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# An integrated home energy management system by the load aggregator in a microgrid using the internet of things infrastructure

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**ABSTRACT**

Smart technologies enable the significant participation of consumers in demand-side management programs. In this paper, the management of electrical energy consumption for a set of residential houses in a microgrid by a load aggregator for a 24-h planning horizon is studied. In this study, consumption management programs are implemented on controllable equipment by sending binary codes by the load aggregator via the internet of things (IoT) infrastructure to residential sockets. To increase the level of customer convenience and provide more flexibility for consumers to participate in demand response programs, a parameter called the value of lost load (VOLL) has been introduced. According to the results, in addition to no need to use the energy management system for each residential house, only by moving shiftable loads to off-peak hours, 18.34% of energy consumption costs are saved daily. Also, from the load aggregator's viewpoint for every 10% change in status from normal to the scheduled priority, there is a reduction of about 3.4% in the consumer's peak-load cost. If solar arrays and storage resources are used, more than 18% of the total consumption cost can be saved.



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## 1. INTRODUCTION

The smart grid is a network of information and communication technologies that enables two-way communications between the consumers and the utilities [1]. Therefore, this grid not only helps to improve network security, increase the penetration of renewable resources, and reduce congestion during peak hours but also reduces the cost of energy consumption and enhances customer satisfaction indices [2]–[5]. One of the potential benefits of implementing such a network is to provide a platform for energy management of residential houses which can make a major contribution to planning the operation of appliances and reducing electricity consumption [6]. A real-time solution for joint energy storage management and load scheduling has been proposed in [7] while considering the battery operation and load delay constraints. In [8], an approach for the management of energy flow in distribution networks considering multiple energy carriers was presented. The proposed model was based on the new concept of energy hubs that made integrated analysis in multi-carrier energy systems possible. In Tang *et al.* [9] conducted their research by considering the peak-to-average ratio (PAR) as well as user convenience by using fuzzy logic and exploratory optimization techniques. The simulation results showed a significant reduction in energy consumption, costs, and PAR. Yoon *et al.* [10] presented a multi-purpose building energy management system that was capable of achieving 5% annual energy savings. Since the home energy management systems (HEMS) lies under the umbrella of demand side management (DSM), it allows residential consumers to supervise and manage the power usage of their appliances to reduce their electricity bills. Nowadays domestic electricity usage accounts for 30% of the global energy consumption [11]. According to the US residential energy consumption survey, a study conducted in [12] shows that 15% of energy savings can be achieved by shifting controllable appliances in a household. In [13], an algorithm for the home energy management system was provided to shift controllable devices in a residential house to bring convenience to the consumer and minimize electricity bills using a multi-time pricing scheme. In [14], presents practical challenges imposed while implementing direct strength method (DSM) using load shifting for internet of things (IoT) enabled HEMS. The issues related to the characterization of home appliances, integration of intermittent renewable energy sources, load categorization, various constraints, dynamic pricing, consumer categorization have been discussed.

Thus far, all studies have touched on the issue of residential energy management (REM) and proposed a variety of solutions. Although the majority of these studies have mainly focused on reducing energy costs [15], [16], other goals such as satisfying user's comfort preferences [17], [18], and smoothing the consumption curve [19] have been addressed in the literature. In [20], proposes a smart socket system called MorSocket that allows the user to control multiple separated sockets within a control webpage. These sockets share the same wireless communication module.

According to the review of the studies conducted in this field, it was found that the integrated and centralized management of a set of residential houses through a load aggregator has not been evaluated. Therefore, in this study, an approach to centralized management of electrical energy consumption of controllable devices in all the residential houses located in the microgrid is provided by considering the priorities set by the consumers. In this approach, the aggregator, by taking into account the constraints of the distribution network and consumer's priorities, scheduled the consumption pattern of controllable devices in such a way that not only the energy cost is minimized but also the convenience level determined by them is preserved. To provide flexibility and increase the level of customer convenience, a parameter called the value of lost load (VOLL) has been defined. The amount of VOLL for each controllable device is determined by the user. By utilizing this parameter, it is easy to apply the demand side's satisfaction into programming.

