ISSN 1870-4069

Design and Implementation of a Stand-Alone Home Energy Management System Based on Internet of Things

Javier E. Sierra, Boris Medina, Ramón Álvarez

Universidad de Sucre, Faculty of Engineering, Sincelejo, Colombia
{javier.sierra, ramon.alvarez, boris.medina}@unisucre.edu.co

Abstract. Smart Grid is the most important technology in energy management, which allows to maintain a balance between supply and demand of electric energy. Traditionally, residential users demand energy incrementally, without control or management over the process, increasingly leading to high consumption and high costs in energy bills. Home Energy Management Systems (HEMS) allow the supply, optimization and automatic control of electrical and electronic appliances, distributing the load at day time, according to energy costs. In this article, we present the results of implementing a stand-alone HEMS in a house, which consists of a central node that has a database, smart meters, an autonomous control software that is fed by a mathematical model and an interconnection with Internet for management by an APPs. Internally in the house, electrical and electronic devices are adapted with Internet of Things (IoT), using Arduinos, ethernet and wifi modules, actuators and sensors. The results of the implementation show the effectiveness of HEMS in terms of cost of electricity, demand and user comfort.

Keywords: smart grid, internet of things, IoT, HEMS, home energy management systems.

1 Introduction

Electric energy currently represents quality of life, economic development and is largely responsible for many of the technological advances made by mankind [1,2]. Today it is inconceivable a community that does not enjoy the great benefits derived from the service of electric energy, such as: specialized medical assistance centers, electric transport systems, information and communication technologies, entertainment systems, appliances to perform tasks in the home, among others. It is evident that we live in an intelligent, interconnected and electro-dependent society, for which electricity is a vital element to preserve the world as we know it today [3].

The exponential growth of energy demand exceeds the implementation of conventional generation systems; this has generated alarms in the world energy sector. In addition, there is a great concern for the massification of energy sources based mainly on the use of fossil resources: coal, natural gas, oil and its derivatives. The use of fossil fuels has caused great concern about the impact on the environment, and it is therefore necessary to investigate and implement strategies aimed at saving or developing alternative sources of generation [4]. Recent research shows the possibility of reducing energy consumption by installing Home Energy Management System

(HEMS). These systems allow the active participation of the consumer in the electricity market, as well as modulate the demand curve, reducing costs, depending on a certain user profile. The user programs a consumption profile which is monitored through a local power management system, which uses intelligent sensors located at each point of consumption and software that manages a database that stores the user profiles [5].

The implementation of the energy management system for the home requires the implementation of smart sensors, relays, data network and a flexible computer platform that guarantees the management process. This management focuses on the prioritization of load consumption, in terms of costs and energy availability. The management system is fed with the consumption profiles of the residence, the patterns of saving and a table of priorities according to the season of the year.

This article proposes a new architecture of a HEMS system based on open software and hardware, as well as a mathematical model that allows to reduce the cost of energy consumption.

2 Basic Architectures of Energy Management Systems at Home

Home Energy Management (HEM) refers to a system that incorporates sensors to appliances through a home network [6]. HEM systems have been developed in order to measure, monitor and control energy consumption at home. Through the implementation of management software to response on demand, HEM systems enable the improvement of the performance of an electrical network. That is, HEMS software can include applications based on the profiles and preferences of residential customers as a result of the interaction between users and the electricity network. A HEM acts as a modern energy meter, being one step ahead of the low-energy consumption appliances [7]. In brief, a HEM measures, monitors and allows adjustment of energy consumption in an intelligent way, through smart meters, devices, appliances and plugs.

Table 1. Classification of articles according to the similarity in architecture

Classification	**Architectural Overview**
Central Controller	Central controller added to monitoring and control nodes found in appliances.
Integrated Module	Module for data collection or management, a module for devices control and a communication module
Monitoring server	Only monitoring and control devices and a domestic server
Monitoring server and gateway	Monitoring and control devices, a home server and a gateway
Hybrids	More elaborate architecture, due to the additional benefits of the HEM presented.

Architectures proposed in the literature [8] can be classified into different groups attending to several criteria related with the monitor structure, the distribution of management packages and the communication capabilities. Table 1 shows the classification of the articles according to similarities in their architecture.

