Integrated Scheduling of Hybrid Generation and Demand Response Program for a Building

Amin Aeenmehr*‡, Nasser Erfani Majd**

*Faculty of Engineering, Shohadaye Hoveizeh University of Technology, Dasht-e Azadegan, Khuzestan, Iran

**Faculty of Engineering, Shohadaye Hoveizeh University of Technology, Dasht-e Azadegan, Khuzestan, Iran

(a.aeenmehr@shhut.ac.ir, n.erfanimajd@shhut.ac.ir)

‡ Amin Aeenmehr; Nasser Erfani Majd, Faculty of Engineering, Shohadaye Hoveizeh University of Technology, Dasht-e Azadegan, Khuzestan, Iran, Tel: +90 613 675 1021, a.aeenmehr@shhut.ac.ir

Received: 16.06.2020 Accepted:21.07.2020

Abstract- This paper illustrates a comprehensive model of an energy management system and a novel algorithm in a building in a grid-connected state. This study attempts to provide an approach including a scheduling algorithm and a hybrid model of electricity generation to reduce the electricity consumption cost and increase the reliability of the grid in summer due to the great demands of electricity for using air condition systems. The model consists of cogeneration of a photovoltaic system and a diesel generator with a battery storage system. The electrical consumption profile of home appliances used in the daytime is modeled. Then an algorithm is introduced to observe and schedule the electrical appliances and charge and discharge the batteries in an optimal way. The results depict that the unified model and proposed control strategy are performed successfully, and the peak of electrical demand is eliminated appropriately. The occupants also can benefit financially in grid-connected mode by selling extra domestic electricity generation to the grid over the peak time period.

Keywords Home energy management system, demand response program, photovoltaic system, diesel generator, battery storage system.

Nomenclature Table

t	Time	$C_{\max}$	The maximum capacity of the battery in the fully charged mode
N_a	The number of appliances	$P_{c,t}$	The battery charging power (kW)
H_c	The control horizon (24Hr)	$P_{d,t}$	The battery discharging power (kW)
t_s	Sample time (s)	DOD	Depth of discharge
p_n	Power of appliance n (kW)	$P_{m,t}$	Grid power at time t (kW)
D_n	Duration of appliance n being operated	$P_{A,t}$	Aggregated power demanded at time t (kW)
A_n	Additional run time of appliance n	$P_{D,t}$	Total power demanded from the grid at time t (kW)
η_c	Battery charging efficiency	P_D	The total power demand from the grid in a day (kW)
η_d	Battery discharging efficiency	$C_{n,t}$	The control signal of appliance n at time interval t
t_u	Time of use of electricity price	SOC	State of charge of the battery
C	The maximum cost	S_t	State of the battery at time t (kWh)
S_n	The start time of appliance n	S_0	The initial state of charge of the battery at time t
e_n	The off-time of appliance n	$P_{g,t}$	The power generated by the diesel generator at time t (kW)
$c_{n,t}^{bl}$	The control signal of appliance n	$P_{v,t}$	The power generated by the photovoltaic system at time t (kW)

1. Introduction

The smart grid concept correlates with the energy management system (EMS) [1] which has been broadly studied for discovering approaches to implement in an electrical distribution network. Resiliency as a new concepts has been investigating. A resilient network can tolerate risky events and failures such as cyberattacks and bad weather conditions [2]. In [3] the techno-economic and environmental comparison of two different resilient energy systems has been studied. Other approaches are summarized in mitigating electricity loss [4] and adding energy resources mainly based on renewable energy resources [5] and storage systems [6, 7]. Various types of storage systems can be used in the grid such as fuel cells, batteries, H2-tank, ultracapacitor, and electrolyzer [8]. Besides, electrical vehicles contribute to support the distribution network during peak time by discharging the stored electrical energy [9]. One of the promising techniques to help the distribution network in energy management is demand-side management (DSM). Demand-side management encompasses a set of actions to encourage consumers' consumption behavior to use electricity less over the peak time periods. DSM can be implemented in various ways which are categorized into three main classes including energy efficiency approach, demand response, and strategic load growth. Energy efficiency strategy attempts to enhance the energy efficiency of home appliances through performing energy efficiencies programs or replacing them with more efficient ones [10]. In strategic load growth, it is assumed that increasing electrical demand is unavoidable due to weather conditions and increased use of electric vehicles. Therefore, using dual-fuel equipment and machines could contribute to reducing the electrical demand level [11]. The demand response technique provides financial incentives for end-users to shift the time of use of appliances from peak to off-peak time periods or curtail the using of loads for grid stability enhancement [10, 12]. Demand response is classified into two main categories including market-based program and reliability based program in literature [13]. In the reliability-based program, the main aim is to control home appliances to reduce load voluntarily or involuntarily [14]. In market-based program, consumers tend to adapt their consumption in accordance with the real-time price of electricity in order to minimize their cost [15]. The conventional method for implementing the market-based strategy is the time of use method which means that the electricity price is predefined in accordance with the peak or off-peak time period [16]. Therefore, the consumers are pursued to shift the time of use of interruptible appliances from peak hours to the off-peak hours when the electricity tariff is inexpensive. This rearranged consumption pattern based on price varying leads to help keeping electrical generation and consumption balance, peak-shaving, valley-filling and the grid stability [17]. As it was mentioned, load control is the key idea of demand response program. From that point of view, household loads would be categorized into four main types; uncontrollable, interruptible, uninterruptible, and curtailable loads [18]. The time of use of an uncontrollable load cannot be shifted at all such as television. The time of use of an interruptible load can be shifted from peak time period to off-peak period such as rechargeable appliances. An uninterruptible load cannot be stopped during operation like washing machine and dryer. Lamps, for instance, can willingly be turned off by consumers at any time. This type of load takes account of curtailable loads to reduce electricity consumption. Home energy management system (HEMS) is an applicable efficient approach to optimize energy consumption in residential units encompassing various techniques, technologies, and models for local generation and consumption. In HEMS, renewable energy resources, battery storage systems, and on-site diesel generators can be employed to provide consumers with electricity in demand over the peak time period and support the power grid [19]. Through implementing a DR program alongside using renewable energy resources, HEMS could act more effective and efficient to reduce electricity consumption [20]. The integration of renewable energy resources is investigated in the literature in both grid-connected and stand-alone modes [21, 22]. A battery storage system is normally employed to alleviate the uncertainties of renewable energy resources exploitation [23]. Electrical vehicles are commonly considered as a backup system to support the power grid during the peak time period [24, 25]. Renewable energy resources and fossil-fuel-based generators can be used to charge electric vehicles [26]. However, it tends to replace diesel generators with renewable energy sources to reduce environmental contamination [27, 28].In [29] a home energy management system with solar photovoltaic system is introduced. Also, in [20] another home energy management system supported by wind-solar-battery has been studied.

