Smart Home Energy Management System for Peak Average Ratio Reduction

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Abstract— **High quality demand-side management has become indispensable in the smart grid infrastructure for enhanced energy reduction and system control. Most of the demand-side management systems that existed were focusing on the interaction between utility company and its customers. Naturally, each home would be interested in minimizing the utility bill. Given price information, an automated DR controller would manage those devices which are flexible to be controlled, to opportunistically take advantage of the times with lower prices. This may cause a "rebound" peak, due to appliances loads flooding to the times with low prices, a reason very different from the one for the day time peak typically caused by the devices which have to run at that time. Consequently, the Home Energy Management (HEM) systems plays a crucial role in realizing residential Demand Response (DR) programs in the smart environment. It provides a homeowner the ability to automatically perform smart load controls based on utility programs, customer's preference and load priority. This paper presents the hardware demonstration of the proposed HEM system for managing the end-use appliances. The proposed algorithm manages the household loads according to their preset priority and fixed the total household power consumption under certain limit. This work achieves the purpose of reducing electricity expense and clipping the peak-to-average ratio (PAR).**

I. Introduction

A power grid has four segments: generation, transmission, distribution and demand. Until now, utilities have been focusing on streamlining their generation, transmission and distribution operations for energy efficiency. While loads have traditionally been a passive part of a grid, with rapid advances in Information and Communication Technology (ICT), demand-side technologies now play an increasingly important role in the energy efficiency of power grids. This paper starts by introducing the key concepts of demand-side management and demand-side load management. Classical demand-side management defines six load shape objectives, of which "peak clipping" and "load shifting" are most widely applicable and most relevant to energy efficiency. At present, the predominant demand-side management activity is demand response (DR).

Demand response (DR) is one of the key technologies to enable smart grid. Demand response can be defined as, changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high market prices or when system reliability is jeopardized [1]. The end-use customers can change the electric usage by e.g., rescheduling the devices or temporary usage reduction during peak periods. A consumer could manually implement some DR strategies, however, an automated architecture [2] that monitors and dynamically adjusts to real time information is the trend.

While utilities have no direct control over their customers' loads, a utility can perform demand-side management, i.e., "to plan, implement and monitor activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape" [3]. Out of the six so- called load shape objectives associated with classical demand-side management, three are relevant to our energy efficiency goal: (i) peak clipping: reduction of peak load; (ii) load shifting: shifting of load from peak to off-peak periods; (iii) strategic conservation: reduction of sales. Peak clipping and load shifting coincide with the energy efficiency strategies which were identified earlier. Peak clipping and load shifting reduce network volatility by shaving local demand peaks, thereby assisting constrained networks to cope with summer and winter demand peaks, and reducing the need for investment in grid-infrastructure reinforcement. Strategic conservation is more relevant to the situation where energy resources are scarce and will not be further pursued here.

The term demand-side load management (equivalently, demand-side energy management, or load management in short) refers loosely to the "adjustment of demand to match supply" [4], and can be understood as a client's response to demand-side management, represented primarily by DR programs. The relations between the concepts just discussed are demonstrated in Fig. 1.

DR programs are either price-based or incentive-based. Price-based DR programs are programs where the tariff fluctuates according to the real-time cost of electricity. Examples are critical peak pricing and time-of-use pricing. In critical peak pricing (aka dynamic peak pricing), customers are notified in advance of critical peak times – limited to several days per year – during which the tariffs will be much higher than average. In time-of-use pricing, the tariff varies with different time blocks of the day.

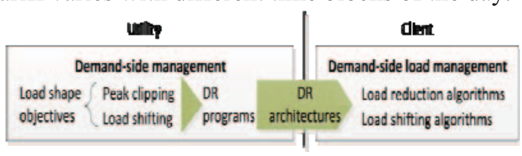

Fig. 1. Relations between demand-side management and demand-side load management concepts.