Although some of the authors indicated in Table 1 present a more elaborate architecture, it is possible to establish a general architecture that includes the basic components required in a HEM. This way, a HEM basically should have:

– A home area network (HAN): It is a local residential network that interconnects devices in a house such as; sensors, smart plugs, smart thermostats and appliances allowing communication between them, either through a wireless network or a wired network.

– Monitoring and control devices: They are end devices that are responsible for monitoring and controlling the energy consumption of household appliances.

– A processor: Used for the concentration, storage and information management. The server and the database would be located in this central module.

– A gateway: Allows connection between the HEM and the outside, so that remote access via Internet can be possible.

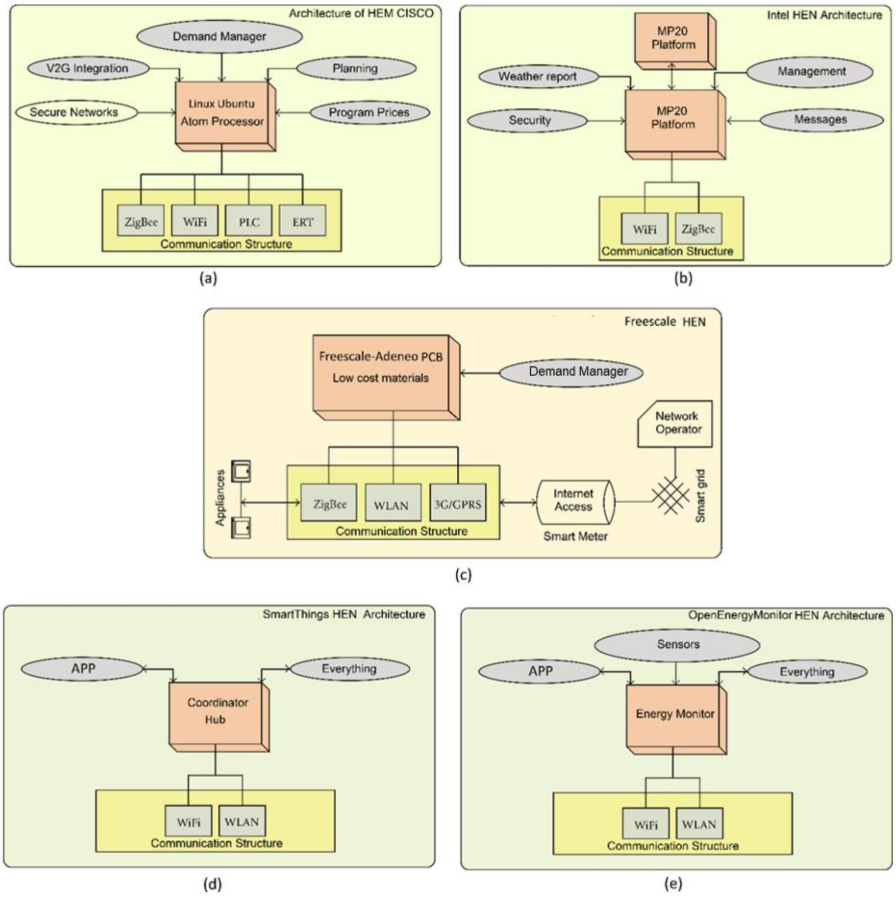

Fig. 1. Basic Architectures of commercial HEMS.

In Fig. 1, five of the found architectures for defining a HEM are summarized. Fig. 1(a) is a HEM that processes in a centralized manner (Atom Processor for CISCO) the services requested by the different levels of software loaded in a platform integrated by a Linux core and external communication modules. The architecture of Fig. 1(b), differs from the previous one, by the use of a multiprocessor structure, which consists of a central processor and auxiliary processors to support the computing tasks. A practical case of such architecture is the HEM proposed by Intel using an MP20 platform. In addition, we have HEM that use a distributed structure based on a communication channel that integrates sensors, household appliances and the central processor, Fig. 1(c). A practical example of the distributed architecture is the one developed by Freescale, which is characterized by the use of low cost devices. On the other hand, they have the compact architectures, conformed by a monitor or coordinator that performs the management of household appliances and is used as interface of the user with an APP. Two practical cases of the compact architectures are the case of the SmartThing HEM and OpenEnergyMonitor, Fig. 1(d) and Fig. 1(e).