In this paper, a solar-diesel-battery is investigated in grid-connected mode. In addition demand response programming is employed for peak-shaving that allows building to sell extra electricity generation to the grid. The main contributions of this paper are listed as follows:

- A comprehensive model for the energy management system is proposed including a photovoltaic system, diesel generator, air condition system, battery storage system..
- The household electrical system is connected to the grid and there exists bilateral electricity trade between the residential unit and the grid.
- A novel strategy control is proposed to minimize daily electricity consumption cost.
- The demand response program is applied to obtain the most financial benefit from peak-shaving.
- The changing electricity tariff is considered for electricity cost calculation.

2. Problem Definition

This study aims to provide a solution to decrease the electricity consumption cost in the residential sector and boost the reliability of the grid. In this regard, an energy management system is designed and implemented including a photovoltaic system, an energy storage system, a diesel generator, uncontrollable, interruptible, uninterruptible, curtailable loads, and air conditioning system with changing power consumption based on the indoor and outdoor temperature in a day. The entire scheme of the home energy management system (HEMS) is depicted in Fig. 1. The daily electricity demand curve and the solar power generation trend of the building are shown in Fig. 2. The HEMS proposed in this paper is investigated in grid-connected mode. In the grid-connected mode, the main energy source of the building is the power grid. The diesel generator sound pollution and air pollution would affect the comfort level of occupants [30]. Hence, using diesel generators should be limited to a certain time period. Alongside these local generators, an energy storage system based on battery exists to store extra electrical power generation to use over the peak time period [24, 31]. The batteries can be recharged by the grid, the photovoltaic system, and the diesel generator. Also, the battery storage system aids HEMS in eliminating the effects of photovoltaic generation uncertainties. The state of charge of batteries requires a control system to set the battery state to charging or discharging mode [32, 33]. When the electricity tariff is changing based on time of use, an effective solution to manage electricity demand is a demand response program that is applied to the building. The air conditioning system and home appliances are considered as loads. Based on consumer's flexibility, some of the appliances are used over the off-peak time period rather than the peak time period. In this way, the cost of electricity consumption can be reduced. In other words, there is a trade-off between consumers' comfort level and the cost of electricity [34].

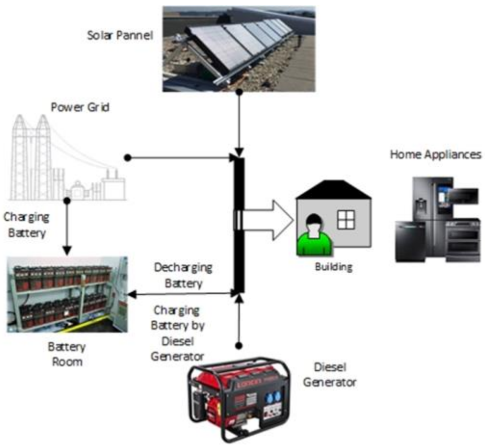

Fig. 1. The scheme of home energy management system.

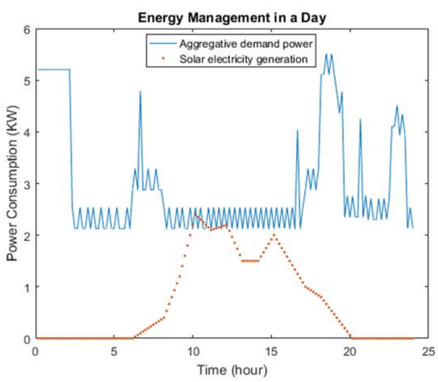

Fig. 2. Daily energy consumption and generation.

The proposed model of energy management system leads to run stochastic planning to manage electricity supply and demand [35]. Therefore, a scheduling method is proposed and applied to minimize consumer cost and maximize consumer's contribution to domestic electricity generation [36]. In this study, it is assumed that the building is connected to the grid and able to sell extra electricity generation to the grid to earn a financial benefit. It is given that by applying the proposed HEMS the electricity cost consumption would not only be minimized but also the peak of load demand would be shaved and thus the grid could benefit from that. The first step for scheduling is obtaining the energy consumption profile and the time of use of appliances during the day. Then, a scheduling method is designed and employed for optimizing load shifting based on a stochastic nonlinear model, scheduling use of home appliances, the air conditioning system, switching on/off the diesel generator, charging/discharging the battery storage system, and the photovoltaic system. In the following for analyzing the results, at first, the efficacy of load shifting is analyzed in terms of the cost-benefit and the effect on the daily electricity demand curve. Then the effect of applying the photovoltaic system on the daily demand curve and electricity cost is studied. After that, the same analysis has been done for the diesel generator. Finally, the effect of using load shifting method, diesel generator and the photovoltaic system simultaneously is investigated on both the daily electricity demand curve and the cost.

3. Mathematical Description

3.1. Home appliances and generation model

In this section, the daily schedule of using household appliances, the air conditioning system, the diesel generator, the photovoltaic system, and charging and discharging state of the energy storage system are described mathematically. In the following, the cost function in terms of electrical energy consumption and generation cost is derived. Minimizing electricity consumption is set as the main goal of the problem in which the comfort level of residents is maintained reasonably. Thereby, the time of using the diesel generator is restricted to a certain time period during the day. The electricity tariff is also changing based on the time of use during the day leading to considering load shifting as a cost-effective approach to demand response program.

The energy cost is calculated based on household appliances scheduling and variable tariff price through equation (1) as follows

$$J_e = \sum_{t=1}^{H_c} \sum_{n=1}^{N_a} P_n t_s t_u u_{n,t}$$
$$P_n > 0, t_u > 0, n = 1, \cdots, N_a, t = 1, \cdots, H_c \tag{1}$$

Where the notations are listed and explained in nomenclature table. In household appliances scheduling there exist three types of constraints including the time of using appliances, continuous operation and maximum cost of energy. There would be extra constraints such as comfort level in case of need. The following formulas describe the constraints mentioned above

$$\sum_{t=1}^{H_c}\sum_{n=1}^{N_a} P_n t_u u_{n,t} t_s \le C \tag{2}$$

$$\sum_{t=s_n}^{e_n} u_{n,t} = D_n + A_t \tag{3}$$

$$\sum_{t=s_n}^{e_n} c_{n,t} c_{n,t+1} c_{n,t+2} \cdots c_{n,t+(N_i-1)} = 1 \tag{4}$$