The downside of these schemes is the potential grid destabilizing rebound effect [2],[5, 6]. As observed during the Californian pilot study of time-of-use and critical peak pricing [7], a local demand peak, called the rebound peak, arises at the end of a critical period when a large number of loads are re-connected to the grid at roughly the same time. Load management algorithm should be designed to avoid this effect. Incentive-based DR programs are programs where a utility rewards its customers for their participation. Examples include peak-time rebate and direct load control. A peak-time rebate program offers a credit or rebate to customers who reduce usage during critical peak hours; the value of this peak-time reduction is monetized in the wholesale market and returned to retail customers by the DR provider (utility most likely) [8]. The difference between peak-time rebate and dynamic pricing programs such as time-of-use and critical peak pricing is that the former rewards the customers if they reduce their peak-time usage, but does not punish them for not changing their usage. Direct load control is a program by which the program operator remotely shuts down or cycles its customers' appliances (e.g., electric water heaters) on short notice [1]. Peak-time rebate and direct load control programs are so far the most widely implemented incentive-based DR programs.

The rest of the paper is arranged such that section II gives a short survey about energy management systems, then section III gives a brief introduction about the smart home and the home energy management systems and it classifications. While, section IV presents the proposed algorithm. The algorithm application on the case study is discussed in section V. Finally section VI contains the conclusion of the paper.

II. ENERGY MANAGEMENT SYSTEM

There is a growing worldwide interest in the evolution of the smart grid, a modern power grid that supports bidirectional communication between energy providers and consumers for fine-grained metering, control, and feedback. One of the key features of the smart grid is enhanced energy efficiency and manageability of available resources.

Energy management systems (EMS) have been in existence in the energy sector for several decades. The key functions of such systems are to monitor, control, and optimize the flow and use of energy. In general, energy management systems have formidable applications in the generation, transmission and distribution systems of the electrical network. Early EMS operations were based on analogue meters with skimpy, but fast, easy to understand information. They were however limited in scope and application [9]. The application developed rapidly in the early 1970s. Most of the systems delivered before 1975 were based on Xeros Sigma 5 and Sigma 9 [10]. The technological evolutions in the 1980s further changed the EMS, particularly with the advent of personal computers. Early developments of EMS, from manufacturers such as General Electric (then Harris Controls), Hitachi, Siemens and Toshiba, were based on proprietary hardware and operating systems [11].

Home Energy Management Systems (HEMS) for residential customers are of recent important development. Demand response (DR), demand-side management (DSM), peak shaving and load shifting which are considered to offer solutions to the network operator have further boosted the drive for more robust and intelligent HEMS. The U.S. Department of Energy classifies DR as having two options: price-based options and incentive- based options [1]. The price-based options and Direct Load Control (DLC) (one of the incentive-based options) are listed as follows since they are primarily offered to residential customers.

- Time-of-use (TOU): a rate with different unit prices for usage during different blocks of time, usually defined for a 24 hour day.
- Real-time pricing (RTP): a rate in which the price typically fluctuate hourly reflecting changes in the wholesale price of electricity. Customers are typically notified of RTP prices on a day-ahead or hour-ahead basis.
- Critical Peak Pricing (CPP): a hybrid of the TOU and RTP design. The basic rate structure is TOU. A much higher CPP price is applied when the demand is very high or system supply is limited.
- Direct Load Control (DLC): a program in which the utility remotely switch off a customer's electrical equipment (e.g. air conditioner, water heater) on a short notice

In residential sectors, the DR enable technologies usually related to smart home, which features an equipment of a home Energy Management System (EMS) that intelligently controls household loads with association of smart meters, smart appliances, Plug-in Hybrid Electric Vehicles (PHEVs), and home power generation and storage equipment as shown in Fig. 2. In the research work of a home energy management, it was noticed that it can be composed from either energy consumption scheduling or home area networks as summarized in ref [12].