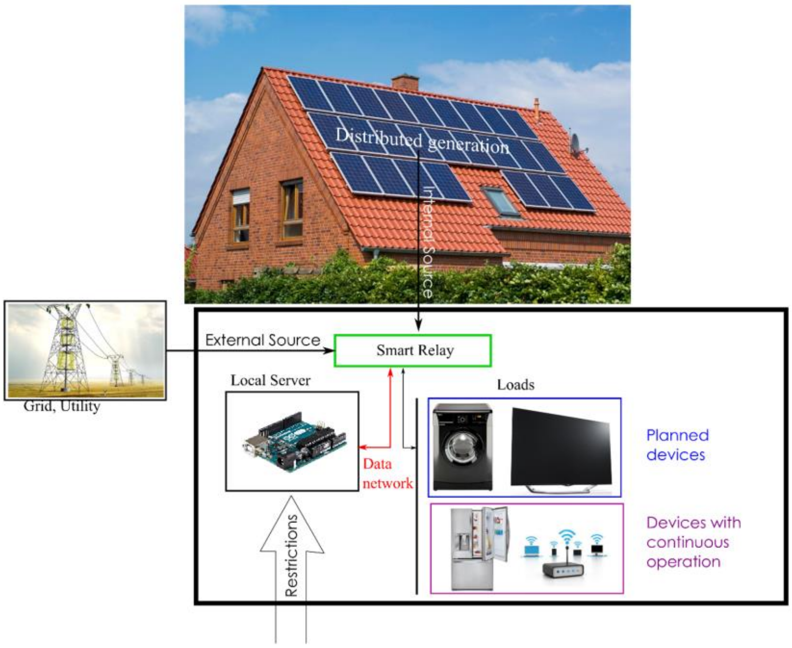

Fig. 2. Basic Architectures of proposed HEMS.

3 Proposed Architecture for Home Energy Management Systems

Our proposed architecture is shown in Fig. 2. The architecture employs a four-core computing system and a Graphics Processing Unit (GPU), which enables process optimization through multi-thread programming. The proposed architecture uses smart relays, which allow load interconnection and the sensing of electrical variables. Each electrical outlet is equipped with a smart relay with sensing and transmission of electrical variables such as voltage, current and power. In addition, the proposed HEM manages continuous and programmed loads to optimize the energy demand.

The control software is implemented under the philosophy of open source, under the Linux platform. The user interface receives the information corresponding to user consumption profiles, which are due to many factors such as: the policies and regulations defined by the regulator of the electrical system, economic and socio-cultural aspects, environmental requirements and technology used (in the future these variables may be considered). It is clear that the future of energy management systems in the home is very promising, but due to the large number of aspects associated with consumption profiles, it is necessary to continue working to overcome many difficulties associated with such technology in the present.

4 Mathematical Model

We consider a power system installed at the end of the user that can calculate, optimize and manage the flow and use of energy. Fig. 2 shows the system model considered where a HEMS module is connected to the smart meter and to all devices. The smart meter is a device that calculates energy consumption and communicates with the unit simultaneously. The meter receives utility pricing signals from Power Line Carrier (PLC) and communicates price values to HEMS. The smart meter, HEMS and home appliances are connected through the local area network (LAN) and share a common control channel [9].

The basic functions of the HEMS module are to collect the data of the devices, the processing of the data and to control the loads. During the data collection, the HEMS identifies the electricity consumption, calculates the price of the electric energy used in kwh and collects data relating to the priority of the customers for different appliances. Additionally, it determines the type of energy source to be used, if the one of the electric supplier or the one of an alternative source that is in home. The processing contains the analysis of the data collected and carries out the strategies for the control of the load. The planning strategies consist of modeling the system according to the mathematical model indicated in the present article. Finally, the HEMS controls the load based on the developed schemes. Communication between devices and HEMS for data collection and load control can be done with the help of existing LAN access protocols, eg Wi-Fi, Zigbee that can accommodate various communication applications [10]. In this article we consider two types of devices:

- Type 1 Planned devices: these are fully flexible devices and can be activated or programmed at a later time when the price of electricity in real time is reasonable. For example, washing machine, dishwasher and air conditioning. Let 'X' be the total number of devices that can be planned.
- Type 2 Devices with continuous operation: these are devices that have a low degree of flexibility and depend on the basic needs and the priority of the consumers. Lighting devices, computers and televisions are examples of this category. Let "Y" be the number of devices with continuous operation.