The main contributions of this article can be listed: i) introducing a new approach for energy management of a set of residential houses through a load aggregator to minimize the cost of energy consumption of consumers by considering the constraints of the distribution network; ii) integrated demand planning by considering renewable energy sources and storage resources for the optimal use of all the microgrid capabilities; iii) using the IoT and 3G/4G platform for connection between the central controller installed in the load aggregator and consumer's sockets as well as unmediated control of controllable devices (no need for HEMS); and iv) introducing the possibility of applying the customer's opinions in programming to increase the level of convenience and improve the flexibility to encourage participation in demand-side management programs.

The rest of the paper is organized. In section 2, the proposed IoT-based energy management system architecture and the interaction with the power aggregator are explained. Mathematical modeling of the objective function and corresponding constraints, tariff rate, and characteristics of controllable devices, and the concept of the value of lost load (VOLL) are presented in section 3. A comparison of results obtained by different scenarios is presented in section 4. Finally, in section 5 concluding remarks of the paper will be presented.

## 2. PROPOSED IOT BASED ENERGY MANAGEMENT SYSTEM ARCHITECTURE

The IoT-based energy management system consists of a smart socket, home gateway, cloud server, and controller in the central computer located in the aggregator. It is assumed that all consumers are equipped with smart sockets. Smart sensors embedded in sockets can measure the current and voltage consumed by the equipment in specific time steps and can send the data to the aggregator. The wireless communication protocol between smart sockets and home gateway is ZigBee which consumes very low power and is often employed by personal area networks. The communication protocols between the central controller and home gateway can be 3G, 4G, or internet (and Wi-Fi) since the data transmitted between them is often large and long-distant. Figure 1 shows the architecture of an IoT-based energy management system.

### 2.1. Information gathering

In this article, it is assumed that all consumers are equipped with smart sockets. To consider consumer convenience and deploy management plans based on the consumers' desired priorities, the VOLL parameter has been introduced and used in the problem objective function. The amount of this parameter for each controllable device must be selected by the users. The priorities based on which the devices can be used are listed: economic, scheduled, and normal priority. To select this parameter by the user, four microswitches are installed on each smart socket, two of which represent the economic and normal priority states and the other two microswitches for the scheduled priorities (schedule-low and schedule high). In the economic priority, the controllable device is not used on the next planning horizon and is designed for a time when the user does not want to use that device for the next day.

The scheduled priority includes low and high priorities, and by selecting each of these two items, the importance of the operation of the device from the user's point of view is determined. The controller located in the aggregator is allowed to plan the energy consumption only for the hours within the permissible period specified for that device in which the energy tariff rate is less than the VOLL amount defined for the controllable devices. If for any reason, such as limitation of maximum energy consumption in the time intervals or restrictions on the power distribution in the distribution network, the aggregator is not capable of turning the controllable device on at those hours, the device is no longer turned on until the end of the programming horizon.

Normal priority is defined for situations in which the consumer has an urgent need to operate the device at the desired moment, and in these situations, the energy tariff rate does not affect the operation of the device. In addition to the four microswitches on the smart sockets, there is another micro switch that is used to specify the allowable on/off hours of each socket. This mode can be used to prevent the operation of controllable devices that produce a lot of noise during work (such as dishwashers or washing machines) and limit their performance at certain hours of the day. After gathering the electricity data sent by smart sockets, the home gateway transmits the data to the energy management controller in the aggregator via the Internet or a mobile communication network.

