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A Novel Smart Home Energy Management System: Architecture and Optimization Model

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Abstract

Objective: To optimize energy consumption in a home, through a new architecture that incorporates a Home Energy Management System (HEMS) and a decision algorithm that takes into account a mathematical model that includes different automated electronic devices. **Methods:** We propose a new architecture for a Home Energy Management System (HEMS), which includes a WEB server, interconnection with the different electrical and electronic devices through the Wi-Fi network or Power Line Communications (PLC), and automated electronic devices employing arduinos. Additionally, a mathematical model is proposed to define the decision algorithm, as to which is the best profile or scenario that should be set in the home to minimize the cost of energy. The model takes into account the electricity service rate. **Findings:** We simulate the proposed model in architecture with 8 electronic devices, evaluating 4 scenarios or user profiles, which take into account the demand of each one, as well as the cost of electric energy in the course of the day. In the software CPLEX, we evaluated the mathematical model and this allowed determining the costs of each scenario, according to the demand in different time slots. The simulation results show that with the proposed architecture and the decision algorithm, fed by the results of the mathematical model, it is possible to minimize the cost of electric power in the home. **Application:** The proposed architecture can be implemented economically in the home, taking into account user profiles or the season of the year. The model allows minimizing the cost of electrical energy of a house, taking into account the electronic equipment that can be planned and those of continuous operation.

Keywords: Energy Demand, Optimization, Smart Grids, Smart Home, HEMS

1. Introduction

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

The growth of energy demand comes at a rate that significantly exceeds the implementation of conventional generation systems. This has ignited the alarms of the energy sector worldwide. In addition, there is great concern about the massification of energy sources, based mainly on the use of so-called 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, therefore, it is necessary to investigate and implement strategies aimed at saving and/or developing alternative sources of generation[4].

The creation of new electrical and electronic equipment, and how they have been incorporated into daily life, has produced a significant increase in the demand for electrical energy. Recent research has shown the possibility of reducing energy consumption through the installation of Home Energy Management System (HEMS). These systems allow the active participation of the consumer in the electric power market, allowing modulating the demand curve according to a certain user

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profile. That is, 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 profiles of user[5].

The implementation of an energy management system for the home suggests the implementation of intelligent sensors, intelligent 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 each of the users of the residence, the saving guidelines and a table of priorities.

This article proposes a new architecture of a HEMS system, based on open software and hardware, as well as a mathematical model that allows optimizing the cost of energy consumed in the home. The results show that the proposed model optimizes the cost of energy consumed in the home.

2. Materials and Methods

2.1 Basic Architecture of Home Energy Management Systems

A Home Energy Management System (HEMS) is a system that incorporates sensors in household appliances, through a home network[6]. The HEMS is developed for controlling power consumption, to improve the performance of a smart grid, with the optimization of the demand of the enabled devices in the residential customers. A HEMS acts as a modern energy meter, this being an evolution of low-consumption appliances. In summary, a HEMS intelligently monitors and adjusts power consumption by interacting with smart meters, smart devices, appliances and smart plugs, thus providing efficient power and better management of the maximum load[7].

The architectures for HEMS, proposed by researchers in different articles[8], can be classified into several groups, taking into account some criteria related to the structure of monitoring, management, distribution and communication capabilities. Table 1 shows the classification of the architectures that allow the control of energy consumption.

Although some of the authors indicated in Table 1 present in their articles other more specific architectures, it is possible to establish a general architecture that includes the basic components required in HEMS. In this way, a HEMS should basically consist of:

- **A Home Area Network (HAN)** is a local residential network that interconnects devices in a home, such as sensors, smart plugs, intelligent thermostats, and devices that allow communication between them, whether over a wireless network or a wired network.
- **Monitoring and Control Devices:** These are final devices that are responsible for monitoring and controlling the energy consumption of appliances.
- **A Processor:** Used for concentration, storage and management of information. The server and the database would be located in this central module.
- **A Gateway:** Allows the connection between the HEMS and the outside, so that the remote access, through the Internet, is possible.