The rapid increase in energy demand forces energy companies to produce high-cost electricity, which directly affects the budget and user fees. The proposed system can significantly reduce the cost of residential consumption. The aim is to minimize the cost by programming the system devices such that demand in a given time interval does not lead to a peak in the load curve and that the operation of the devices in real time does not affect the user. Let $T = \{t_1, t_2, t_3 . . . t_N\}$ be the set of N scheduling time slots with t_n denoting the *n-th* slot. Generally, the behavior of energy use is random and has scheduling ranges in which a higher consumption occurs. We define the set of schedulable devices $S = \{a_1, a_2, a_3. . . A\}$ and the set of real-time devices $R = \{b_1, b_2, b_3. . . B\}$. A series of real-time and schedulable devices may be active at each time interval of the set T.

We define a binary variable $v_{i,n}$ such that:

$$v_{i,n} = \begin{cases} 1 & if\ i\text{th devices is ON in time } t_n \quad \forall i = 1 \dots X, n = 1 \dots N, \\ 0 & otherwise. \end{cases} \tag{1}$$

Therefore, the number of planned devices (type 1) that are activated in the time slot t_n can be represented as:

$$\gamma_{ON}^{n} = \sum_{i=1}^{X} (v_{i,n}), \qquad \forall n. \tag{2}$$

We define $z_{j,n}$ a binary variable for devices with continuous operation (type 2):

$$z_{j,n} = \begin{cases} 1 & if\ j\text{th devices is ON in time } t_n \quad \forall i = 1 \dots Y, n = 1 \dots N \\ 0 & otherwise \end{cases}. \tag{3}$$

Thus, in a given time interval t_n, devices with continuous operation are:

$$\Delta_{ON}^{n} = \sum_{j=1}^{Y} (z_{j,n}), \qquad \forall n. \tag{4}$$

The proposed model has the following restrictions:

To ensure that demand at peak hours does not increase greatly, the energy consumed by the combination of devices with continuous operation and the planned devices in any time interval must be kept under a target value E. Therefore, we have:

$$\sum_{i=1}^{X} \varphi_i^n + \sum_{j=1}^{Y} \omega_j^n \leq E, \qquad \forall n, \tag{5}$$

with $\varphi_i^n = (P_{i,n})(v_{i,n})$ and $\omega_j^n = (Q_{j,n})(z_{j,n})$ where $P_{i,n}$ and $Q_{j,n}$ are the powers consumed in time slot t_n by el ith planned device and de jth devices with continuous operation, respectively.

Ideally the devices in set Y should be turned ON all time due to lower degree of flexibility:

$$\sum_{j=1}^{Y} (z_{j,n}) = |Y|, \qquad \forall n, \tag{6}$$

$$\sum_{n=1}^{N} (z_{j,n}) = N, \qquad \forall j, \tag{7}$$

where the operator $|.|$denotes the cardinality of the set. However, for a greater number of devices with continuous operation, it may be impossible to accommodate all in each time interval. Therefore, the above restrictions are reformulated as:

$$\Delta_{ON}^{n} = Y', \qquad \forall n, \tag{8}$$

$$0 \leq \sum_{n=1}^{N} \left(z_{j,n}\right) = N, \qquad \forall j, \tag{9}$$

where $Y' = Y$ if $\sum_{j=1}^{Y} w_j^n \leq E$ and $Y' \subset Y$ if $\sum_{j=1}^{Y} w_j^n > E$. The above expressions ensure that at least one devices with continuous operation is turned ON and if a device is turned on it will remain active for the entire time. Planned devices have high operational flexibility. If in a given slot, the real time devices demand more than *E* no device from the set *S* will be scheduled. On the other hand, for a very limited requirement from set *R*, all the *'X'* devices can enjoy the turned ON status. Thus:

$$\varphi_{ON}^{n} = X', \qquad \forall n, \tag{10}$$

$$\sum_{n=1}^{N} \left(v_{i,n}\right) \leq N, \qquad \forall i \tag{11}$$

where $X' = X$ if $\sum_{i=1}^{X} \varphi_i^n \leq E - \sum_{j=1}^{Y} w_j^n$ and $X' \subset X$ in case of $\sum_{i=1}^{X} \varphi_i^n > E - \sum_{j=1}^{Y} w_j^n$. Unlike the previous case, the latter equation shows that depending on the required operating time, a particular device could be programmed only for a fraction of the full-time window.