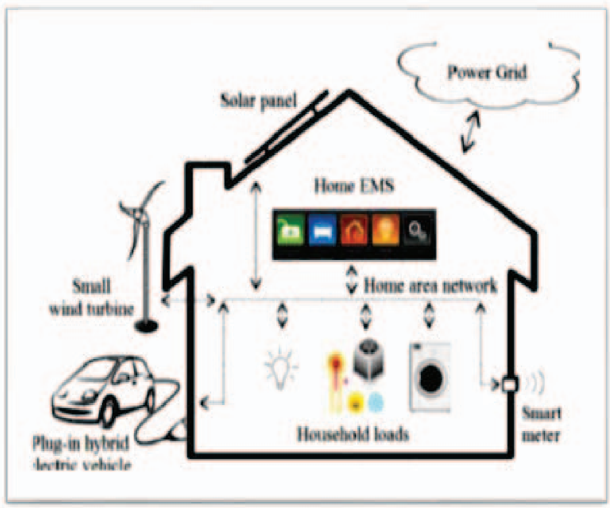

Fig. 2: A smart home with a home EMS

A. *Energy Consumption Scheduling*

The problem of smart scheduling from the consumer's point of view or side mainly is considered in this section. Like in ref. [13], it proposes a power scheduling approval based on RTP combined with IBR prices and it was effective for electricity cost reduction in residents' houses and the PAR reduction in the utility. Several optimization algorithms were introduced in ref. [14] which addressed the scheduling of energy resources in a smart home and the results showed that linear programming (LP) algorithm could get the best solution with less complexity but not suitable for extensions and the Action Dependent Heuristic Dynamic Programming (ADHDP) got closer performance in the case study. In [15] the author compared between some optimization techniques for energy resources scheduling in smart homes with focusing on the attainable performances independency on battery features and also the ADHDP gives more benefits in battery model by battery size reduction with keeping other features and total energy cost unchanged. As proposed in [16] the optimization algorithm had an overall cost objective function for household user incentive compatible and the algorithm was efficient in cost saving and energy peak shaving that take shift ability depending on a day ahead prices.

In ref, [17], the author had categorized some objectives as, first minimize the overall electrical energy consumption by scheduling the devices, second shift-appliances use to off peak periods without user comfort disturbs, and finally manage the grid energy storage with household renewable energy sources. Authors in [18] presented scheduling scheme for home appliances operating over a consumer-praise communication network incorporated with smart pricing-based or DLC-based of other DR schemes. The model of direct load control was evaluated as 2-dimensional Markov chain protocol. Ref. [19] purposed time series method for electrical consumption of individual households by using Service Location Protocol (SLP). This method generated realistic time series of standard load profiles of electrical demand with a high resolution up to 1 second.

B. Home Area Networks (HAN)

Moving towards the smart energy management will require changes not only in the way energy supplied, but in the way it is used or controlled, and reducing the energy consumption. All these goals will need networks to achieve it. As a result a lot of researches are trying to apply networks to the smart home. A ZigBee sensor networks are proposed in [20] to build up Smart HEMS (SHEMS) to make homes more intelligent and automatic in managing the use of energy. The authors in [21] presented architecture of home gateway (HGW), the management system was crucial for realizing a better ecological home network. Electricity saving and CO2 reduction are aims reached by the authors in [22] by implementing EMS based on cloud platform and depending on Zigbee hub to collect data from appliances. The cloud computing system and software development project in [23] proposed study of a lightweight electronics appliance recognition method for designing smart meter. The average recognition rate of a single electronic appliance reaches 96.14 percent, while the parallel is about 84.14 percent. The Zigbee packet monitor and control panel was developed in [24] to record the transmitted messages, establishing protocol that is feasible for SHEMS.

To enable addressing the unbalance between consumer and utility, a wireless sensor network (WSN) was found for the renovation of the power grid by the integration of ICT. Wide spread of adoption of renewable energy sources, monitoring utility assets and self-healing under failures, all this work was presented in [25]. In [26], a wired smart home is an application of Machine to Machine (M2M) with European Telecommunications System Institute (ETSI) activities on its standardization, open metering system specification and emergency communication with using a new web tool. The authors in [27] showed a HEMS on web and determine the role that status of the remote browsing control web from practical stand point which enables user to configure or operate his smart home. The energy reduction and efficiency were confirmed by the actual test of the system and improved effectively. An approach based on secured web services was used to build up HEMS to allow remote interact with home elements for managing energy consumption using Zigbee wireless network was presented in [28].