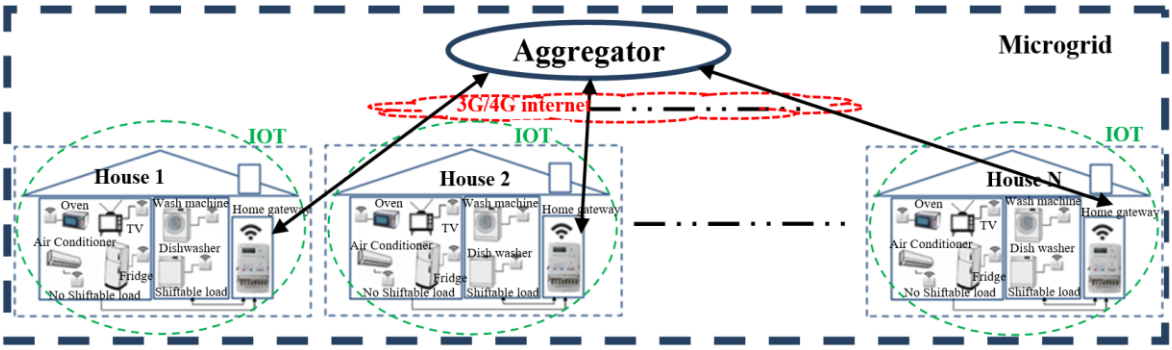


Figure 1. The proposed IoT-based system architecture

## 2.2. Central controller function

The energy management controller located in the aggregator collects the data and then stores it in the statistical table previously created in the cloud server. The statistical table of each house contains information about smart sockets. The energy management controller, in addition to storing power data, also determines the status of the socket and manages the energy consumption of the house. After accurately estimating the amount of energy produced by renewable sources and considering the tariff rate along with the time constraints and operating restrictions of the distribution network, optimal planning for the operation of all the controllable devices is performed by the central controller to meet the consumer's priority and minimize the energy consumption cost. The performance of the controller is shown in Figure 2.

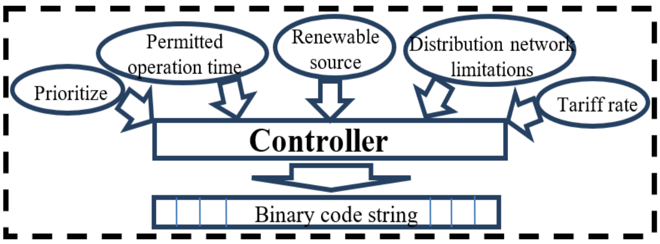


Figure 2. The performance of the central controller in the aggregator

## 3. THE PROPOSED PROBLEM MODELING

### 3.1. Objective function and constraints

The objective function of the problem (minimizing customer's electrical energy consumption cost with considering welfare level) is defined as (1). In this regard, the first term (2) represents the energy cost (EC), and the second term (3) represents the reliability cost (RC). RC is defined to model the controllable device's consumption priority. In this respect, VOLL indicates the value of the operation of the controllable devices from the consumer's point of view [21]. The variable x is a binary vector that specifies the performance status of the shiftable loads for each time step. This variable is considered the output of the programming unit located in the load aggregator and determines the status of the controllable devices in every time step. In (4), it is stated that the total amount of a consumer's energy consumption consists of the consumption of shiftable and fixed loads.

$$min\, O.F = EC + RC \tag{1}$$

$$EC = \sum_{i\in N}\sum_{t\in T} l_i^t \,.Tar^t \tag{2}$$

$$RC = \sum_{t\in T}\sum_{a\in A}\sum_{i\in N}(1 - x_{a,i}^t).VOLL_{a.i}.\,l\_s_{a,i} \tag{3}$$

$$l_i^t = \sum_{a\in A} x_{a,i}^t \,.\,l\_s_{a,i} + l\_ns_i^t \tag{4}$$

Where $l_i^t$ is the total amount of energy consumed by the *i*$^{th}$ customer in the *t*$^{th}$ time step, $Tar^t$ is tariff rate in the *t*$^{th}$ time step, $l\_s_{a,i}$ is the amount of energy consumed by the *a*$^{th}$ shiftable load from *i*$^{th}$ costumer, $l\_ns_i^t$ is the amount of energy consumed by total unshiftable loads from *i*$^{th}$ costumer, $VOLL_{a,i}$ is the value of the lost load of a controllable device from the common $i$, $x_{a,i}^t$ is the performance status of the a$^{th}$ shiftable load from *i*$^{th}$ customer in the *t*$^{th}$ time step, $T$ is time horizon, $A$ is total number of controllable devices, and $N$ is total number of consumers.

The constraints considered for this study are (5)-(8). In (5), it is expressed that the total energy consumption of each controllable device within the allowable time duration set by the user should not exceed the maximum allowable amount. The power consumption of each controllable device at each time step must also be within the specified range as (6). In (7), it is stated that the power flow through the distribution network lines should always be less than the maximum limit. Finally, in (8), the voltage magnitude of the grid buses must not exceed the allowable range.