Objective function

Let C_n represent the per unit cost at time t_n. Thus, during *n-th* slot the cost of a planned devices and devices with continuous operation are $\gamma_{planned}^{n} = P_{i,n} C_n$ and $\gamma_{cont}^{n} = Q_{j,n} C_n$, respectively. Our target is to minimize the sum cost over all the scheduling hours such that no violation occurs for any stated constraint. The optimization problem can be defined mathematically as:

$$\min_{v_{i,n} z_{j,n}} \sum_{t=1}^{N} \left(\sum_{i=1}^{X} \Gamma_{i,n}^{planned} (P_{i,n}, \varphi_i^n, \gamma_{planned}^{n}) + \sum_{j=1}^{Y} \Gamma_{j,n}^{cont} (Q_{j,n}, w_j^n, \gamma_{cont}^{n}) \right), \tag{12}$$

with the constraints shown in equations (3), (6), (7), (8),(9) and $v_{i,n} \in \{0,1\}, z_{j,n} \in \{0,1\}$ $\forall i, n.$ The two cost functions $\Gamma_{i,n}^{planned}$ and $\Gamma_{j,n}^{cont}$ represent the cost of *i-th* planned devices if it is scheduled in *n-th* time slot and *j-th* devices with continuous operations when it is scheduled to turn ON in *n-th* tiem slot, respectively, and are given:

$$\Gamma_{i,n}^{planned} = \frac{\varphi_i^n \gamma_{planned}^{n}}{P_{i,n}}, \tag{13}$$

$$\Gamma_{j,n}^{cont} = \frac{w_i^n \gamma_{cont}^n}{Q_{i,n}}. \tag{14}$$

The above optimization aims to find the total of $N(X + Y)$ variables, i.e., the optimum values of $v_{i,n}, \forall i, \forall n$ and $z_{j,n}, \forall j, \forall n$, which provide the minimum possible cost keeping total demand in each hour under a predefined limit.

The formulated problem is a mixed binary integer programming problem and has a high computational complexity to find the optimal solution.

5 Results

We simulate in the CPLEX software the mathematical model to verify the effectiveness of our proposed architecture. The demand of the users varies during the course of the day, in Fig. 3 shows a typical behavior of a residential user. Given this, we simulate for several time slot ($T = \{t_1, t_2, t_3, t_4\}$) in 4 different scenarios. For the purpose of the simulation we consider that the user has fixed ten applications, but the demands of several devices may vary over the course of the day.

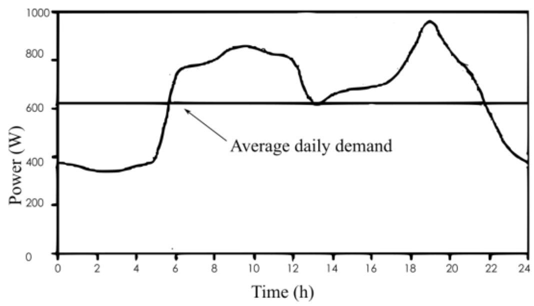

Fig 3. Typical Residential Demand Response.

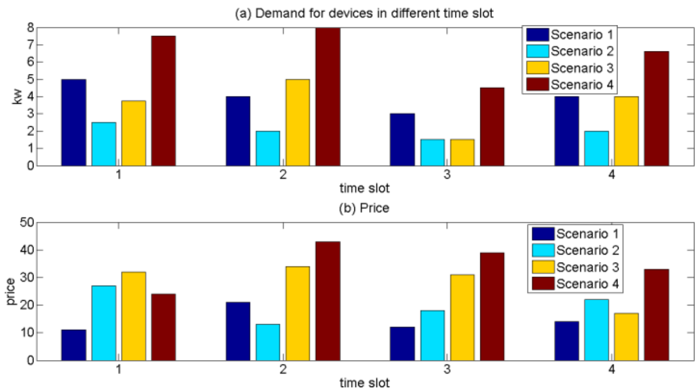

Fig 4. Demand and Cost for devices in different time slot**.**

There are 8 devices connected to the network for the simulation, of which two of them are operating in continuous time, ie always remain ON. Fig. 4a shows the demands required for each time slot in the four simulated scenarios. We have considered the TOU pricing model [11,12], that will assign a different cost (p_i) for each t_i, where p_i represents the price per unit. Each set has a unique cost in a given time interval, although it varies in different time intervals due to the TOU price model. For example, the cost of each scenario in scheduling schedules is shown in Fig. 4b.