The equation (2) demonstrates the maximum cost that consumer anticipates to pay in a day. The additional operation time might be needed for some appliances in some cases which is described in (3). The continuous operation is compulsory when appliances are being used. This issue is described mathematically by (4). According to the controllability of the household appliances the home devices are classified into 4 categories including uncontrollable (uninterruptible), curtailable, interruptible and adjustable devices. Uncontrollable devices are not interruptible and must work all the time. Curtailable devices can be turned off at any moment if it is needed. The use of interruptible appliances would be postponed and adjustable devices can be used during certain time periods based on the flexibility of consumers. The operational characteristics of household appliances in terms of electricity consumption and operating time are listed in table 1. This table is inspired by [37] and localized based on a survey of residents' electricity consumption behavior living in a building. A set of additional constraints stem from providing coordination between household appliances are listed through equations (5) to (21) [37]. Some household appliances interrelate with each other and it means that a set of constraints should be defined to demonstrate the interconnections between appliances. The washing machine, for instance, is equipped with a dryer. Thus, technically, drying up clothes could not be done before washing clothes. On the other hand, drying clothes could be interrupted and postponed to another time period. Those mentioned working conditions lead to setting constraints described through equations (5) and (6).

$$c_{6,t} + c_{7,t} \le 1, t = 1,\cdots,H_c \tag{5}$$

$$s_7 + D_7 \le s_6 \tag{6}$$

Based on the survey, the TV and the DVD player or the TV and the decoder are using at the same time [37]. This fact is described by equation (7). On the contrary, the DVD player and the decoder cannot be used simultaneously. This constraint can be shown by equation (8). On the other hand, whenever the TV turns off, the DVD player should be off too. Equation (9) describes the state.

$$c_{11,t} - c_{13,t} = 0, t = 1,\cdots,H_C \tag{7}$$

$$c_{12,t} - c_{13,t} \ge 1, t = 1,\cdots,H_C \tag{8}$$

$$if\ c_{11,t} = 0\, then\, c_{12,t} = 0 \tag{9}$$

As a general rule, lights would be turned on while their respective room is being used. The maximum consumption power of each device is limited and shown by equation (10)

$$0 \le P_{n,t} \le P_n^{max} \tag{10}$$

The charging and discharging of the batteries are continuously carried out. The state of charge of the batteries is described by equation (11).

$$S_t = S_0 + \eta_c \sum_{\gamma=1}^{t} P_{b,t} t_s - \eta_d \sum_{\gamma=1}^{t} P_{d,t}, 1 \le t \le T \tag{11}$$

It is obvious that the battery will be considered as a consumer while it is charging and as a generator while is discharging. The cost function of SOC of the BESS entails minimizing the cost of charging and maximizing the cost of discharging. Thereby, the cost function of the charging operation is obtained by the equation (12).

$$J_{b,c} = \sum_{t=1}^{T} P_{c,t} t_u t_s \tag{12}$$

The charging and discharging of the BESS are limited to a certain span. In addition, there is a relation between the maximum charging capacity and the minimum discharging level of the battery. Both mentioned constraints are defined by equations (13) and (14). $S^{min} \le S_t \le S^{max}, t = 1 \cdots T$ (13)

$$S^{min} = (1 - DOD) S^{max} \tag{14}$$

Where S^{max} and S^{min} are the maximum and minimum limitations of charging the battery. It is worth mentioning that the discharging and charging operations cannot be done at the same time. This constraint is described mathematically by equation (15).

$$P_{c,t} \times P_{d,t} = 0 \tag{15}$$

Another generator which is employed locally is a diesel generator. The cost function of generating electricity is described in equation (16). Apart from maintenance cost, as shown in (16), it can be seen that the cost of fuel is the only parameter that affects the cost of fuel-based electricity generation.

$$J_G = \sum_{t=1}^{T} P_{g,t} c_{g,t} \Psi t_s \tag{16}$$

The electricity is demanded by the consumer side is met by the grid, discharging the batteries, the photovoltaic system, and the diesel generator if it is operated. This issue can be shown by equation (17).

$$P_{c,t} + P_{m,t} + P_{g,t} + P_{v,t} = P_{D,t} \tag{17}$$

Table 1. : Electricity consumption profile of household appliances

Class	No.	Appliance	Rated Power (kW)	Run-time (mins)	Baseline
Uncontrollable	1	Refrigerator	2	All the time	All the time
	2	7-stage water purifier	0.048	All the time	All the time
Curtailable	3	Kitchen lights	0.011		Same as kitchen appliances
	4	TV room lights	0.011		Same as the TV set
	5	Laundry room lights	0.011		Same as laundry appliances
Interruptible	6	Clothes dryer	2	30	11:30 – 12 or 23:00 – 23:30
	7	Electric vehicle	16		Could be charged after 21:00
Adjustable	8	Washing machine	2	60	10:00 – 11:00 or 22:00 -23:00
	9	Dishwasher	1.8	150	8:00 – 9:00 or 22:30 – 23:30
	10	Electric kettle	1.5	15	6:30-6:35 and 16:30-16:35 and 20:30-20:35
	11	1Hp water pump	0.75	240	6:00 – 8:00 and 17:00 – 19:00
	12	Television	0.133	300	18:00-23:00
	13	DVD player	0.025	120	21:00-23:00
	14	Decoder	0.075	180	18:00-21:00

The power demand includes power required for charging batteries and the power needed to use household appliances leads to defining accumulative power needed at any given time t. The accumulative power is also calculated by equation (19).

$$P_{D,t} = P_{A,t} + \eta P_{c,t} \tag{18}$$

$$P_{A,t} = \sum_{i=1}^{N_a} P_n c_{n,t} \tag{19}$$

The aggregated demand power is obtained by equation (20)

$$P_D = \sum_{t=1}^{T} (P_{A,t} + \eta_c P_{c,t}) \tag{20}$$

The discomfiture happens during the diesel generator operation and when there is a disparity between baseline and optimal shift-loaded schedule. These two factors are embedded in equation (21) to calculate the inconvenience level of the residents.

$$I = \sum_{t=1}^{T} \sum_{n=1}^{N_a} \left(c_{n,t}^{bl} - c_{i,t}\right)^2 + \mu \sum_{t=1}^{T} c_{g,t} \tag{21}$$

Where μ is the inconvenience coefficient caused by the diesel generator operation in equation (21).