Figure 1 shows the five of the architectures found for the definition of HEMS. Figure 1(a) is a HEMS that processes the services requested by the different levels of software centrally (Atom Processor for CISCO), loaded on a platform integrated by a Linux kernel and external communication modules. The architecture of Figure 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 calculation tasks. A practical case of such architecture is the HEMS proposed by Intel using an MP20 platform. In addition, we present HEMS that uses a distributed structure, based on a communication channel that integrates sensors, appliances and the central processor, as shown in Figure

Table 1. Classification of related architectures

Classification	Architectural Overview
Central Controller	Central controller added to monitoring and control nodes found in electrical-electronic devices.
Integrated Module	Data storage and management module, device control module and communication module.
Monitoring server	Monitoring server for monitoring and control devices.
Monitoring server and gateway	Monitoring and control devices, a home server and a gateway.
Hybrids	More elaborated architecture, due to the additional benefits of HEM presented.

1(c). A practical example of 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 who performs the management of the electrical appliances and is used as a user interface with an APP. Two practical cases of the compact architectures are the case of SmartThing HEMS [Figure 1(d)] and OpenEnergyMonitor [Figure 1(e)].

2.2 Proposed Architecture for Home Energy Management Systems

The proposed architecture is shown in Figure 2. The architecture uses a WEB server and a SQL database for storing information. It also enables interaction with the Internet through a Gateway for management from abroad through mobile applications. The information on the cost of Kwh is obtained from the Internet and is updated permanently. The architecture allows the interconnection