Fig. 5 presents the total cost of scheduling the demands for different load scenarios, in each of the time slots. It is observed that the mathematical model determines the cost for each scenario, identifying the elements that must be programmed in the required times. It is necessary to propose heuristic techniques that seek to solve the problem raised in an optimum time.

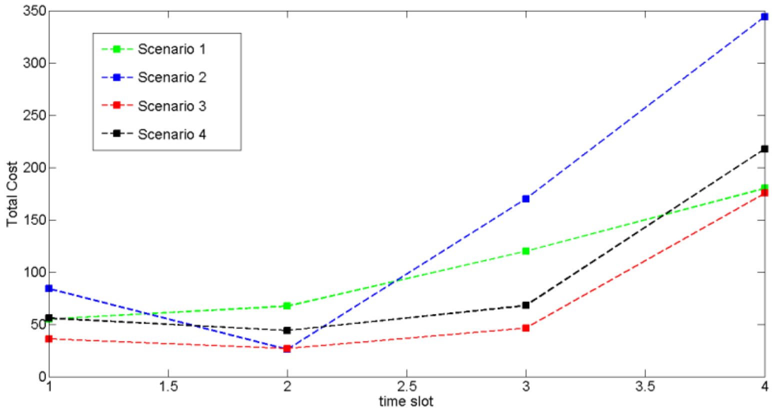

Fig. 5. Total cost in different time slot**.**

6 Conclusions

This article proposes a new architecture for domestic use that uses a Home Energy Management System (HEMS). The proposed architecture consists of a server in the house that collects the data of consumption and of the generation of energy, analyzes them through the proposed algorithm and controls the use of energy to minimize the cost of energy. The architecture, as well as the mathematical model evaluated show that it is possible to minimize the cost of energy consumption.

References

1. Gyorvari, B., Vokony, I.: Technical issues of solar- and gas engine based MicroGrids: Assessment on feasibility by using present technologies. In: 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) 2017, pp. 1–6 (2017)
2. U.S. Energy Information Administration: EIA's Annual Energy Outlook (2017)

3. Basit, A., Sidhu, G.A.S., Mahmood, A., Gao, F.: Efficient and Autonomous Energy Management Techniques for the Future Smart Homes. IEEE Trans. Smart Grid, pp. 1–10 (2015)
4. Langhammer, N, Kays, R.: Performance Evaluation of Wireless Home Automation Networks in Indoor Scenarios. IEEE Trans Smart Grid. 3(4), 52–61 (2012)
5. Han, J., Choi, C., Park, W., Lee, I., Kim, S.: Smart home energy management system including renewable energy based on ZigBee and PLC. IEEE Trans. Consum. Electron. 60(2), 198–202 (2014)
6. Choi C.S., Park W.K., Han J.S., Lee I.W.: The architecture and implementation of proactive Green Home Energy Management System. In: 2010 International Conference on Information and Communication Technology Convergence, pp. 457–458 (2010)
7. D'Alessandro, S., Tonello, A.M., Monacchi, A., Elmenreich, W.: Home energy management systems: Design guidelines for the communication infrastructure. In: ENERGYCON 2014 - IEEE International Energy Conference, pp. 805–812 (2014)
8. De la Cruz, Z., Alvarez-Lopez, R., Fernandez-Vilas, A., Díaz-Redondo, R.: Tendencia tecnológica de los sistemas de administración de energía eléctrica en el hogar: revisión bibliográfica. DYNA Energía y Sostenibilidad 5 (2016)
9. Zhou, B., *et al.*: Smart home energy management systems: Concept, configurations, and scheduling strategies. Renew. Sustain. Energy Rev. 61, 30–40 (2016)
10. Cheah, P.H., Zhang, R., Gooi, H.B., Yu, H., Foo, M.K.: Consumer energy portal and home energy management system for smart grid applications. In: 2012 10th International Power & Energy Conference (IPEC), pp. 407–411 (2012)
11. Huang, Y, Tian, H, Wang, L.: Demand response for home energy management system. Int J Electr Power Energy Syst. 73, 448–455 (2015)
12. Mehta, R., Srinivasan, D., Verma, P.: Intelligent appliance control algorithm for optimizing user energy demand in smart homes. In: 2017 IEEE Congress on Evolutionary Computation (CEC), pp. 1255–1262 (2017)