval t. Its value is 1 when the appliance is on and it is zero when the appliance is off. Secondly, all appliances must be operated in 24-hour; this issue is presented in Eq. (2).

$$\sum\nolimits_{t=1}^{n_p} S_{j,t} \geq 1 \tag{2}$$

Thirdly, each appliance should have a constant operational period (OP_j) using Eq. (3).

$$\sum\nolimits_{t=t_{ET}}^{t_{ST}} S_{j,t} = OP_j \tag{3}$$

where t_{ST} and t_{ET} represent the ST and ending time (ET) interval of appliance j, respectively. So, the ST of each appliance should be selected based on Eq. (4).

$$t_{ST} \leq t_{ET} - OP_j + 1 \tag{4}$$

B. Rooftop photovoltaic panel

In urban areas, the roof of buildings is a suitable place for allocating renewable resources, especially photovoltaic panels, in order to generate green electrical energy. In other words, the rooftop PV unit is a practical way for utilizing the unused roof space in order to generate electricity. The produced power of PV is uncertain because of the stochastic behavior of solar irradiance. Thus, the Beta probabilistic distribution function (PDF) is utilized to formulate the stochastic performance of solar irradiance [25]. The Beta PDF for solar irradiance is mathematically presented by Eq. (5).

$$pdf\left(r_{si}\right) = \frac{\tau\left(A+B\right)}{\tau\left(A\right)\tau\left(B\right)} \times {r_{si}}^{(A-1)} \times \left(1-r_{si}\right)^{(B-1)} \tag{5}$$

where,

$$B = (1-\mu) \times \left(\frac{\mu \times (1+\mu)}{\sigma^2} - 1\right) \tag{6}$$

$$A = \frac{\mu \times B}{1-\mu} \tag{7}$$

where, A and B are parameters of the Beta PDF. r_{si}, μ and σ are the value of solar irradiance, mean and standard deviation. After calculating the amount of solar irradiance, Eq. (8) is used to calculate the PV's power.

$$P_{PV}\left(r_{si}\right) = \eta_{panel} \times A_{panel} \times r_{si} \tag{8}$$

Here, η_{panel} and A_{panel} are the efficiency and area of the PV panel.

C. Electric vehicle

Electric vehicles with the V2H technology have a high ability to participate in HEMS programs due to their bidirectional operation with the SH. For instance, the HEMS can use the EV's energy for supplying the demand of the SH when the market price is high or in the unavailability of renewable energy. On the other hand, the EV can be charged when the market price is low or solar energy is available. In HEMS, the EV is formulated in two steps including a stochastic behavior model and charge/discharge schedule [26].

- Stochastic behavior model:
  An electric vehicle has three stochastic parameters including initial state of charge (SOC), arrival time (AT) to the parking, and departure time (DT) from the parking. The Truncated Gaussian PDF is utilized to formulate these stochastic parameters of the EV. Eqs. (9-11) present the formulation of this PDF for each of the EV's mentioned parameters.

$$pdf\left(SOC^{ins}\right) = f_{TG}\left(X; \mu_X; \sigma_X^2; x_{min}^X; x_{max}^X\right) \tag{9}$$

$$pdf\left(T^{AT}\right) = f_{TG}\left(X; \mu_X; \sigma_X^2; x_{min}^X; x_{max}^X\right) \tag{10}$$

$$pdf\left(T^{DT}\right) = f_{TG}\left(X; \mu_X; \sigma_X^2; \max\left(x_{min}^X, T^{AT}\right); x_{max}^X\right) \tag{11}$$

In these equations, the stochastic parameter (X) of the EV is calculated using Truncated Gaussian PDF considering mean (μ_X), variance (σ_X^2), minimum (x_{min}^X) and maximum (x_{max}^X) amount its parameter.

- Charge/discharge schedule:
  The EV's energy scheduling in HEMS is optimized considering the eight following equations.

1. Based on Eq. (12), the charge and discharge should not be in the same interval. Here, S_t^{Ch} and S_t^{Dis} show a 0 or 1 variable for off and on modes.

$$S_t^{Ch} + S_t^{Dis} \leq 1 \tag{12}$$

2. According to Eq. (13), the SOC of the EV should be in the range between the minimum (SOC_{min}) and the maximum (SOC_{max}).

$$SOC_{min} \leq SOC_t \leq SOC_{max} \tag{13}$$

3. Based on Eq. (14), the charged power of the EV should be lower than the allowable maximum charge rate (R_{ch}).

$$0 \leq P_t^{Ch} \leq R_{ch} \tag{14}$$

4. The discharged power of the EV should be lower than the allowable maximum discharge rate (R_{Dis}) based on Eq. (15).

$$0 \leq P_t^{Dis} \leq R_{Dis} \tag{15}$$

5. Eq. (16) is the basic equation for calculating the hourly SOC. It presents that the SOC is equal to the combination of the SOC at the previous period (SOC_{t-1}) and charge or discharge amount of the EV during the current period.

$$SOC_t = SOC_{t-1} + \left(P_t^{Ch} \times \eta_{Ch}\right) - \left(P_t^{Dis} \times \eta_{Dis}\right) \tag{16}$$