III. SMART HOMES

Use Smart home with its distinctive centrally managed infrastructure represents the ideal partner in energy management programs. The acronym "Smart Home" is used for a modern living environment which is in contrast to conventional build living environments distinguished by a large degree of routine process atomization, flexibility and comfort. Smart home represents household with highly advanced automated systems for [29]:

- Lighting
- Temperature and Ventilation Control
- Automated appliances and kitchen equipment
- Multimedia and computer and consumer electronics
- Security, windows and doors operation, visualization and management
- Telemedicine
- Power micro-generation
- Home Energy Management (HEM)

Smart Home connects a variety of automated systems and appliances into common Home Area Network (HAN) with central management and control. The main aim is to balance the householders' desired level of life comfort with energy cost saving with making life easier and more convenient. All smart devices or appliances can be centrally controlled and managed throughout Home Energy Controller (HEC), which is a device with user interface and management logic. By using the HEC the householders are able to check and set:

- Historical and current status and use of energy per smart device.
- Energy price per kWh and tariff
- Ambient Parameters and Weather Forecast

Smart devices can be connected into HAN with many wired or wireless communication technologies like WiFi, ZigBee, Z-Wave, Ethernet, KNX, etc. Wireless technologies are more likely to be implemented as it doesn't need any pre-wiring installation from the householders and he is able to change also the places of each appliance as he want without restrictions [29]. The system architecture for the Home Energy Management (HEM) system in a smart home with its main components the HEC and the HAN is shown in Fig. 3.

A. Home Energy Management (HEM)

HEM use allows loads to be controlled either by a utility or by a householder. The former one is the Direct Load Control (DLC) DR option and the latter pattern is thus defined as indirect load control, in the DLC option, the utility remotely control a customer's electrical equipment by sending a signal to the HEM system.

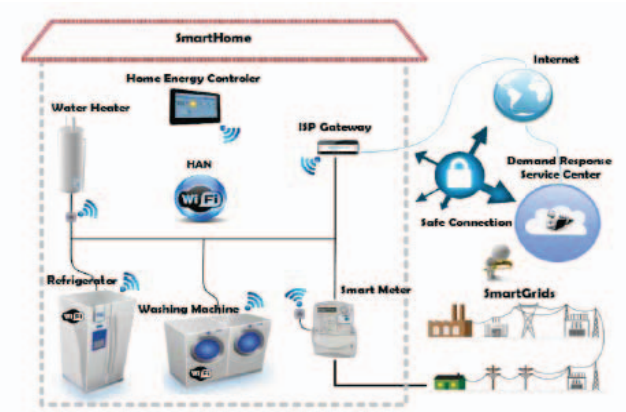

Fig.3: Smart Home architecture.

In indirect load control, customers configure the HEM system to control the equipment. The configurations include comfort levels, maximum consumption, maximum demand limit etc. that are influenced by price-based options such as Time-of-use (TOU), Real-time pricing (RTP) and Critical Peak Pricing (CPP) [30].

Various optimization algorithms are available to assist customers to schedule their electrical equipment as in [31]-[36] according to information received from a utility such as price-based signals or curtailment-base signals. The HEM system enables scheduling end-use equipment by switching on/off selected controlled household loads or by managing home generation and storage equipment, to reach an optimization objective in terms of electric bills and customer comfort. The selected loads are usually one or multiple of the controllable loads shown in Table 1.

Moving towards the smart energy management will require changes not only in the way energy supplied, but in the way it is used or controlled, and reducing the energy consumption. All these goals will need networks to achieve it. As a result a lot of researches are trying to apply networks to the smart home. The Home Area Network is an essential part of the HEM systems that include a lot of ways to connect the appliances with the EMC and vice versa using WiFi, ZigBee, and other technologies each are presented in [22, 23],[25].

B. *Fundamental Components of HEMS*

The HEM systems have several integrated parts. Technically, it consists of five groups of components depicted in Fig. 4.