3.2. Air condition system model

Air condition systems are vital equipment providing cool weather for buildings and comfort for occupants. The massive use of air conditioners in summertime leads to an increase in electricity demand. The power consumption of the air condition system is described in equation (22) as following [38]

$$W_{cool} = \frac{\dot{m}_{ac} c_p \Delta T}{SHR \cdot COP(\Delta T)} \tag{22}$$

Where SHR is the sensible heat ratio, $\dot{m}_{ac}$ is the mass flow rate of air, c_p is the specific heat capacity of air constant pressure, ΔT is the deficiency between ambient temperature and the air temperature blowing from the air condition system, and the COP is the coefficient of performance of the system. The technical specification of the air condition system is listed in table 2.

Table 2. Technical specification of the air condition system

Energy efficiency ratio	3.01
Cooling capacity (Btu/h)	30026
Power consumption (kW)	2.92

The compressor is switched on when there exists a deficiency between room temperature and the set-point. When the deficiency is removed then the compressor will be switched off. Thereby, the electricity demand rises when the compressor is switched on and declines when the compressor is switched off. The proposed control method is responsible for keep temperature at the comfort level. The variable ambient temperature on a summer day and the room temperature kept cool by the air conditioner are shown in Fig. 3. Also, the air condition system power consumption is shown in Fig. 4. The ambient temperature is shown in Fig. 3 is related to a day in the Persian month 'Mordad' (23 July – 22 August). The desired temperature of the room is set to 24^{0c}. As shown in Fig. 3, the temperature in the daytime is changing and considered as a disturbance. Figure 4 shows the successive switching on/off of the compressor to keep the room temperature steady at approximately 24^{0C}.

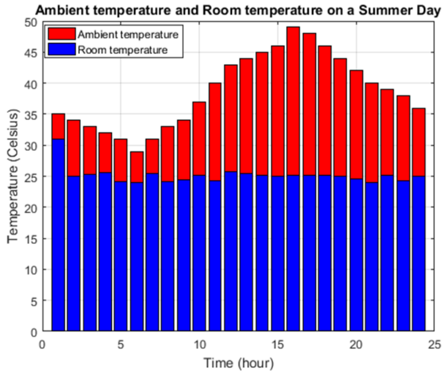

Fig. 3. Ambient and controlled room temperature.

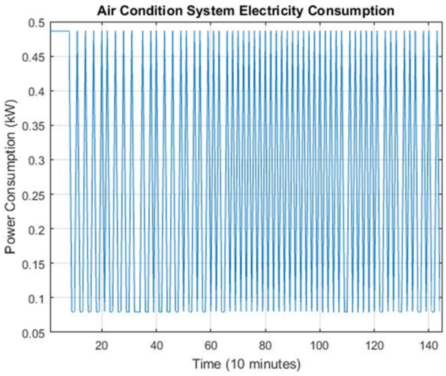

Fig. 4. Electricity consumption of the air condition system.

When the compressor is switched on the electrical power consumption increases to 0.48 kW. But when the compressor is switched off the power consumption decreases to 80 W. Thereby, there exists a fluctuation in the air condition power consumption curve as shown in Fig. 4.

3.3. Electricity Tariff

Electricity Tariff in Iran is defined based on geographical differentiation, season, and time of use .The electricity price based on the time of use on a summer day is shown in Fig. 5. In accordance with [39], table 3 shows the electricity tariff over the off-peak, low-peak, and the peak time periods. It is worth mentioning that to estimate the electricity generation, the maintenance cost and the electricity cost should be considered in the calculation.

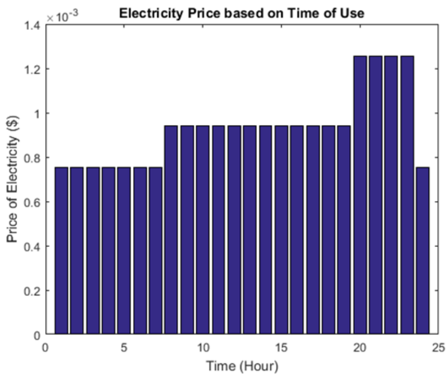

Fig. 5. The electricity price on a summer day.

The maintenance cost includes the maintenance costs of batteries and the diesel generator; however, the maintenance cost of the solar panel is insignificant as the panels selected are fixed tilt angle type.

Table 3. Electricity tariff based on time of use

	Time period (hour)	Cost ($)
Low-peak	7:00 am – 19:00 pm	0.0018
Off-peak	23:00 pm – 7:00 am	0.0007
On-peak	19:00 pm – 23:00 pm	0.0037

4. Calculation and Results

4.1. HEMS algorithm control

According to equation (1), the main aim is to reduce the electricity consumption cost as much as possible. As a result, a proposed algorithm is employed in order to schedule household appliances, charge and discharge batteries, switch off/on the diesel generator and shift loads. When the cost of electricity consumption is expensive (means not in the off-peak time period), the algorithm starts the load shifting program which is done by firefly-based nonlinear model predictive control. Hence the operation of electrical devices postpones to the off-peak time period or low-peak hours. At each time interval, the output power of the PV panel, the status of electrical appliances, the SOC of battery, room temperature, the diesel generator output, and the price are checked. Then based on the amount of electricity demand, at first the algorithm tries to meet the demand by finding a suitable local generator (PV panel, battery storage system, diesel generator). Then if the demand is still violated then tries to turn off curtailable and even interruptible loads respectively. In the end, if the demand is not yet responded by local generators then the demand is met by the grid alongside the local generators. The flowchart of the proposed algorithm is presented in Fig. 6.

4.2. Load shifting

Load shifting means that the time of use of load shifts to another time with less electricity cost based on consumer's flexibility in order to minimize the electricity cost [37]. In this study, the occupants announced the frequent time of use of household appliances. In table 1, the electricity consumption profile of appliances and the common time of use of them are listed. Table 3, also, illustrates that the electricity price is changing over time in a day. As can be seen in table 1, there exist four categories of appliances including uncontrollable (uninterruptible), curtailable, interruptible and adjustable devices. Thereby, some appliances can be used over the inexpensive time period and even curtailable loads could be turned off during the peak time period such as lights. In this way, a load-shifting strategy could be performed. Figures 7 shows the results of the load shifting program which has done in this study. As shown in Fig. 7, the time of use of household appliances is shifted to the inexpensive time periods would lead to minimizing electricity cost.