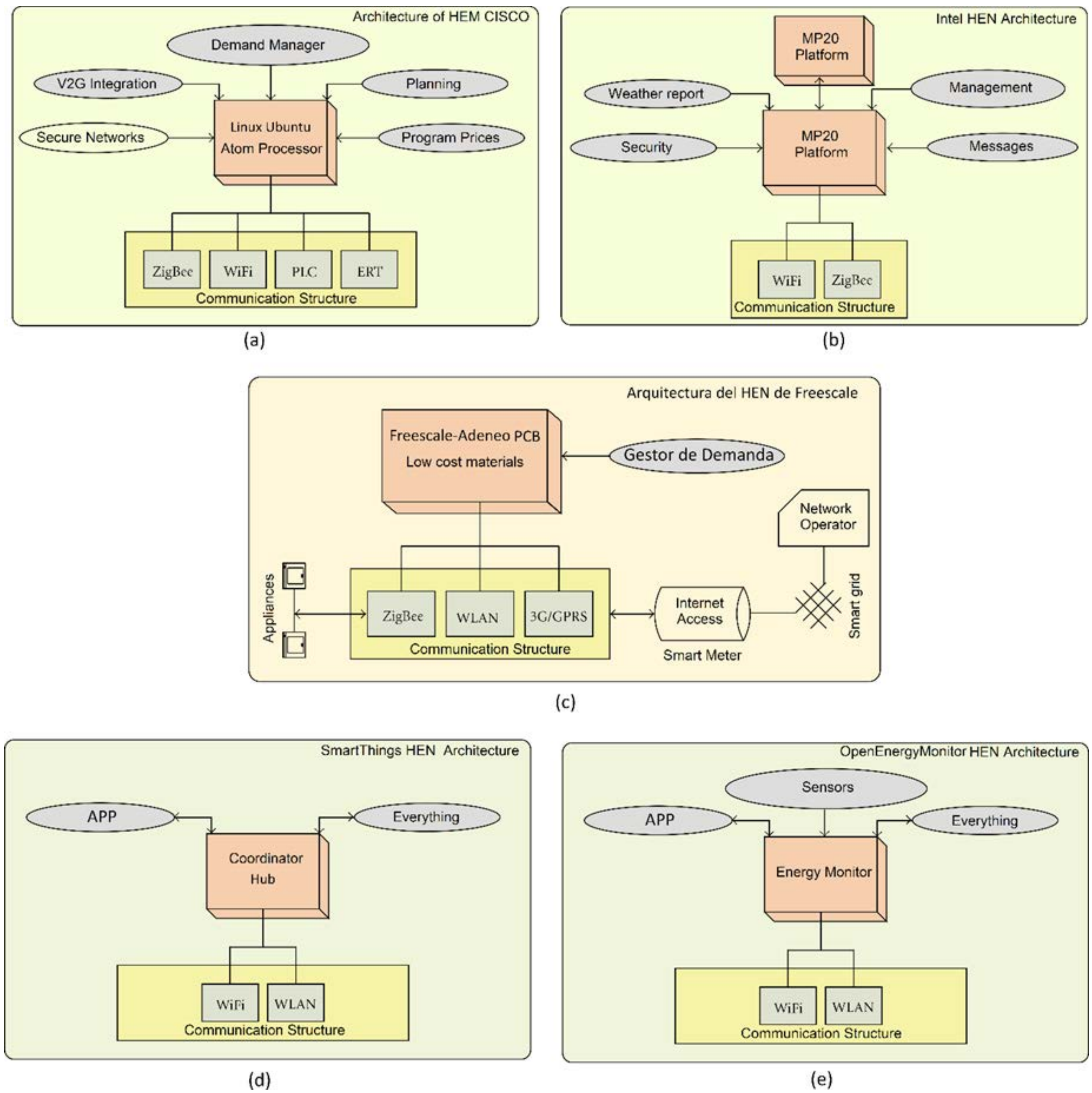

Figure 1. Basic architectures of commercial HEMS.

with different electrical-electronic devices through the Wi-Fi network or by Power Line Communications (PLC)[9]. The electronic devices are automated using arduinos that use the Wi-Fi module ESP8266. All devices are interconnected to HEMS and function as an intelligent relay with detection and transmission of electrical variables such as voltage, current and power. In the case of lighting and electrical outlets, they can be interconnected with the HEMS by means of PLC, to save costs in the interconnection. The architecture is modular, depending on the layout of the house and the location of the devices. The operation of the HEMS allows classifying the loads in continuous and those that can be programmed, as well as to establish user profiles or work scenarios according to the conditions that each one of them requires. With this data a decision algorithm is established, which is supported in the proposed mathematical model.

Figure 2. Architecture for home energy management systems.

The proposed architecture control software is implemented under the open source philosophy. The software allows you to configure user profiles, depending on the season of the year, working hours, people who live in the house and others. The software can be interconnected through the Internet to obtain information on the policies and regulations defined by the regulator of the electrical system. 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 on new proposals to overcome many difficulties associated with this technology in the present.

2.3 Mathematical Model

The mathematical model considers an electrical system with the proposed architecture in a house, and allows generating the algorithm of decision with respect to the electronic devices that must be ignited in the home to save the consumption of electrical energy. The model can calculate, optimize and manage the flow and use of energy. Figure 2 shows the configuration of the system in question, where a HEMS module is connected to the house. The system contains an intelligent meter, the server, the communications network and the connection to all the devices that wish to interconnect[10].

The basic functions of the HEMS module are to collect the data of the devices, the data processing and the control of the loads. During data collection, the HEMS identify the electricity consumption; calculate the price of the electric energy used in Kwh and collects data relating to the priority of the customers for different appliances. This data is processed to optimize the operation of the system. The model presented only considers an energy source and is the commercial power grid. The processing is carried out with the analysis of the collected data and, from the loaded profile; it carries out the strategies for the control of the devices of the network. Planning strategies are designed to program devices based on the optimization proposed in this article. In this paper, we consider two types of electrical-electronic devices:

- **Type 1-Planned Devices:** They are fully flexible devices for their operation and can be activated or programmed later, when the price of electricity in real time of the day is more economical. For example, washing machine, dishwasher, irrigation processes in gardens, air conditioning. Let 'X' be the total number of devices that can be planned.
- **Type 2 Devices with Continuous Operation:** They are devices that have a low degree of flexibility and depend on the basic needs and the priority of the users of the home. The lighting system, 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 power companies to produce high-cost electricity, which directly affects the budget and user fees. The proposed system allows to significantly reducing the cost of residential consumption. The aim is to minimize the cost of the invoice by programming the system devices so that the 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 programming time slots with *n-th* slot denoting the nth time slot. Generally, the behavior of the energy use is random and has programming intervals in which a greater consumption takes place. We define the set of plausible devices *S= {a_1, a_1, a_1,…A}* and the set of devices with continuous operation *R = {b_1, b_2, b_3... B}*. A plurality of continuous and schedulable operation devices may be active at each time interval of the set *T*.