- Sensing devices
- Measuring devices
- Smart appliances
- Enabling Information and Communication Technology (ICT)
- Energy management systems

In general HEM offers either of the following functionalities [37]:

- Informative overviews about energy usage data in various graphical forms (bar graphs, pie charts, etc) to the users.
- Automated actions which offer customer options to set priorities and wishes for the operation of household appliances and/or local generations.

Fig.4: Fundamental components of home energy management system

TABLE I. RESIDENTIAL LOAD CATEGORY

Critical Loads	Controllable Loads	
	Thermostatically Controlled	Non-thermostatically Controlled
Lighting Refrigeration Freezing	HVACs Water Heating	Dish Washer Washers Dryers Ranges PHEVs

- Advanced functions: this includes information, automation and control either locally or from third parties.
- Integrated systems with all the features of the advanced functions but also includes the possibility for forecasting and scheduling of loads and local generations at household levels.

IV. THE PROPOSED ALGORITHM

The first step before the proposed HEM algorithm can operate is for a homeowner to set their load priority and comfort preference. An example of load priority and preference settings is shown in Table 2. As shown for this house, the water heater is of the highest priority. This is followed by the space cooling unit, the clothes dryer, and the electric vehicle. Comfort level settings can be specified for each appliance [38].

In this paper the algorithm is applied by the utility company as a program built in the smart meter direct as it can play the role of the HEM system (Fig. 5). The function of the smart meter is to provide an infrastructure for communication, data gathering, and data processing of consumer's electrical loads. Data such as real-time consumption will be controlled through the smart meter.

TABLE II. AN EXAMPLE OF LOAD PRIORITY AND PREFERENCE SETTINGS

Appliance	Load Priority	Homeowner Preference
Water Heater	1	Water Temperature: 110-120□ F
Space Cooling Unit	2	Room Temperature: 76□ F (±2□ F)
Clothes Dryer	3	Finish the jop by midnight Maximum OFF time: 30 mins Minimum ON time: 30 mins
EV (Level 2 charging w/240V single phase)	4	Fully charged by 8 AM Minimum charge time: 30 mins

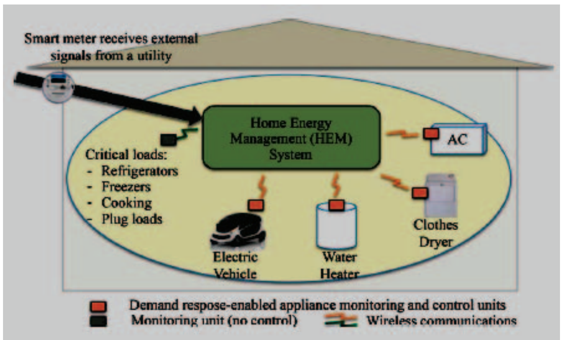

Fig.5: The HEM architecture.

This paper proposes an algorithm that aims to minimize the monetary expenses of the customer through a power budget approach that consider to limit the real-time power consumption under certain optimal limit that also achieve a reduction in the PAR.

As illustrated in Fig. 5 a house may include various household appliances such as refrigerators, Dish washers, washing machines, cookers, etc. Let x denote an appliance and X denote the set of all appliances. For each $x \in X$, the power consumption vector P is defined in equation 1 as:

$$P \triangleq [p_1^{N1}, \dots, p_i^{Ni}, \dots, p_X^{NX}] \quad \forall\ i=1, \dots, x \qquad (1)$$

where Ni is the total number of appliances of type i. Oftentimes, there is a limit value on the total power consumed by various appliances of the household. Let MXA denote the value of power limit, then the inequality

$$\sum_{x \in X} P_x^X \le M_A^X \qquad (2)$$

The power limit MXA is given as:

$$M_A^X = \sum_{x \in X} P_{x(max)}^X (1 + \beta) \qquad (3)$$

Where, $\sum_{x \in X} P_{x(max)}^X$ is the maximum power consumed by the appliances and β is the power margin which is used to give the ability to more than one appliance is working in the same time as there is uncontrollable or critical loads have to be used without any stop. β is given in equation (4) and the whole algorithm is shown in the flow chart in Fig. 6, where for initiation of the algorithm the switches are all ON.

$$\beta = \frac{\sum_{x \in X} P_{x(critical)}^X}{\sum_{x \in X} P_x^X} \qquad (4)$$

Where $P_{x(critical)}^X$ is the power consumed by the critical loads that must be working for the 24 hours without any disturbance.