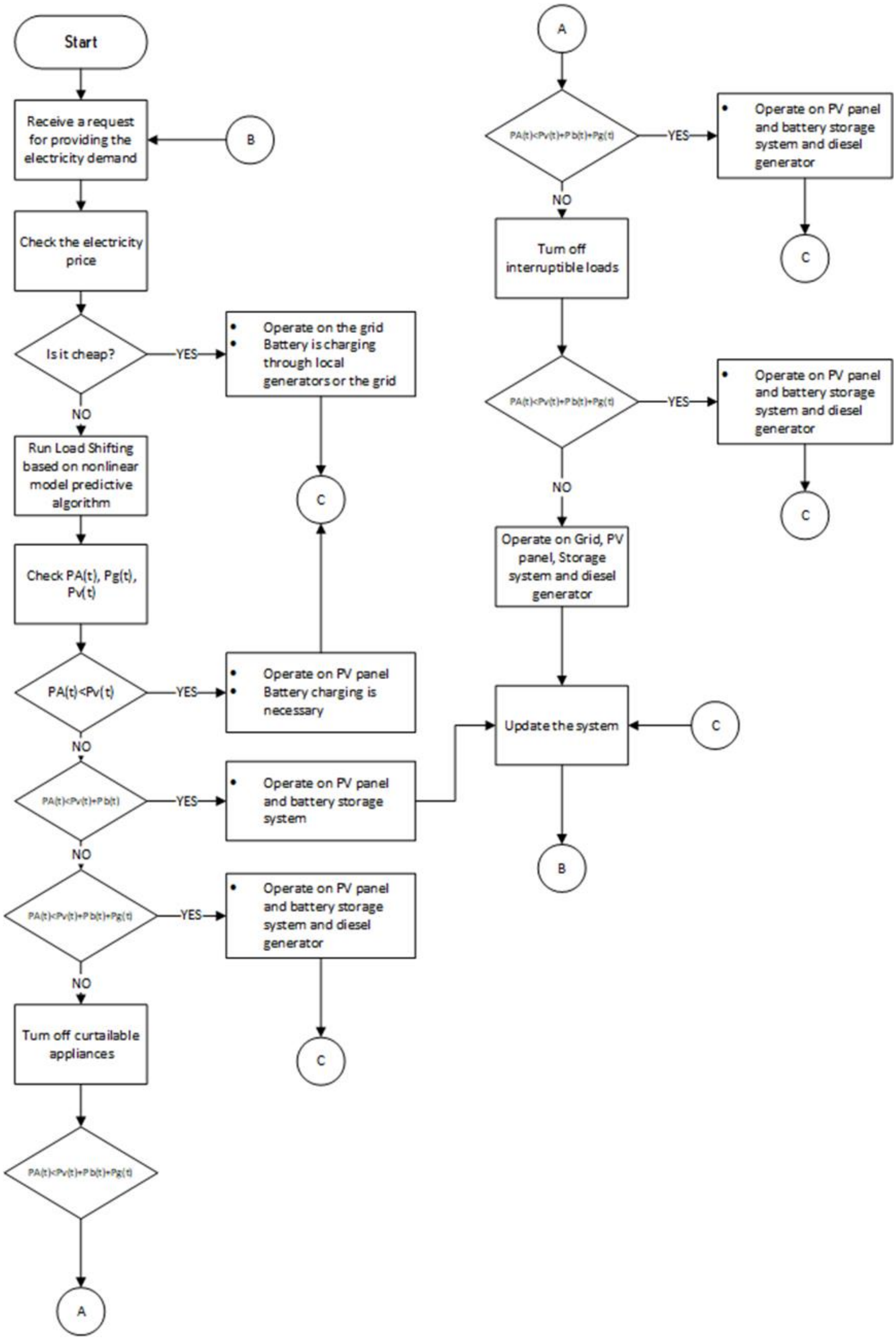

Fig. 6. Flowchart of the proposed novel control algorithm

As a result, peak-time shaving is accomplished. Load shifting results for three appliances including washing machine, clothes dryer, and water pump are shown in Fig. 8. Some appliances such as clothe dryer have two suggested time of use, therefore, the optimization algorithm tries to select the lower price time of use to minimize the cost. The fluctuations in electricity demand are related to compressor switching on-off which is done sequentially to maintain the temperature of the room at the set-point level.

The economic data of running shift loading program in Persian month 'Mordad' (23 July – 22 August) in summer is shown in table 4.

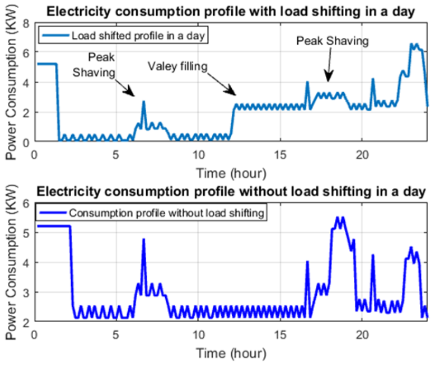

Fig. 7. Electricity consumption profile in a day with load shifting and without load shifting

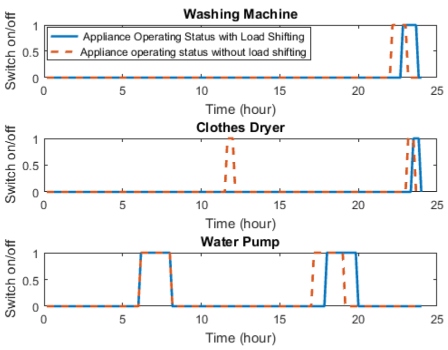

Fig. 8. Load shifting three appliances including washing machine, clothes dryer, and water pump

Table 4. The economic data of running demand response program for a month

	without load shifting	with load shifting
Household appliances plus air condition system electricity cost	11.4$	10.3$
Battery charging cost	1.24$	0.93$
Total cost	12.64$	11.23$

As shown in table 4, it can be seen that the economic benefit from shift loading is not considerable for consumers and this is due to the fact that the electricity price in Iran is cheap due to the huge subside devoted to the household sector [40]. But load shifting has a great benefit for producers during the peak time period in summer.

4.3. The solar panel effect on the HEMS

The installed solar electricity generation system consists of the solar panel manufactured by Sharp company, inverter manufactured by Delta Energy, and cables [41]. The solar panel is a fixed tilted angle typed with tilt angle 60'one which is mounted on the roof. The solar system parameters are listed in table 5. The solar electricity generation trend is shown in Fig. 9.