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

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

Therefore, the number of schedulable devices (Type 1) that are activated in the time interval t_n can be represented as:

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

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

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

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

$$\Delta_{ON}^{n} = \sum_{j=1}^{Y}(z_{j,n}), \qquad \forall n \tag{2}$$

The proposed model has the following restrictions:

To ensure that demand at peak hours does not increase too much, 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:

$$\sum_{i=1}^{X}\varphi_i^n + \sum_{j=1}^{Y}\omega_j^n \leq E, \qquad \forall n \tag{3}$$

With $\varphi_i^n = (P_{i,n})(v_{i,n})$ y $\omega_j^n = (Q_{j,n})(z_{j,n})$ where $P_{i,n}$ and $Q_{j,n}$ are the power consumed in the time slot t_n by the *i*th schedulable device and the *j*th device with continuous operation, respectively.

Ideally, the devices in the *Y*-set should be activated all the time because of a lower degree of flexibility,

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

$$\sum_{n=1}^{N}(z_{j,n}) = N, \qquad \forall j \tag{5}$$

Where the $|\cdot|$ 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:

$$\Delta_{ON}^{n} = Y', \qquad \forall n \tag{6}$$

$$0 \leq \sum_{n=1}^{N}(z_{j,n}) = N, \qquad \forall j \tag{7}$$

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 of the devices with continuous operation is ON and if a device is 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 of the set *S* will be programmed. On the other hand, for a very limited requirement of the set *R*, all the '*X*' devices can enjoy the activated state. So,

$$\varphi_{ON}^{n} = X', \qquad \forall n \tag{8}$$

$$\sum_{n=1}^{N}(v_{i,n}) \leq N, \qquad \forall i \tag{9}$$

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 the case that $\sum_{i=1}^{X}\varphi_i^n > E - \sum_{j=1}^{Y} w_j^n$. 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 time window.

2.3.1 Objective Function

Let C_n be the cost per unit at time t_n. Therefore, during the *n-th* slot, the cost of the planned devices and the devices with continuous operation are $\gamma_{planned}^{n} = P_{i,n} C_n$ and $\gamma_{cont}^{n} = Q_{j,n} C_n$, respectively. Our goal is to minimize the cost of summation during all scheduling hours, so that no breach occurs for any set restrictions. The optimization problem can be mathematically defined as:

$$\min_{v_{i,n} z_{j,n}} \sum_{t=1}^{N} \left(\sum_{i=1}^{X} [\Gamma_{i,n}^{planned}(P_{i,n},]\varphi_i^n . \gamma_{planned}^{n}) . + \sum_{j=1}^{Y} [\Gamma_{j,n}^{cont}(Q_{j,n},]w_j^n, \gamma_{cont}^{n}) \right) \quad (10)$$

With the constraints shown in Equations (3), (6), (7), (8), (9) y $v_{i,n} \in \{0,1\}, z_{j,n} \in \{0,1\} \forall i, n.$

The two cost functions $\Gamma_{i,n}^{planned}$ and $\Gamma_{j,n}^{cont}$ represent the cost of the *ith* schedulable devices if programmed in the *n-th* time slot and the *j-th* devices with continuous operations , When it is programmed to light up in the slot of the *n-th* time slot, respectively, and are given:

$$\Gamma_{i,n}^{planned} = \frac{\varphi_i^n \gamma_{planned}^{n}}{P_{i,n}} \quad (11)$$

$$\Gamma_{j,n}^{cont} = \frac{w_i^n \gamma_{cont}^{n}}{Q_{i,n}} \quad (12)$$

The previous optimization aims to find the total of the variables $N(X + Y)$, that is, the optimal values of $v_{i,n}, \forall i, \forall n$ y $z_{j,n}, \forall j, \forall n$, which provide the lowest possible cost by maintaining the total demand in each hour under a predefined limit.

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

3. Results and Discussion

To perform the tests and validation of the mathematical model, 4 scenarios were established, which can be at any given time the seasons of the year, or the selected user profile. Each of these scenarios was simulated with 8 devices to the network, according to the proposed infrastructure, of which two are operating in continuous time, therefore, always remain ON. The rest of the equipment is plannable, depending on the energy tariff and the selected scenario.