$$\sum_{t\in\alpha_{a,i}}^{\beta_{a,i}} l_{a,i}^t \leq E_{a,i}^{max} \tag{5}$$

$$l_{a,i}^{min_{a,i}^{t}{}_{a,i}^{max}} \tag{6}$$

$$Flow_j \leq Flow_j^{max} \tag{7}$$

$$V_k^{min_k{}_k^{max}} \tag{8}$$

Where, $\alpha_{a,i}, \beta_{a,i}$ is the beginning and the end of allowable time duration of operation of the *a*$^{th}$ shiftable loads from *i*$^{th}$ costumer, $l_{a,i}^{min_{a,i}^{max}}$ is min. and max. consumption of the *a*$^{th}$ shiftable loads from *i*$^{th}$ costumer, $Flow_j^{max}$ is the Max. flow of line *j*$^{th}$, $V_k^{min_k^{max}}$ is the upper and lower limit of *k*$^{th}$ bus voltage, $J$ is total power lines of microgrid, $K$ is total buses of microgrid.

A genetic algorithm (GA) has been used to optimize the consumption pattern of consumers. This algorithm is easy to implement and can simultaneously process a large number of problem variables with continuous and discrete constraints in a short amount of time. By extracting the consumption data of the customers (consumption rate of all electrical equipment along with the prioritization of controllable devices) and considering the tariff rate and microgrid's power flow constraints, the optimal program is designed by GA in the central control unit. Then the output results are sent to the smart sockets through the IoT infrastructure. In this approach, unlike HEMS, there is no need to use a house control unit, thus significant savings in the operator's cost and time are achieved. In addition, the consumers only specify the priority of the controllable devices and there is no need for them to design the program. On the other hand, the programming is done in a way that the interests of the consumers are observed and the level of stability and security of the microgrid is increased by dispatching the power flow and moving the allowable load from peak hours to off-peak hours.

### 3.2. Specifications of controllable devices

In this article, the tariff rate of the year 2019 set by the Ministry of Energy in Iran has been used to calculate the cost of energy consumption. In these conditions, the price rate per kWh of energy consumption for off-peak hours (11 to 7 am) is equal to 262 Iranian Rials, for mid-peak hours (7 to 5 pm and 9 to 11 pm) equal to 524 Iranian Rials, and it is equal to 1,048 Iranian Rials for peak-load hours (5 to 9 pm). In this research, two controllable devices (washing machine and dishwasher) are used to schedule energy consumption. Although the duration of allowable ranges of these devices needs to be determined by the consumer, a default model for simulation is provided and its specifications are given in Table 1.

### 3.3. Value of lost load

By using VOLL, consumers can participate in demand-side management [22]. In this approach, each consumer, according to the desired level of convenience (economic, scheduled, and normal) by selecting each micro switch on smart sockets, can determine the corresponding value of VOLL based on Table 2 for each controllable device. The higher the VOLL selected by the consumer (greater convenience) is, the more appropriate the range of operation of the controllable device will be, but the energy costs might become higher.

Table 1. Specifications of controllable equipment

| Device type | Power consumption (Watt) | Number of operations per week | Allowed period of operation |
|---|---|---|---|
| Washing machine | 800 | 2 times | 6 p.m.-8 a.m. |
| Dish Washer | 900 | 3 times | 5 p.m.-7 a.m. |

Table 2. Types of priorities with corresponding VOLL

| VOLL | Priority |
|---|---|
| 100 | Economic |
| 200-1,000 | Schedule (low-high) |
| 2,000 | Normal |

### 3.4. System characteristics

The system studied in this research consists of three microgrids A, B, and C, which are shown in Figure 3. The information of all the loads is extracted from [23]. The connection between different components of microgrid with power aggregator is shown in Figure 4. Microgrid A is equipped with three solar array units each with a capacity of 360 kW and equipped with a battery set with a capacity of 2,500 kWh and a maximum power of 500 kW. As the demand, 7,000 houses with an average power of 5 kW have been considered for this microgrid.

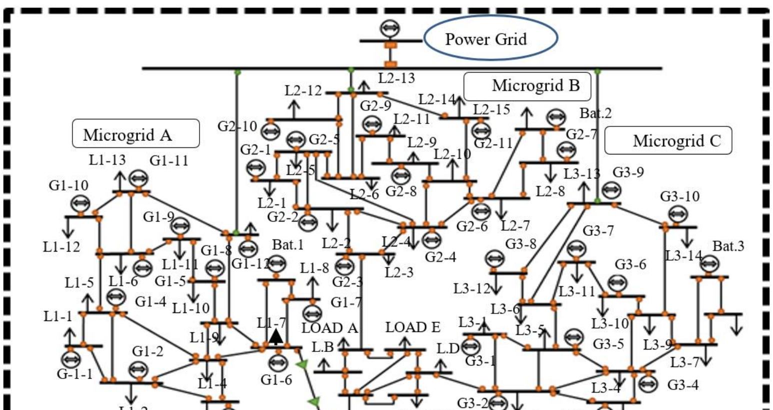


Figure 3. IEEE standard microgrid [23]