V. Case Study

After In our study we took a single room house (Fig. 7) to study its loads and the householder's energy use, and Table 3 presents all the appliances in that house with their power consumption both the maximum and the average for some of them, while in Fig. 8 the total energy consumption for this house in 24 hours is shown for the chosen loads only as shown in table 4.

After all the measurements and the analyses that have been done for the energy consumption of that house, we built up our approach using microcontroller (Arduino Mega 2560) as a brain for the designed smart meter that is able to control the loads of the house and reducing the PAR with taking in consideration the householder's comfort by enabling him the choice of the priority of the use of them as shown in table 4.

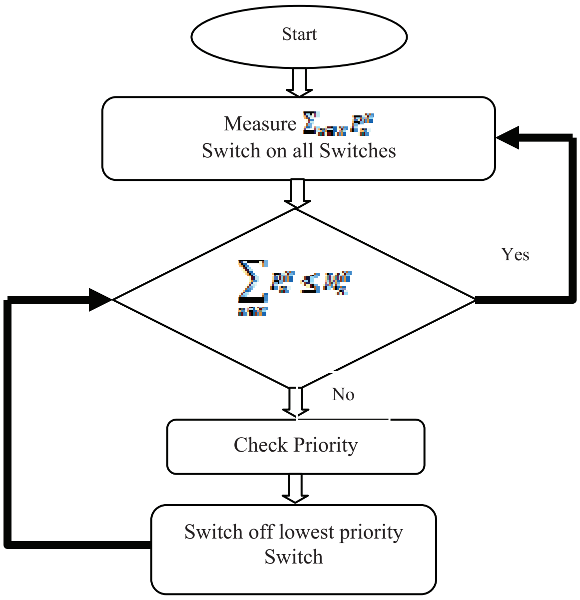

Fig 6: The Algorithm Flow Chart

Fig. 7: The Single Room House

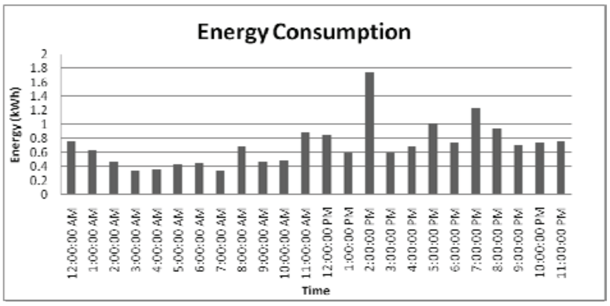

Fig. 8: The energy consumption for the House

The functions of the smart meters are to provide an infrastructure for communication, data gathering, and data processing of consumer's electrical load. Data such as real-time energy consumption will be controlled through smart meters. The smart meter that have been built is shown in Fig. 9, and the schematic diagram shown in Fig. 10 presents the method of applying the approach to control the loads and this smart meter was designed to be installed and programmed depending on the appliances' priority. This smart meter including this algorithm is suitable for the cost systems that are using only one tariff for the energy consumption but it can be modified to all types of cost systems.