Table 5. The technical specification of the installed solar panel

Field type	Fixed tilted angle
Plane tilt angle	60'
Plane azimuth angle	0'
Power	2.5 kW
Sub-array numbers	1
Module numbers	10
Connection type	Series
Area	16 m^2
Inverter	1 unit, 2.5 kW

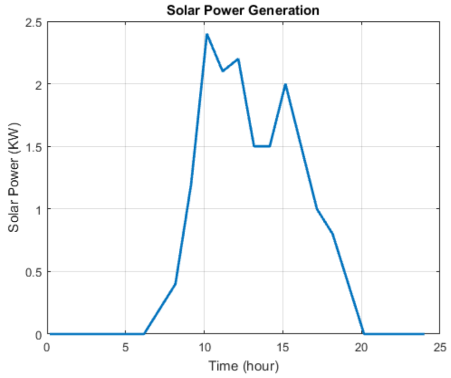

Fig. 9. The electrical power gained from the solar panel

4.4. Battery-based Energy Storage System

The studied building is equipped with a battery storage system that contributes to provide electricity during peak time period. The type of batteries is employed in the storage system is lead-acid one which has relatively low investment cost, high availability, reasonable performances, and long-life characteristics. The size of the battery storage system is considered 9kWh. According to the literature review, the charging and discharging efficiencies of lead-acid batteries are 65%-85% and 100% respectively [18]. The technical and economic features of batteries employed in this study are listed in table 6. The optimal pattern of charging and discharging batteries is depicted in Fig. 10. As shown in Fig. 10, it is obvious that the proposed control strategy optimizes the charging and discharging actions to minimize the cost of charging and maximize the cost of discharging.

Table 6. The technical data of the battery storage system

Battery room capacity	9kWh
Battery technology	Lead-acid
Charging efficiency	70%
Discharging efficiency	100%
DOD	50%
Investment cost on the power of the battery ($/kW)	32.4
Maintenance and operational cost ($/kWh)	1e-3$
Battery lifetime	8 year

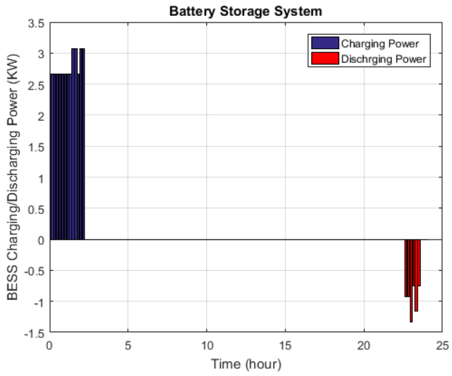

Fig. 10. The optimal pattern of charging and discharging the batteries.

As a result, charging of batteries is done from 00:00 to 3:00 am and discharging is done from 23:00 to 24:00 when the loads are augmented due to the shift loading and the diesel generator and the photovoltaic system have no contributions to provide electricity anymore. The economic data of using batteries are listed in table 7 for the Persian month 'Mordad'.

Table 7. The economic data of charging and discharging the energy storage system for a day

Electricity cost for charging the batteries	0.93$
Earning from discharging the batteries	0.51$

4.5. Diesel generator effect on the HEMS

As fossil fuel is relatively inexpensive and available in Iran, diesel generators are popular and installed on-site and generate electricity. When diesel generators are used in residential areas the comfort level of residents should be considered. One low-cost solution to lessen the unwanted effects of diesel generators would be limited to the operating time of diesel generators. The employed diesel generator is a LONCIN LC3500A type which is manufactured in China. The diesel generator is a 4 stroke 6.5HP one with dB rating 75dB [42][41]. The other technical specification of the diesel generator is listed in table 8.

Figure 11 shows the rate of electricity generated by the diesel generator.

Table 8. The technical specifications of LONCIN LC3500A Diesel Generator[43]

Maximum output	3.1kW
Continuous output	2.8kW
Fuel tank size	18 Liters
Number of outlets	2 * 15 Amp
Continuous working time	15
Maintenance cost ($/kWh)	0.005$

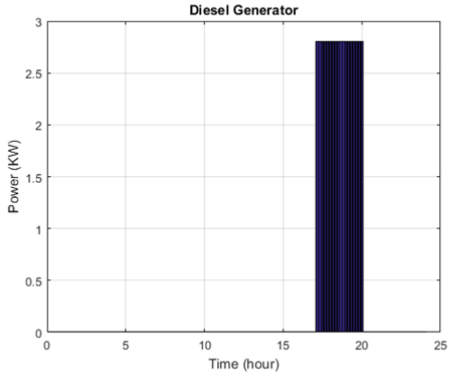

Fig. 11. The electrical power produced by the diesel generator.

To preserve the comfort level of residents it is assumed that the operation of the diesel generator is constrained and not allowed to operate from 00:00 to 7:00, from 14:00 to 17:00, and from 21:00 to 24:00. The diesel generator can contribute to charge the batteries along and support the grid over the peak time period. Residents benefit from fuel-based electricity generation by reducing their demand for electricity provided by the grid during the peak time period leading to a decrease in their electricity cost. The fuel price is assumed 0.076$.

4.6. The whole model analysis

The studied building is equipped with a photovoltaic system, diesel generator, and battery storage system which is connected to the grid and contributes to electricity generation to decrease the electricity provided by the grid. Regarding building is connected to the grid, there is a bilateral relation between the grid and the electrical system of the building. To be more precise, for responding to the requirements of the building, the building produces electricity via on-site electrical generators and the storage system to supply the electricity being in demand alongside the grid as the main source of providing electricity. In addition, load shifting based on consumers' flexibility is performed which leads to shifting time of using electricity from peak time period to off-peak or low-peak time period. The electricity provided by the grid is shown in Fig. 12. The on-site electricity generation curves are shown in Fig. 13. In addition, the electricity consumed and generated in a day in the building are shown in Fig.14 simultaneously.

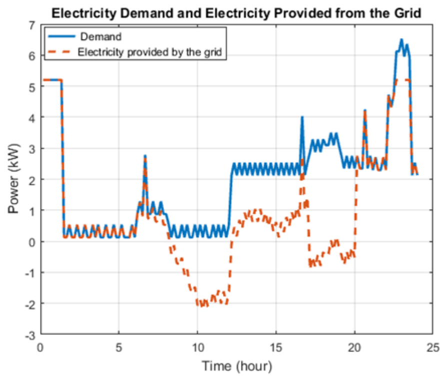

Fig. 12. The electricity provided by the grid and electricity demand

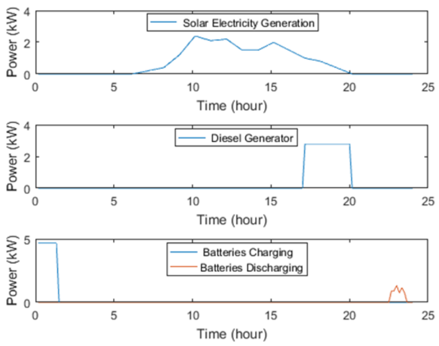

Fig. 13. On-site electricity generation curves

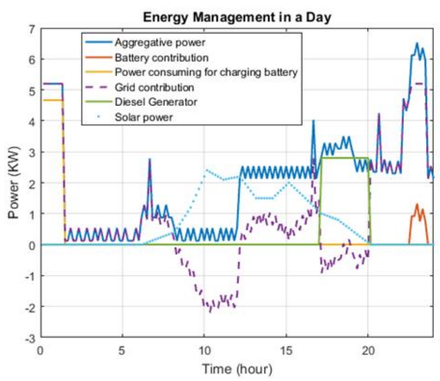

Fig. 14. Energy management result curve including local generations and the electricity provided by the grid