6. Based on Eq. (17), the SOC is equal to the initial SOC when the EV arrives at the SH (Parking).

$$SOC_t = SOC_{Ins} \quad if \quad t = t_{AT} \tag{17}$$

7. Eq. (18) represents that the SOC should be equal to the maximum SOC when the EV departures from the SH.

$$SOC_t = SOC_{max} \quad if \quad t = t_{DT} \tag{18}$$

8. Finally, based on Eq. (19), the available SOC of EV for charging and discharging is zero when the EV is out of the SH.

$$SOC_t = P_t^{Ch} = P_t^{Dis} = 0 \quad if \quad t_{DT} < t < t_{AT} \tag{19}$$

D. Seasonal behavior

The HEMS is investigated during various seasons. For this reason, the produced power of the PV unit and also the initial parameters of the EV are considered different in each season based on the statistical data. In other words, the different data of solar irradiance, initial SOC, AT, and DT are considered for implementing the mentioned PDFs for calculating the uncertain parameters of the PV and EV in different seasons. The required seasonal data is presented in section 4. The considered stochastic program for calculating the seasonal uncertain parameters is the combination of Latin hypercube sampling (LHS) and K-means algorithms (see Ref. [27] for more studying).

3. ENERGY MANAGEMENT METHOD

The proposed HEMS is presented in this section. First, the objective function and constraints are formulated and then the multi-objective intelligent algorithm is presented. Finally, the overall process of the HEMS is explained completely.

A. Objective functions

The considered index which is including the daily demand as the technical index and the daily energy cost as the economic index is optimized multi-objectively during the energy management of smart home devices. Eq. (20) represents the main goal of the HEMS. Here, SH_D and SH_{EC}show the daily demand and energy cost of the SH.

$$Objective_{function} = min \ \{SH_D \ \& \ SH_{EC}\} \tag{20}$$

- Technical part of the index:

  Today, the rapid increase in electricity demand creates an operational challenge for the electric system and operators of generating units because supply and demand for electricity should be balanced in real-time. The reduction of the buildings' dependence on the electrical energy of the grid is one of the advantages of implementing the concept of the smart home. For this reason, minimizing the daily demand of the SH which should be bought from the grid is considered as the technical index of the objective function. The daily demand of the SH is formulated by Eq. (21). Here, Dem_t is the required demand of the SH, which should be supplied from the grid, at the period t.

  $$SH_D = \sum_{t=1}^{n_{TI}} Dem_t \tag{21}$$

  where,

  $$Dem_t = AP_t - DP_t \tag{22}$$

  where, AP_t and DP_t are the appliances' required power and sources' produced power at period t.

- Economic part of the index:

  The energy cost has a straight relation with the daily expenses of households so that reducing this index can improve the economic situation of the families. For this reason, the daily energy cost is considered as the economic part of the main index. Mathematically, this index consists of two parts including the cost of purchased power (C_{G2H}) and the revenue of sold power (R_{H2G}) according to Eq. (23).

  $$SH_{EC} = C_{G2H} - R_{H2G} \tag{23}$$

  For calculating the parameter of this equation, firstly, the supply and demand of the SH at each time interval should be calculated.

Eq. (24) is utilized to calculate the required demand at period t. In this equation, n_{App} and $Dem_{App,i}$ demonstrate appliances' number and demand and $Power_{App_t}$ is the total energy consumption at time-interval t.

$$Power_{App_t} = \sum_{i=1}^{n_{App}} Dem_{App,i} \tag{24}$$

Eq. (25) is used for computing the produced power of rooftop PV unit at period t. n_{DG} is the number of PV units and $G_{PV,j}$ is the produced power of PV unit j.

$$Power_{PV_t} = \sum_{j=1}^{n_{DG}} G_{PV,j} \tag{25}$$

The EV absorbs/injects electricity from/into the SH when it is in the charge/discharge state. Thus, the power of the EV at period t is:

$$Power_{EV_t} = \sum_{i=1}^{n_{EV}} p_{EV,i} \times S_i \times \eta_{ch/dis} \tag{26}$$

where, n_{EV} and $p_{EV,i}$ are the EV's number and power at each time interval. S_i shows the situation of the EV; it is equal to 1 in discharge mode, -1 in the charge one, and 0 when the EV is idle. η is the efficiency.

Eq. (27) is formulated for calculating the power of the SH at period t ($Power_{SH_t}$) which must be supplied from the grid.

$$Power_{SH_t} = Power_{App_t} - (Power_{PV_t} + Power_{EV_t}) \tag{27}$$

According to Eq. (27), the purchased/sold power from/to the grid can be calculated at each period. The HEMS has to buy the extra demand from the grid when the SH's power is higher than zero ($P_{SH_t} > 0$). On the other hand, the HEMS can inject the extra power into the grid when the SH's power is lower than zero ($Power_{SH_t} < 0$). Therefore, the smart home's daily cost is calculated by Eq. (28) and the daily revenue is computed by Eq. (29).

$$C_{G2H} = \sum_{t=1}^{n_{TI}} Power_{SH_t} \times Tr_t \qquad if \qquad Power_{SH_t} > 0 \tag{28}$$

$$R_{H2G} = \sum_{t=1}^{n_{TI}} -1 \times Power_{SH_t} \times pr_t \qquad if \qquad Power_{SH_t} < 0 \tag{29}$$

where, Tr_t is the electricity tariff and pr_t shows the tariff of bought electricity from the end-user (smart home) at period t.