TABLE III. LIST OF APPLIANCES IN THE HOUSE

Appliance	Quantity	Power (kW)	Duration (h)
Refrigerator	1	0.115	24
		0.55	
Washing Machine	1	0.14	2
		0.85	
Dish Washer	1	0.55	2
		2.15	
Iron	1	1.1	0.5
Computer	2	0.04	8
TV	1	0.15	6
Receiver	1	0.015	24
WiFi	1	0.065	24
Toaster	1	0.66	0.1667
Toaster Oven	1	1.45	2
Kittle	1	1.85	0.083
Kitchen Machine	1	0.3	0.25
Mobil Charger	2	0.0125	2
Electric Broom	1	1.95	1

Fig. 9: The smart meter diagram

The results of the energy consumption with the power limit due to equation (3) that gives a power limit of 2.5 kW as β = 0.16 with the critical loads sum of 0.9 kW (Loads 1 and 2) as it means that when the door of the refrigerator is opened and all the lighting are on in same time it will consume about the 0.9kW, which will not happened for a long time during the day. The result of using the smart meter is shown in Fig.11 while in Fig.12, 13 and 14 the comparison between the energy consumption with the smart meter and without is presented for random one day, one week and one month respectively and without using the same routine for the same periods. The results prove that the smart meter algorithm is very efficient in reducing the peaks of the power consumption achieving an optimal reduction in the PAR that results in a minimization of the electricity bill and satisfying the householders' comfort. As a result of this energy management system it helps in smoothing the operation of energy production.

TABLE IV. THE PRIORITY OF THE APPLIANCES

Switch Number	Load	Priority	Power (W)
S1	Refrigerator	1	550
S2	Lighting & Sockets	2	350
S3	TV & Computers	3	200
S4	Toaster	4	1450
S5	Washing Machine	5	850
S6	Dish Washer	6	2150

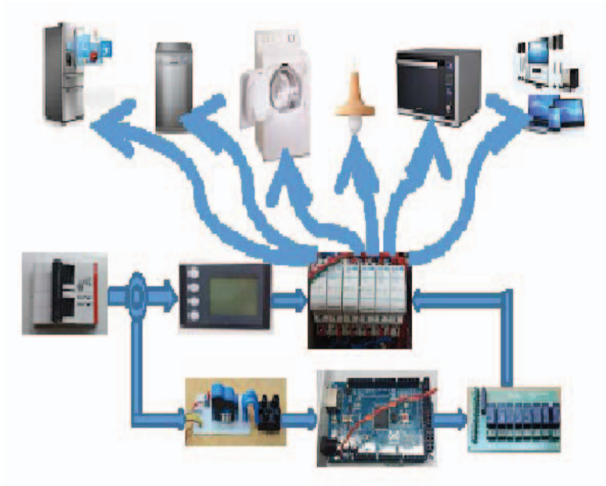

Fig. 10: The schematic diagram

VI. CONCLUSION

The home energy management systems are used to reduce the environmental burden, and supporting human's life style. The technical aspects of management include peak shaving, valley filling, load shifting, flexible load curve, strategic conservation and strategic load growth. Another important aspect of energy management systems is economic impact of such system. The paper presented the important role of the demand-side management in the smart grid infrastructure for enhanced energy reduction and system control. As a reason the HEM systems was discussed as a main part of the demand-side management that realizing residential Demand Response (DR) programs in the smart environment. The paper provided the homeowner the ability to automatically perform smart load controls based on utility programs, customer's preference and load priority. This paper presented an effective hardware demonstration of the proposed HEM system for managing the end-use appliances. The proposed algorithm manages the household loads according to their preset priority and fixed the total household power consumption under certain limit. This study succeeded to achieve the purpose of reducing electricity expense and clipping the peak-to-average ratio (PAR) as a kind of load shading.