In accordance with Figure 14, it is evident that by running the demand response program scheduled by the proposed control algorithm, the prosumer not only provides the electricity in demand but also sells the extra electricity generation over the peak time period and benefits financially which is shown by the grid contribution trend in Fig. 14. The opportunity of selling electricity over the peak time period is created by the implementation of the demand response program and the utilizing local generators and the battery storage system. In Iran, there exist financial incentives to provide electricity on-site by consumers. The extra electricity generation is guaranteed to be bought by the government and priced at 0.061$ which is more considerable than the electricity price provided by the grid. The economic data of the energy management in the building in the grid-connected state in Persian month 'Mordad' is listed in table 9.

Table 9. The balance sheet of trading electricity between the household unit and the grid for a month

Grid electricity cost	7.64$
Fixed tilt angle solar panel maintenance cost	0
Diesel generator fuel cost	8.37$
Diesel generator maintenance cost	1.39$
Batteries maintenance cost	0.558$
Expenditures	17.96$
Earning from the electricity sold in Mordad	13.24$
Balance of payments	4.72$

According to table 9, it was shown that the total expenditures is 13.24$. However, by implementing load shifting and equipping the building with battery storage systems, and local generators including solar panel and diesel generator the balance of payment for electricity consumption is declined to 4.72$. As can be seen in the table 9, the expenditures include diesel generator fuel and maintenance cost, batteries maintenance cost, and spending on electricity provided by the grid. But, according to the table 9, the key factor contributing to decline the electricity cost is selling extra generated electricity to the grid over the peak-time period at the incentive price.

5. Conclusion

In this study, the home management system for a grid-connected residential building is investigated. The electricity tariff is variable and dependable to the time of use. A demand response program and a control algorithm were proposed and implemented which resulted in proper peak shaving during the peak time period and valley filling over the low-peak or off-peak time periods. In addition, a hybrid local electricity generation system including a photovoltaic system and a diesel generator alongside a battery storage system was designed and applied. To sum up, in according to the obtained results, it is evident that through the proposed energy management system prosumers not only would be able to reduce their electricity demand provided by the grid but also over the peak time period could sell their extra electricity generation to the grid and benefit from the considerable financial incentives leading to reduce the electricity consumption cost.

Acknowledgements

This study has been extracted from the interior research project titled "Application of Generalized Model Predictive Control in Industrial Process" which was approved in the engineering faculty of the Shohadaye Hoveizeh University of Technology.

References

[1] M. Abdelaziz Mohamed ,A. M. Eltamaly, Modeling and Simulation of Smart Grid Integrated with Hybrid Renewable Energy Systems, 1st ed. Springer, 2018, pp. 41-43.

[2] H. Mehrjerdi ,R. Hemmati, “Coordination of vehicle-to-home and renewable capacity resources for energy management in resilience and self-healing building”, Renewable Energy, vol. 146, pp. 568-579, Februrary 2020.

[3] J. Faraji, M. Babaei, N. Bayati, and M. A.Hejazi, “A Comparative Study between Traditional Backup Generator Systems and Renewable Energy Based Microgrids for Power Resilience Enhancement of a Local Clinic”, Electronics, vol. 8, No. 12, pp. 1485-1505, 2019.

[4] Y. Yang, S.-C. Tan ,S. Y. R. Hui, “Mitigating distribution power loss of DC microgrids with DC electric springs”, IEEE Transactions on Smart Grid, vol. 9, No. 6, pp. 5897-5906, 2018.

[5] S. Bahrami, M. H. Amini, M. Shafie-Khah, and J. P. S. Catalão, “A Decentralized Renewable Generation Management and Demand Response in Power Distribution Networks”, IEEE Transactions on Sustainable Energy, vol. 9, No. 4, pp. 1783-1797, 2018.

[6] F. Baronti, S. Vazquez ,M.-Y. Chow, “Modeling, control, and integration of energy storage systems in e-transportation and smart grid”, IEEE Transactions on Industrial Electronics, vol. 65, No. 8, pp. 6548-6551, 2018.

[7] K. K. Zame, C. A. Brehm, A. T. Nitica, C. L. Richard, and G. D. Schweitzer III, “Smart grid and energy storage: Policy recommendations”, Renewable and Sustainable Energy Reviews, vol. 82, pp. 1646-1654, 2018.

[8] F. Garcia-Torres, C. Bordons ,M. A. Ridao, “Optimal economic schedule for a network of microgrids with hybrid energy storage system using distributed model predictive control”, IEEE Transactions on Industrial Electronics, vol. 66, No. 3, pp. 1919-1929, 2019.

[9] R. Mehta, D. Srinivasan, A. M. Khambadkone, J. Yang, and A. Trivedi, “Smart charging strategies for optimal integration of plug-in electric vehicles within existing distribution system infrastructure”, IEEE Transactions on Smart Grid, vol. 9, No. 1, pp. 299-312, 2018.

[10] H. Jabir, J. Teh, D. Ishak, and H. J. E. Abunima, “Impacts of demand-side management on electrical power systems: A review”, Energies, vol. 11, No. 5, p. 1050, April 2018.

[11] C. W. Gellings, “Evolving practice of demand-side management”, Journal of Modern Power Systems and Clean Energy, vol. 5, No. 1, pp. 1-9, January 2017.

[12] E. S. Jones, H. Gong ,D. M. Ionel, “Optimal Combinations of Utility Level Renewable Generators for a Net Zero Energy Microgrid Considering Different Utility Charge Rates”, 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 1014-1017, 2019.

[13] Exploring the Relationship Between Demand Response and Energy Efficiency: A Review of Experience and Discussion of Key Issues, American Council for and Energy-Efficient Economy, 2005.

[14] N. Ahmed, M. Levorato ,G.-P. Li, “Residential consumer-centric demand side management”, IEEE Transactions on Smart Grid, vol. 9, No. 5, pp. 4513-4524, 2018.

[15] S. Parhizi, A. Khodaei ,M. Shahidehpour, “Market-Based Versus Price-Based Microgrid Optimal Scheduling”, IEEE Transactions on Smart Grid, vol. 9, No. 2, pp. 615-623, 2018.