B. Constraints

During the optimization of the HEMS, the power balance should be evaluated each period by Eq. (30).

$$E_t^{APP} + E_t^{EV,\,Ch} + E_t^{H2G} = E_t^{G2H} + E_t^{PV} + E_t^{EV,Dis} \tag{30}$$

This constraint represents that the combination of the appliances' demand (E_t^{APP}), the EV's absorbed energy ($E_t^{EV,\,Ch}$), and the grid's injected energy (E_t^{H2G}) should be equal to the combination of the home's injected energy (E_t^{G2H}), the PV's energy (E_t^{PV}), and the EV's injected energy ($E_t^{EV,Dis}$). In PV, the range of the produced power is another constraint of energy management. Mathematically, based on Eq. (31), the produced power of the rooftop PV unit at period t should be in the allowable range.

$$Power_{min} \leq Power_{PV,t} \leq Power_{max} \tag{31}$$

C. Intelligent algorithm

The considered multi-objective algorithm of the HEMS is the combination of MODA, which is used for non-dominated optimization, and fuzzy mechanism, which is utilized to select the best schedule. The MODA is inspired by the behavior of real dragonflies. It has the ability to modify the initial random population, converge towards the global optimum, and provide very competitive results compare to other multi-objective algorithms. In MODA, the movement vector of each artificial dragonfly is calculated by Eq. (32) [22].

$$\Delta V_{t+1} = (sS_i + aA_i + cC_i + fF_i + eE_i) + w\Delta V_t \tag{32}$$

In this equation, each of the parameters formulates a special behavior of real dragonflies. So, the expanded movement vector at iterations is calculated by Eq. (33).

$$\Delta V_{t+1} = \begin{bmatrix} \left(-s\sum_{j=1}^{N} P - P_j\right) + \\ \left(a\sum_{j=1}^{N} V_j/N\right) + \\ \left(c\left(\left(\sum_{j=1}^{N} P_j/N\right) - P\right)\right) + \\ \left(f\left(P^{+} - P\right)\right) + \\ \left(e\left(P^{-} - P\right)\right) \end{bmatrix} + w\Delta V_t \tag{33}$$

Here, N is the number of neighboring particles. The position and velocity of these particles demonstrate with P_j and V_j. P, P^{+}, and P^{-} are the position of the current particle, food, and enemy. Then, the position of each artificial dragonfly is updated by Eq. (34).

$$P_{t+1} = P_t + \Delta V_{t+1} \tag{34}$$

As mentioned above, the fuzzy mechanism is used to select the best schedule after applying the MODA. Firstly, the membership function is defined for each non-dominated solution by Eq. (35). Then, the normalized membership value is calculated by Eq. (36). Finally, the best operational schedule is equal to the particle with the highest membership value [29].

$$MV_j^{OF} = \begin{cases} 1 & V_j^{OF} \le V_j^{min} \\ \frac{V_j^{max} - V_j^{OF}}{V_j^{max} - V_j^{min}} & V_j^{min} < V_j^{OF} < V_j^{max} \\ 0 & V_j^{max} \le V_j^{k} \end{cases} \tag{35}$$

$$MV^{OF} = \frac{\sum_{j=1}^{N_J} MV_j^{OF}}{\sum_{OF=1}^{N_{OF}} \sum_{j=1}^{N_J} MV_j^{OF}} \tag{36}$$

D. Overall process of HEMS

In the previous sections, all required subjects for implementing the proposed HEMS is completely presented. In this section, the overall process of utilizing these matters and the proposed procedure for optimizing the HEMS in a SH is demonstrated in Fig. 2 step by step. According to this figure, firstly, initial data of the SH such as details of appliances, PV, EV and economic parameters are input. After selecting the type of the season, the stochastic program is utilized to select the probabilistic data. Then, the MODA algorithm is implemented to optimize the technical and economic indices of the SH considering the constraints. Finally, the fuzzy decision-making method is used to select the best operational schedule of home devices. This method is applied for different seasons. The proposed method is implemented in MATLAB software on a Laptop with Intel Core i7 3.00 GHz CPU and 8 GB RAM.