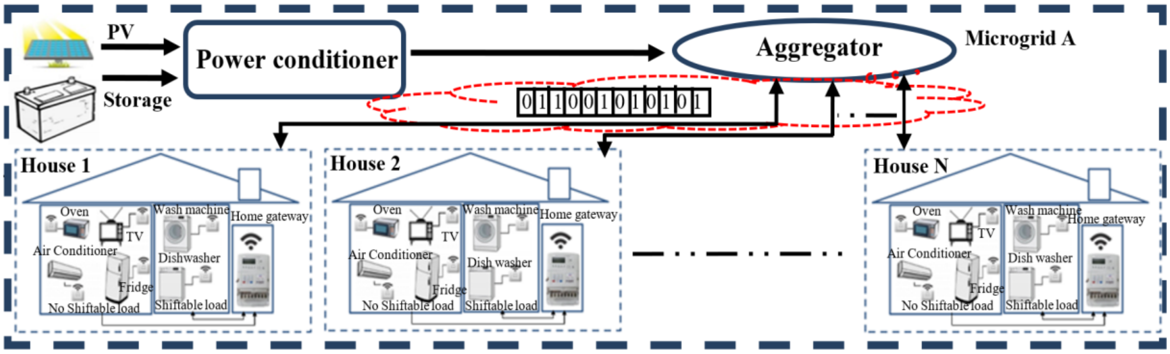


Figure 4. Schematic of the microgrid examined

## 4. SIMULATION RESULTS

To evaluate the proposed approach, two situations have been considered: in the first status, energy management has been done only for one residential house. Under this circumstance, the results obtained from the implementation of economic, normal, and scheduled priorities are calculated and compared with each other. In the second status, the consumption management is done for 7,000 residential houses (of 4 people whose daily energy consumption of each residential house is considered 5 KW) via the power aggregator simultaneously. Due to the various combinations of priorities for all consumers, 4 different scenarios have been defined. In these scenarios, 10%, 40%, 70%, and 100% of the consumers have changed their consumption pattern of controllable devices from normal to scheduled priority, respectively. By comparing the results obtained from these scenarios, the sensitivity of energy cost changing to load pattern shifting can be achieved.

### 4.1. Energy management: one microgrid consumer

In this status, it is assumed that the energy consumption planning is performed only for one residential house by the aggregator. First, the prioritization of the controllable devices along with the allowable operating time duration is determined by the consumer and then is sent to the load aggregator together with the amount of the consumption of fixed electrical devices by the smart socket. In the aggregation unit, the equipment performance planning is done based on the information obtained along with the tariff rate and by considering the distribution network constraints. After that, the results are sent to the home gateway and then sent to the smart sockets in the form of a series of binary codes through the IoT infrastructure. The purpose of implementing such a structure is to minimize the cost of energy consumption by considering the level of convenience and observing the restrictions of the distribution network. To find the optimal solution, a genetic algorithm (GA) is used. The output of this algorithm specifies the components of the vector x in 96-time steps for each of the controllable devices. So that, if the status of this variable is 1 for a device, means that the device is allowed to operate in that time step, and if it is zero, according to the energy management system controller located in the aggregator, the controllable equipment should not operate in this time step. Since the operation of controllable appliances such as dishwashers and washing machines must be done continuously after the start-up (eight continuous time steps for washing machines and six continuous time steps for dishwashers), uninterrupted operation of such devices has been considered in the scheduling.

In simulations, the average consumption pattern of a 4-person household is used. For each house, there are 12 electrical devices, in which two of them (dishwasher and washing machine) are considered as controllable appliances, and all planning programs are done for scheduling their operating time [24]. The time horizon is considered 24 hours consisting of 15-min time-steps. To better understanding, the results in different working conditions, three different priorities (economic-scheduled-normal) are defined in this regard, and the results are compared with each other in Table 3. The results show that changing the priority from normal to schedule-high saves 322,260 Iranian Rials (12.22%) case in the consumer’s energy costs and by changing to schedule-low saves 483,390 Iranian Rials or 18.34% per day is saved in costs. also, by changing the priority from normal to economic, power consumption during peak hours is reduced 615 w per day which saves 644,520 Iranian Rials, equivalent to 24.45% in the consumer’s energy costs per day.