[16] F. Wang, L. Zhou, H. Ren, X. Liu, S. Talari, M. Shafie-khah, and J. P. S. Catalão, “Multi-Objective Optimization Model of Source–Load–Storage Synergetic Dispatch for a Building Energy Management System Based on TOU Price Demand Response”, IEEE Transactions on Industry Applications, vol. 54, No. 2, pp. 1017-1028, 2018.

[17] A. Nilsson, D. Lazarevic, N. Brandt, and O. Kordas, “Household responsiveness to residential demand response strategies: Results and policy implications from a Swedish field study”, Energy Policy, vol. 122, pp. 273-286, November 2018.

[18] R. Hemmati, “Technical and economic analysis of home energy management system incorporating small-scale wind turbine and battery energy storage system”, Journal of Cleaner Production, vol. 159, pp. 106-118, August 2017.

[19] B. Zhou, W. Li, K. W. Chan, Y. Cao, Y. Kuang, X. Liu, and X. Wang, “Smart home energy management systems: Concept, configurations, and scheduling strategies”, Renewable and Sustainable Energy Reviews, vol. 61, pp. 30-40, 2016.

[20] H. Mehrjerdi, M. Bornapour, R. Hemmati, and S. M. S. Ghiasi, “Unified energy management and load control in building equipped with wind-solar-battery incorporating electric and hydrogen vehicles under both connected to the grid and islanding modes”, Energy, vol. 168, pp. 919-930, 2019.

[21] S. Das ,A. K. Akella, “Power flow control of PV-wind-battery hybrid renewable energy systems for stand-alone application”, International Journal of Renewable Energy Research, vol. 8, No. 1, pp. 36-43, 2018.

[22] D. Arcos-Aviles, J. Pascual, L. Marroyo, P. Sanchis, and F. Guinjoan, “Fuzzy logic-based energy management system design for residential grid-connected microgrids”, IEEE Transactions on Smart Grid, vol. 9, No. 2, pp. 530-543, 2018.

[23] M. Farrokhabadi, S. König, C. A. Cañizares, K. Bhattacharya, and T. Leibfried, “Battery Energy Storage System Models for Microgrid Stability Analysis and Dynamic Simulation”, IEEE Transactions on Power Systems, vol. 33, No. 2, pp. 2301-2312, 2018.

[24] N. Saxena, I. Hussain, B. Singh, and A. L. Vyas, “Implementation of a Grid-Integrated PV-Battery System for Residential and Electrical Vehicle Applications”, IEEE Transactions on Industrial Electronics, vol. 65, No. 8, pp. 6592-6601, 2018.

[25] C. Ion ,C. Marinescu, “Optimal Charging Scheduling of Electrical Vehicles in a Residential Microgrid based on RES”, 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 397-400, 2019.

[26] L. Barote ,C. Marinescu, “Li-Ion energy storage capacity estimation in residential applications with EV”, 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 326-330, 2019.

[27] S. Bellocchi, M. Gambini, M. Manno, T. Stilo, and M. Vellini, “Positive interactions between electric vehicles and renewable energy sources in CO2-reduced energy scenarios: The Italian case”, Energy, vol. 161, pp. 172-182, 2018.

[28] H. Fathabadi, “Plug-In Hybrid Electric Vehicles: Replacing Internal Combustion Engine With Clean and Renewable Energy Based Auxiliary Power Sources”, IEEE Transactions on Power Electronics, vol. 33, No. 11, pp. 9611-9618, 2018.

[29] M. Shakeri, M. Shayestegan, S. M. S. Reza, I. Yahya, B. Bais, M. Akhtaruzzaman, K. Sopian, and N. Amin, “Implementation of a novel home energy management system (HEMS) architecture with solar photovoltaic system as supplementary source”, Renewable Energy, vol. 125, pp. 108-120, September 2018.

[30] Z. Movahediyan ,A. Askarzadeh, “Multi-objective optimization framework of a photovoltaic-diesel generator hybrid energy system considering operating reserve”, Sustainable cities and society, vol. 41, pp. 1-12, 2018.

[31] K. Yuasa, I. Omura, M. Ueshima, and T. Babasaki, “Power Energy Cost Reduction Effects by Applying Optimized Long-Term Storage Battery Operation Strategy”, 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 107-112, 2019.

[32] M. Alimardani, M. Narimani ,N. Al-Mutawaly, “A New Approach to Improve Li-Ion Battery Lifetime in Home Energy Storage System with Photovoltaic Modules”, 2018 IEEE Canadian Conference on Electrical & Computer Engineering (CCECE), pp. 1-4, 2018.

[33] M. T. Elsir, M. A. Abdulgalil, A. T. Al-Awami, and M. Khalid, “Sizing and Allocation for Solar Energy Storage System Considering the Cost Optimization”, 8th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 407-412, 2019.

[34] D. Setlhaolo, X. Xia ,J. Zhang, “Optimal scheduling of household appliances for demand response”, Electric Power Systems Research, vol. 116, pp. 24-28, November 2014.

[35] I. B. Sperstad ,M. Korpås, “Energy storage scheduling in distribution systems considering wind and photovoltaic generation uncertainties”, Energies, vol. 12, No. 7, p. 1231, 2019.

[36] A. Divecha, S. Stockar ,G. Rizzoni, “Nonlinear Model Predictive Control for the Coordination of Electric Loads in Smart Homes”, ASME 2017 Dynamic Systems and Control Conference, pp. V003T42A005-V003T42A005, 2017.

[37] D. Setlhaolo ,X. Xia, “Optimal scheduling of household appliances with a battery storage system and coordination”, Energy and Buildings, vol. 94, pp. 61-70, May 2015.

[38] M. Maiorino, S. Stockar, M. Sorrentino, and G. Rizzoni, “Modeling and Simulation of Residential Power Demand Including Transportation”, ASME 2015 Dynamic Systems and Control Conference, Columbus, USA, October, 2015.

[39] The Electricity Tariff of Household Sector, The Minestery of Energy, 2018.

[40] F. Hessari, “Sectoral energy consumption in Iran”, Renewable and Sustainable Energy Reviews, vol. 9, No. 2, pp. 203-214, 2005.

[41] J. Palm, “Household installation of solar panels–Motives and barriers in a 10-year perspective”, Energy Policy, vol. 113, pp. 1-8, 2018.

[42] Gasoline Generator Owner's Manual, Loncin Motor Co. ltd.,

[43] LC Series User Manual Available: https://www.dualpumps.co.uk/files/pdf/products/User%20Manuals/LONCIN/LON%20LC%20SERIES%20USER%20MANUAL.pdf