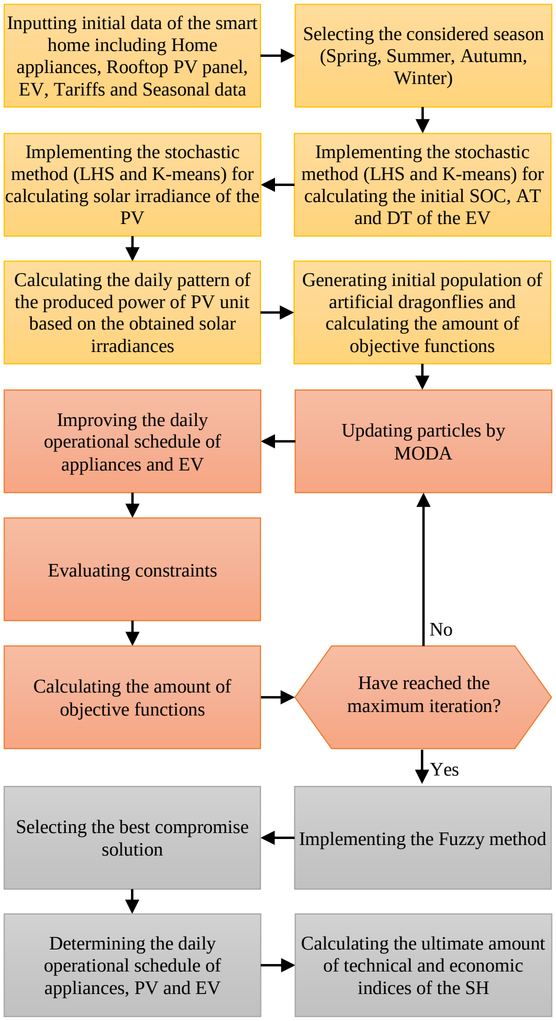


Fig. 2. Flowchart of the proposed seasonal HEMS

4. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results of applying the proposed HEMS to a sample smart home and discussion on the efficiency of the method are presented in this section. The SH has 11 appliances which are divided into controllable and uncontrollable ones. The required operational time intervals of appliances are written in Table 1. Fig. 3 shows their required power at each operational time interval [30]. In this figure, the number of different colors shows the number of required time intervals for each appliance. Moreover, the length of each color represents the required power of the appliance at that time. For example, the iron needs two time intervals for operating while its power is 0.37 and 0.015 at the first and second time intervals, respectively.

It is considered that the roof of the building has the capacity for allocating 10 photovoltaic panels. The type of PV panels is 335W SolarPower X21. The rated illumination intensity, shape, and scale indices of PV units are 1000 w.m-2, 1.8, and 5.5, respectively [31]. Fig. 4 demonstrates the hourly mean value of solar irradiance in different seasons [32].

The owner of the smart home has a CHEVROLET VOLT electric vehicle. The battery of the EV is 16 kWh. The maximum charge and discharge rate is 3.3 kWh with the efficiency of 95 % [33]. The vehicle's battery should be full-charged at the DT. The mean values of the SOC, AT, and DT of the electric vehicle in different seasons are presented in Table 2 [34].

Fig. 5 shows the market price in different seasons. According to the agreement between the distribution company and the owner of the SH, the tariff of bought electricity from the end-user is 0.138 $/kWh [35].

As mentioned above, after entering the initial data into the proposed method, the stochastic produced power of the rooftop panels is calculated using the stochastic program. In Fig. 6, the hourly produced power of the PV panels, which is the output of the stochastic program, is shown in different seasons. As it can be shown in this figure, the availability hours of solar energy and its value in spring and summer are higher than in autumn and winter days. The uncertain parameters of the EV are also calculated using the introduced stochastic program. According to the output of LHS and K-means, the initial SOC in spring, summer, autumn, and winter is 54.53, 51.67, 55.51, and 57.54 %, respectively. Moreover, the availability of the EV at the SH is shown in Fig. 7. The EV is in the parking when its situation is one while it is out of the home when the situation is zero.

In this step, the MODA is implemented to optimize the main indices. Then the fuzzy mechanism is run to choose the optimal compromise result. The procedure of the multi-objective optimization is demonstrated in Fig. 8. Fig. 8-a shows the ultimate optimal Pareto front after concluding the MODA while Figs. 8-b and 8-c demonstrate the process of minimizing the considered indices of the SH.

Before evaluating the details of technical and economic indices, the efficiency of the proposed HEMS in finding the best operational schedule of the SH is compared with other intelligent algorithms including the non-dominated sorting firefly algorithm (NSFA) [36], non-dominated sorting genetic algorithm-II (NSGA-II) [37], and multi-objective particle swarm optimization (MOPSO) [38].

In Table 3, the value of indices is presented after implementing various intelligent algorithms. According to this table, the proposed method has higher efficiency in HEMS than other ones. In other words, the MODA has a better convergence rate, more accurate results, and more index improvement in the energy management problem. Based on the electricity cost, the result of the MODA is better than other methods about 10-40% in various seasons. The daily demand of the SH is also reduced considerably in the various seasons when the home devices are managed using the MODA algorithm. So it can be said that the proposed method has higher performance in an energy management problem. In the following, its efficiency is more pondered based on the details of indices of the SH.

The ST of appliances in various seasons can be seen in Table 4. It is worth mentioning that the ST of uncontrollable appliances has been constant while the ST of controllable devices has been optimized during the energy management program. The operational time of appliances has been selected so that the electricity cost and dependence of the SH on the power of the grid are reduced. The hourly demand of all appliances of the SH in various seasons is demonstrated in Fig. 9. As shown in this figure, the ST of appliances is selected so that the domestic energy unit is available. In spring and summer, in which solar energy is more available, the appliances are operated in the middle times of the day. In autumn, they are usually started in the first hours because of the availability of EV energy. In the winter, the ST of appliances is distributed at different hours of the day.

In Table 5, the hourly transferred power of the SH with the network is presented in different seasons. In the spring and summer, the produced power of PV units is high. For this reason, the value of the injected energy of the SH to the distribution system is more than in other seasons. The value of the technical index in these seasons is about -20 kWh. It means that the daily injected energy of the SH to the grid is approximately 20 kWh more than the daily bought energy from the grid. In the autumn and winter, this index is about -10 kWh. In other words, although the daily sold energy of the SH is more than the daily bought one, its value is reduced by half than the warm seasons.