We simulate the mathematical model in the CPLEX software to verify the effectiveness of our proposed architecture. The demand of the users varies during the course of the day. Figure 3 shows typical behavior of a residential user. Given this, we simulate for several time intervals ($T = \{t_1, t_2, t_3, t_4\}$) in 4 different scenarios. For the purpose of the simulation, we consider that the user has fixed 8 applications, but the demands of various devices can vary throughout the day. Figure 4a shows the demands required for each time interval in the four simulated scenarios.

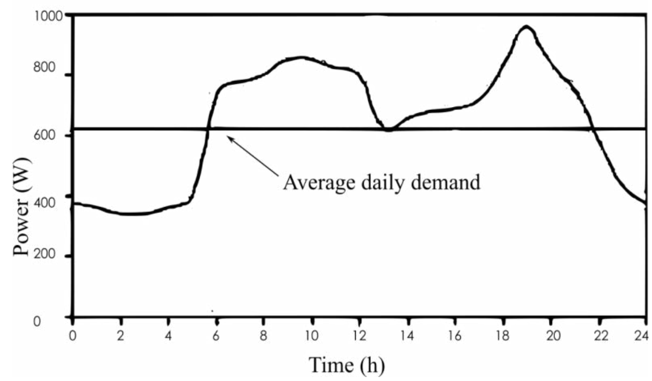

Figure 3. Typical residential demand Response.

We consider the TOU valuation model[11,12] with consequent cost reduction, is one of the main challenges for the present and future smart grid. Demand response (DR, which assigns 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 Figure 4b.

Because of the optimization process, it is possible to optimize the energy cost, depending on the selected profile or scenario. For example, if scenario 4 is the summer season, it could be identified that there is a higher consumption given the use of conditioned air, but the model would always seek to limit the energy expenditure given by the use of that appliance. The model would then allow the establishment of consumption profiles that minimize the cost of the electricity bill. Figure 5 presents the total cost of scheduling the demands for different load scenarios, identifying that scenario 2 in time slot 2 is a profile that allows saving energy consumption efficiently, with respect to other profiles, in each of the time slots. Another improvement that is evident in the system is, for example, in Scenario 3, that although the energy value in slot 4 is higher, the model allows to lower the energy consumption in that scenario compared to Scenario 1, 2 and 4 (optimizing by 46%). It is observed, then, that the mathematical model determines the cost of 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 posed in an optimal time.