### 4.2. Energy management: total microgrid consumers

To implement flexibility for the operation of controllable devices, three priorities are defined. In the economic priority, the consumer does not need to use the device and no message is sent to the socket by the aggregator. In the scheduled priority (low and high), the consumer can select the value of 200 to 1,000 for VOLL by selecting each micro switch on smart sockets. Then according to the selected priority, the rate of tariff, and by considering the distribution constraints, the central controller in the load aggregator performs optimal planning to minimize the consumer's costs and take into account their level of convenience and sends the control signals to sockets in residential houses. To make a better comparison and evaluation between the different situations, four scenarios are considered and all the scenarios were calculated for three modes: Without using photovoltaic (PV) and battery; using PV alone, and using PV and battery. The number of consumers in each mode is expressed as a percentage of the total and the results are shown in Table 4.

Table 3. Comparison of cost-saving results for one consumer

| Priority | Energy consumption (watt) of one day | | | Cost saving (%) |
|---|---|---|---|---|
| | Off-Peak | Mid-Peak | Peak | |
| Normal | 306 | 1,426 | 1,725 | - |
| Schedule-high | 306 | 2,041 | 1,110 | 12.22% |
| Schedule-low | 921 | 1,426 | 1,110 | 18.34% |
| Economic | 306 | 1,426 | 1,110 | 24.45% |

Table 4. Comparison of cost savings for different scenarios in microgrid A

| Scenario | Scheduled (%) | Normal (%) | Cost-saving in PEAK (%) | | | Cost-saving in TOTAL (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Without PV | With PV | Without PV | With PV | Without PV | With PV |
| 1 | 10 | 90 | 2.91% | 2.95% | 3.46% | 1.21% | 1.67% | 1.83% |
| 2 | 40 | 60 | 11.60% | 11.78% | 13.80% | 4.83% | 6.66% | 7.28% |
| 3 | 70 | 30 | 20.26% | 20.58% | 24.09% | 8.42% | 11.61% | 12.69% |
| 4 | 100 | 0 | 28.95% | 29.41% | 34.43% | 12.03% | 16.60% | 18.14% |

In the first scenario, only 10% of the consumers would be able to change the status from normal to scheduled priority. The amount of saving cost in three different conditions (without PV, with PV, with PV, and battery) is equal to 1.21%, 1.67%, and 1.83%, respectively. In the second scenario, 40% of the consumers change the status from normal priority to scheduled priority. According to the simulation results, the saving cost in the peak-load equals 11.60%, 11.78%, and 13.80%, respectively. On the other hand, total costs will be reduced to 4.83%, 6.66%, and 7.28%, respectively, which in the case of the peak-load cost, is a decrease of 10% compared with the first scenario and a decrease of 6% in the case of total costs.

In the third scenario, 70% of consumers participated in changing the priority from normal to schedule. The amount of savings created in the total cost of electricity consumption is increased to 8.42%, 11.61%, and 12.69%, respectively. In the fourth scenario, it is assumed that the priority of all the controllable devices has changed from normal to schedule priority, which usually saves 12.03% in total electricity costs without using solar energy sources and batteries. If solar energy sources are used, this cost-saving in electricity consumption reaches 16.60%. Finally, with the addition of batteries to solar energy production and by injecting them into the grid at peak-load times, the total cost reduction in power consumption changes to 18.14%, which is a significant amount. The results of all four scenarios are shown in Figure 5.

### 4.3. Comparative evaluation

In recent years, several techniques have been reported to manage energy consumption by exploiting HEMS. This section contains a comparative evaluation of the proposed scheme with a few HEMS-based methods. In conclusion, the proposed scheme can manage electrical energy consumption for a set of residential houses in a microgrid by a load aggregator while the other reviewed schemes cannot.