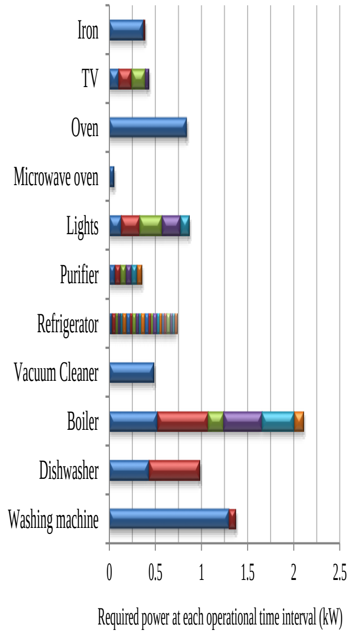


Fig. 3. Required power of appliances at operational time intervals

The situation of hourly bought/sold energy of the SH causes the electricity cost of the SH to be reduced considerably using the proposed method. Of course, it can be said that the owner of the SH gets the profit from selling the electricity to the distribution company. The hourly costs from buying energy and profits from selling energy are shown in Fig. 10 in different seasons. As can be shown in this figure, the SH gets income in the middle hours of the day when solar energy is available. This profit is higher in spring and summer than in autumn and winter. The daily profit of the smart home in spring approximately is twice the profit on a winter day.

The hourly value of the economic index is presented in Table 6. On a spring day, the maximum hourly profit happens at the 15th time interval by about 0.43 $ while on a summer day, the highest hourly profit happens at the 12th time interval. The maximum hourly profit in autumn and winter is also achieved at 14th and 12th time intervals, respectively. The availability of PV power has a considerable effect on the hourly profit of the SH. Based on the economical results, the daily income of the SH from implementing the proposed method is about 2 or 3 $ in different seasons. Therefore, the proposed method of HEMS has higher efficiency in optimizing the operational plan of home appliances, PV, and EV for minimizing the electricity expenses and daily demand of the smart building.

Table 1. The appliances’ operational time intervals

Uncontrollable appliances	
Device	Required time intervals
Refrigerator	24
Purifier	6
Lights	5
Microwave oven	1
Oven	1
Television	4
Iron	2
Controllable appliances	
Device	Required time intervals
Washing machine	2
Dishwasher	2
Boiler	6
Vacuum cleaner	1

Table 2. The mean value of the SOC, AT, and DT of the EV

	Mean value			
	Spring	Summer	Autumn	Winter
Initial SOC (%)	50	50	50	50
Arrival time (h)	8	8	8	8
Departure time (h)	19	19	18	18

Table 3. The value of indices after energy managing by various intelligent algorithms

Index	Algorithm	Season			
		Spring	Summer	Autumn	Winter
Electricity cost ($)	MOPSO	-2.6938	-2.1992	-1.9973	-0.9306
	NSGA-II	-2.6126	-2.2954	-1.6958	-1.1385
	NSFA	-2.4616	-2.5293	-1.7587	-1.1204
	Proposed method	-3.139	-3.0695	-2.159	-1.5707
Daily demand (kWh)	MOPSO	-17.8969	-13.1859	-10.3977	-4.61994
	NSGA-II	-15.3411	-13.0206	-9.74566	-5.58184
	NSFA	-14.7063	-13.8182	-10.0484	-7.67485
	Proposed method	-20.2404	-18.8191	-12.0588	-9.29946

Table 4. The appliances’ ST in different seasons

Type	Appliances	Season			
		Spring	Summer	Autumn	Winter
Controllable appliances	Washing machine	4	7	9	15
	Dishwasher	7	5	1	8
	Boiler	3	6	1	6
	Vacuum cleaner	21	21	24	14
Uncontrollable appliances	Refrigerator	1	1	1	1
	Purifier	9	16	8	17
	Lights	21	22	21	21
	Microwave oven	11	17	7	14
	Oven	13	13	22	13
	Television	12	11	20	19
	Iron	10	19	10	17

Table 5. The hourly transferred power of the SH in various seasons

Hour	The transferred power of smart home (kWh)			
	Spring	Summer	Autumn	Winter
1	0.03	0.03	1.08	0.03
2	0.04	0.04	1.28	0.14
3	0.545	0.025	0.345	0.165
4	1.875	3.325	0.475	0.175
5	0.265	0.455	0.375	0.06
6	0.455	1.11	0.14	0.56
7	-1.007	-2.389	-3.21	0.59
8	-1.213	-1.491	-0.234	0.625
9	-2.104	-1.868	2.978	1.003
10	-2.137	-2.361	-1.854	-1.808
11	-2.779	-2.854	-2.799	-2.722
12	-2.968	-3.087	-2.983	-3.198
13	-2.27	-2.19	-3.06	-2.47
14	-3.058	-2.951	-3.135	-2.692
15	-3.092	-2.819	-2.909	-1.508
16	-2.754	-2.351	-2.241	-2.15
17	-2.209	-1.964	-1.116	-0.759
18	-1.347	-1.417	0.024	0.23
19	-0.433	-0.106	0.025	0.285
20	0.025	0.1	0.025	0.325
21	0.52	0.57	-3.26	-3
22	0.025	0.025	0.865	0.17
23	0.025	0.025	3.325	3.325
24	3.325	3.325	3.805	3.325