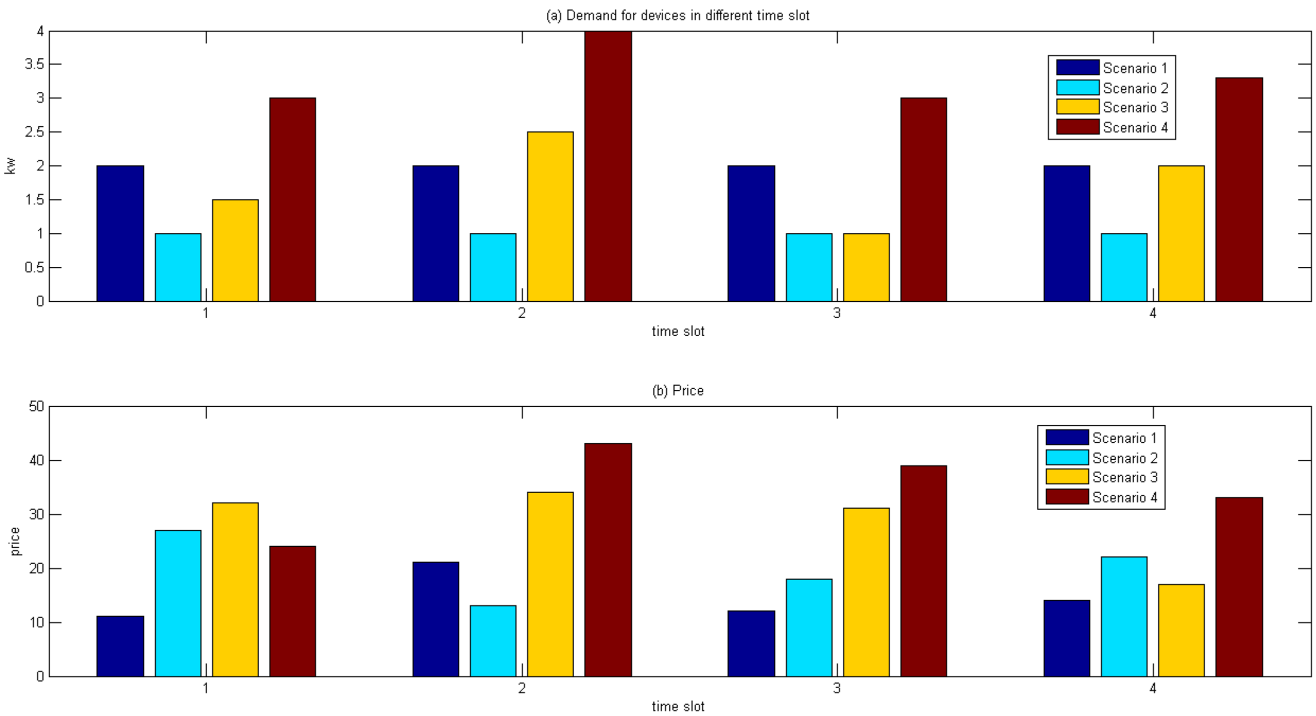

Figure 4. Demand and cost for devices in different time slot.

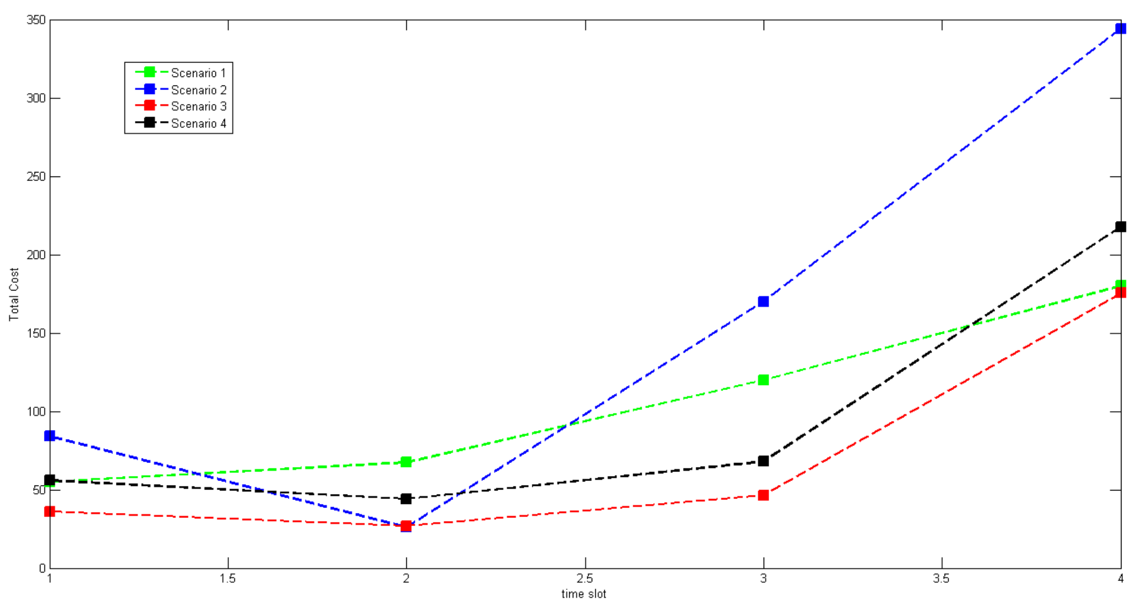

Figure 5. Total cost in different time slot.

4. Conclusions

This article proposes a new architecture for domestic use that uses a Home Energy Management System (HEMS), which through a system of communication via Wi-Fi and PLC allows the management of electronic equipment. The system has computer software that allows optimizing the cost of electrical energy, through the proposed mathematical model. The results show that, with the proposed architecture and the mathematical model, it is possible to establish scenarios or user profiles in different time slot that manage to minimize the cost of electric energy.

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