- At the presence of HEMS, consumers will choose whether to participate in demand response (DR) programs according to their preferences. With the increase in the number of households, the inconvenience level of households may be different. It will bring difficulties to the energy management of the smart home. Consequently, the presented scheme in [25] is not effective for managing a large number of residential houses.
- Improved enhanced differential evolution (EDE) algorithm in [26] discussed the implementation of demand response programs for electricity consumers using evolutionary algorithms. The proposed algorithm also performed favorably in terms of computational time to obtain the optimal parameter settings for maximizing energy cost savings compared to the other considered algorithms, but the research in this paper has focused on a single consumer. Therefore, this algorithm may not be a suitable method for a large group of consumers.

– Because the cost of installing and running HEMS is very expensive. To manage the energy of a microgrid, it may not be possible to force all residential houses to use such a system, and even if implemented, it may not be possible to manage centralized energy for the microgrid.

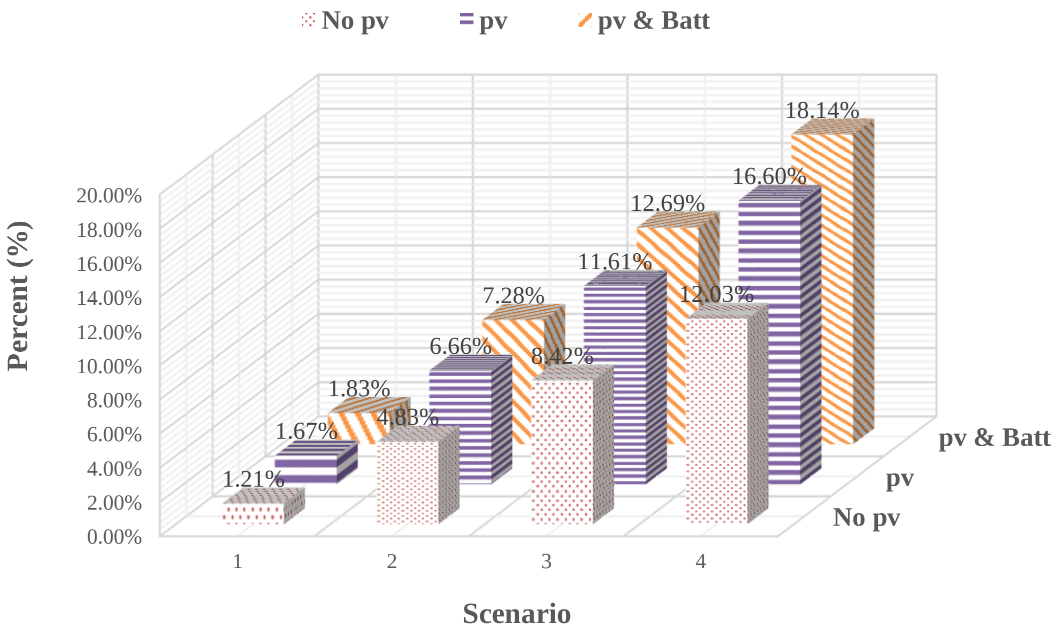


Figure 5. Cost-saving for different scenarios in total microgrid consumers

## 5. CONCLUSION

In this paper, a novel approach for integrated energy management of microgrid consumers through an aggregator is presented. In this design, the number of electrical devices, their energy consumption, the allowable operating range of the controllable devices along their VOLL which was determined by the users, are sent by smart socket via the home gateway to the central controller unit in the load aggregator. The consumer must prioritize the operation of controllable devices and select the desired options between economic, scheduled, and normal priorities for the time horizon. This can provide a high level of flexibility for encouraging participation in demand response programs.

After gathering all the information and considering the power generation conditions in solar arrays and the state of energy storage resources, the operation of controllable devices is planned based on user-defined priorities, energy tariff rates, and distribution network constraints. Finally, control commands via the string of control bits are sent to the home gateway and then sent to the consumer's electrical sockets with the help of IoT technology. In this paper, a GA is used to optimize the operating time step of controllable devices. According to the results, for every 10% change in status from normal to scheduled priority, there is a reduction in consumer's peak-load cost of about 3.4%. If solar arrays and storage resources are used by customers, they can save more than 18% in total consumption cost. In this approach, unlike HEMS, there is no need for using a house control unit and programming by the consumer, thus significant savings in operator's cost and time are achieved. In addition, the level of stability and security of the microgrid is increased by dispatching the power flow and moving the allowable load from peak hours to off-peak hours by the operator.

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