Table 6. The hourly electricity cost of the smart home in different seasons

Hour	The electricity cost of smart home ($)			
	Spring	Summer	Autumn	Winter
1	0.0027	0.0027	0.0972	0.0027
2	0.003	0.003	0.096	0.0105
3	0.0327	0.0015	0.0207	0.0099
4	0.0984	0.1746	0.0249	0.0092
5	0.0148	0.0256	0.0211	0.0034
6	0.0324	0.0791	0.0099	0.0399
7	-0.1391	-0.3296	-0.4429	0.0619
8	-0.1674	-0.2058	-0.0323	0.0769
9	-0.2903	-0.2578	0.3693	0.1243
10	-0.2949	-0.3259	-0.2559	-0.2495
11	-0.3835	-0.3939	-0.3864	-0.3756
12	-0.4096	-0.4261	-0.4117	-0.4413
13	-0.3133	-0.3022	-0.4223	-0.3409
14	-0.422	-0.4073	-0.4326	-0.3715
15	-0.4267	-0.3891	-0.4015	-0.2081
16	-0.3801	-0.3244	-0.3092	-0.2967
17	-0.3048	-0.2709	-0.1541	-0.1047
18	-0.1858	-0.1955	0.0069	0.0644
19	-0.0597	-0.0147	0.0075	0.0855
20	0.0067	0.027	0.0068	0.0878
21	0.1352	0.1482	-0.4499	-0.414
22	0.0065	0.0065	0.2249	0.0442
23	0.0063	0.0063	0.3119	0.3119
24	0.2993	0.2993	0.3425	0.2993

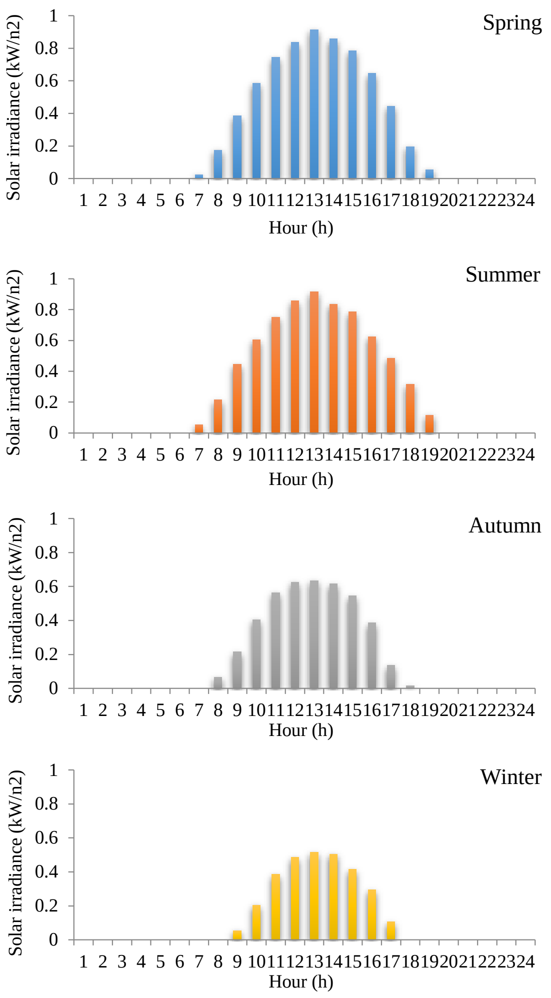


Fig. 4. Hourly mean value of solar irradiance in different seasons

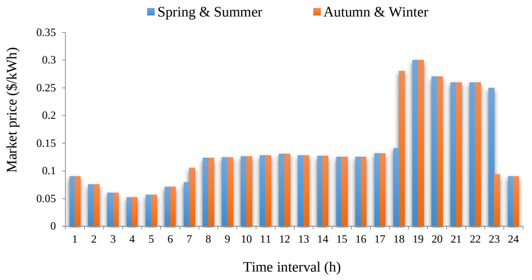


Fig. 5. The market price in different seasons

5. CONCLUSIONS

In this research paper, a novel method based on intelligent algorithms is presented for the home energy management system in the SH including smart appliances, rooftop PV, and EV in the various seasons. The stochastic method is utilized to find the uncertain parameters of PV and EV based on their previous data during each season. The combination of MODA and fuzzy mechanism is implemented in order to minimize the main indices of the SH.

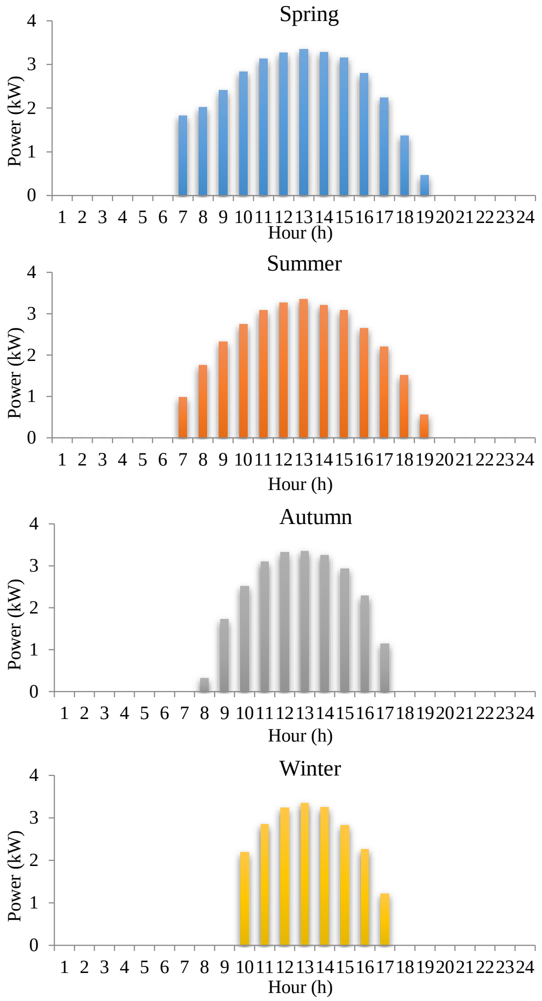


Fig. 6. The hourly produced power of PV in different seasons (Output of stochastic program)

Experimental results, obtained from implementing the proposed method on the sample SH, represent that the proposed HEMS can efficiently optimize the operational plan of home appliances, PV, and EV due to the decline of the mentioned indices of the SH. The proposed algorithm had more accurate results than the NSFA, MOPSO, and NSGA-II algorithms. The technical and economic indices are improved by about 10-50% when the home energy management is optimized using the proposed method. The starting time of home appliances is selected so that both electricity expenses and the required energy of the SH are reduced during the day. The effect of PV panels on the considered indices is considerable. In other words, in spring and summer, when the solar energy is more than in other seasons, the values of technical and economic indices are lower than on autumn and winter days. The daily electricity profit of the SH on spring and summer days is about 3 *whileitisabout*2 on autumn and winter days. According to the technical index, the SH daily can inject energy to the grid by about 20 kWh in spring and summer while this injected energy is about 10 kWh in autumn and winter. On the other hand, the charge and discharge time of the EV is optimized properly in order to optimal operate the smart home based on the considered indices. Hence, the efficiency of the SH

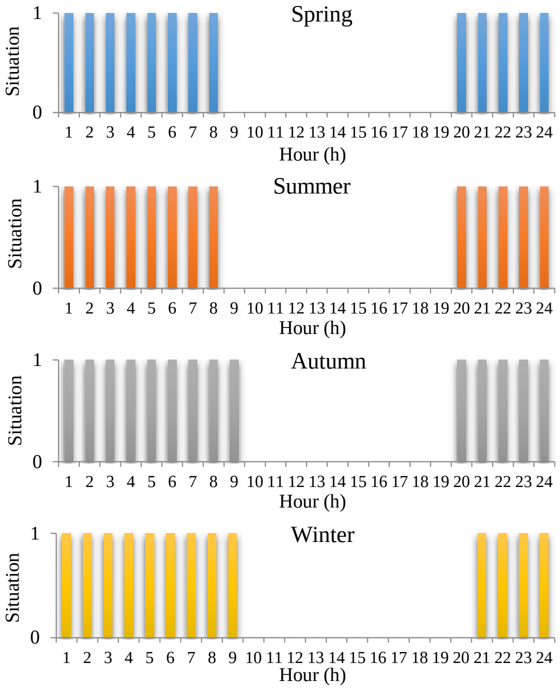
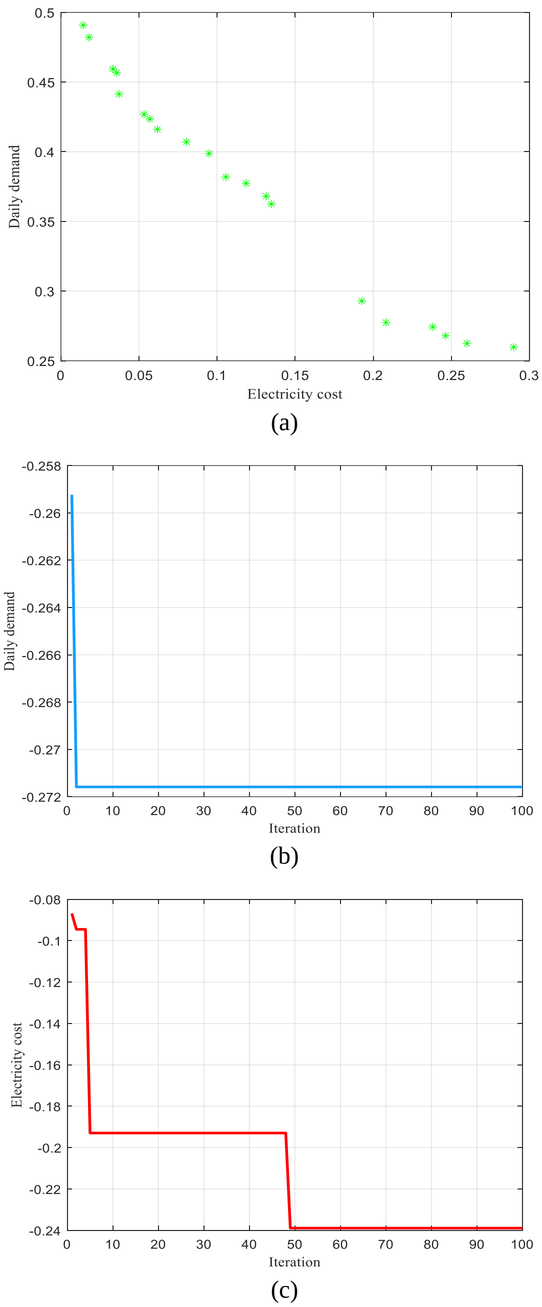


Fig. 7. The availability of the EV at the SH (1: In-home, 0: Out-home)

can be improved considerably by implementing the proposed HEMS and optimal managing the home appliances, rooftop PV, and EV.



(a)

(b)

(c)

Fig. 8. The procedure of the multi-objective optimization, a) Pareto front, b) Technical index, c) Economic index

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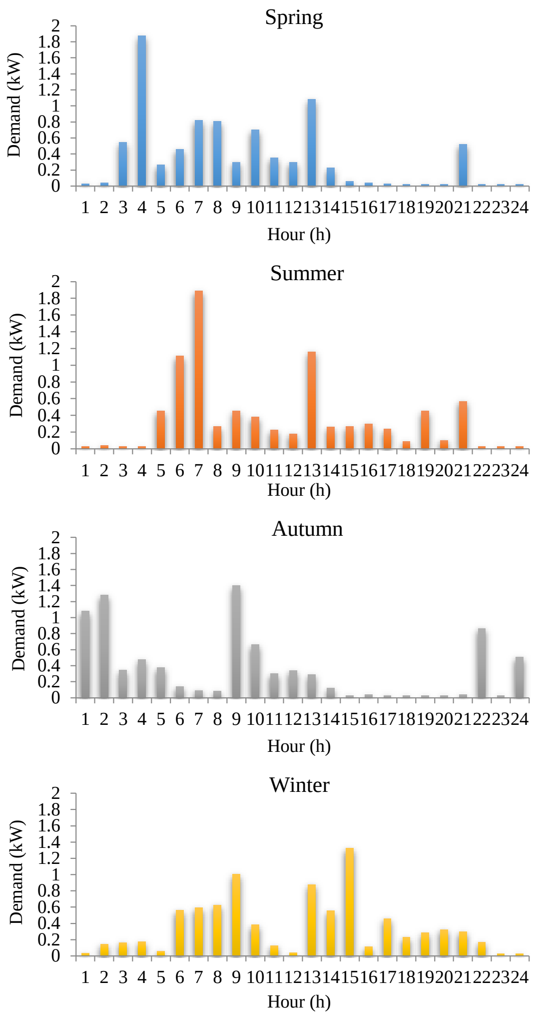

Fig. 9. The hourly demand of home appliances in different seasons

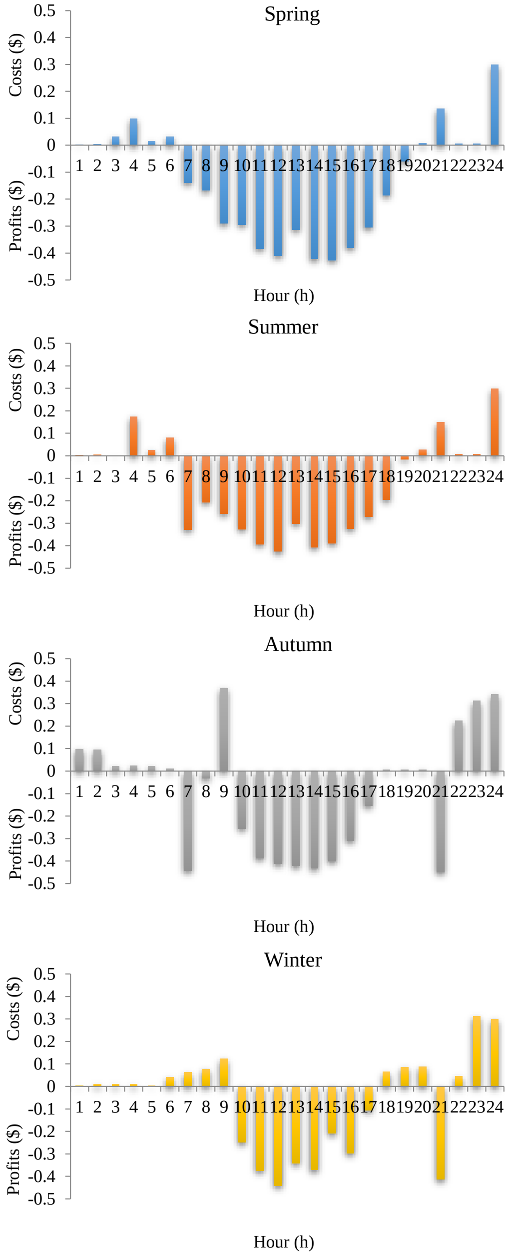

Fig. 10. Hourly costs/profits of the SH from bought/sold energy

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