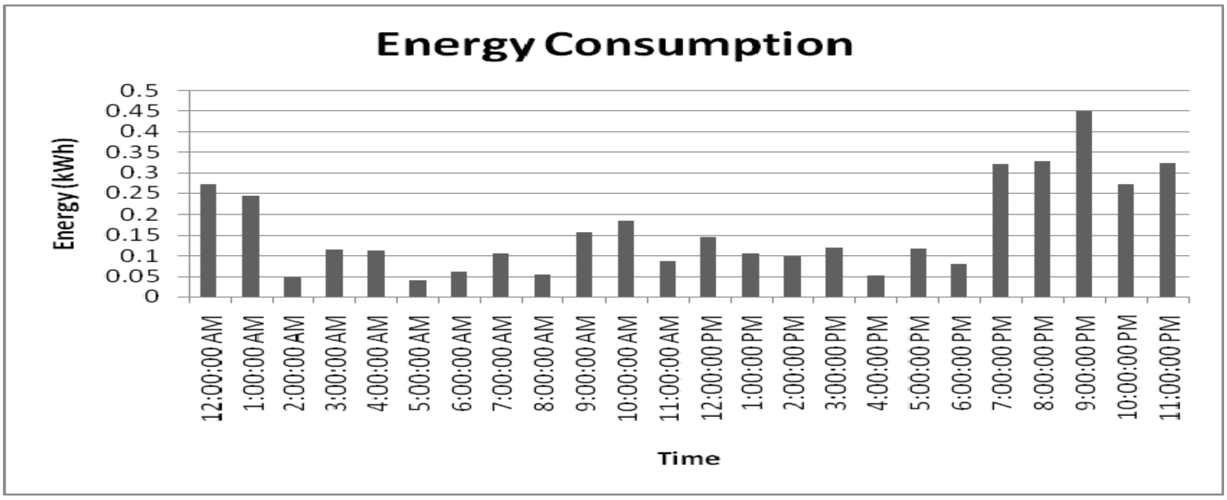

Fig. 11: The energy consumption using smart meter

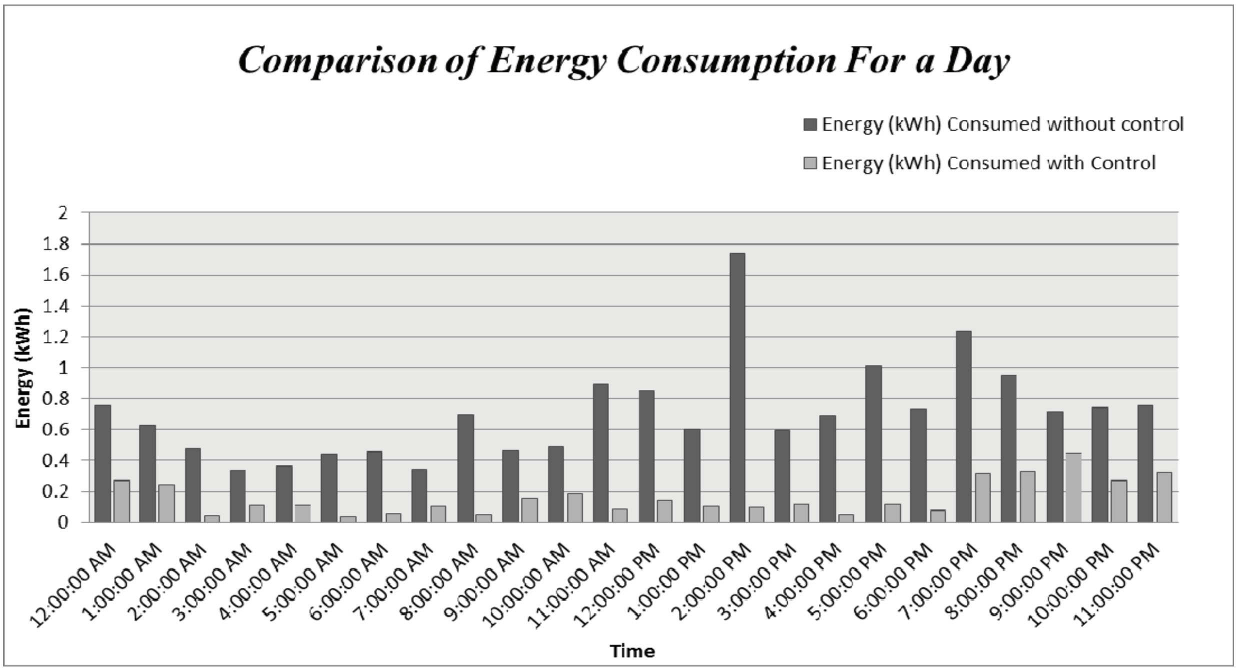

Fig. 12: The results comparison for one day

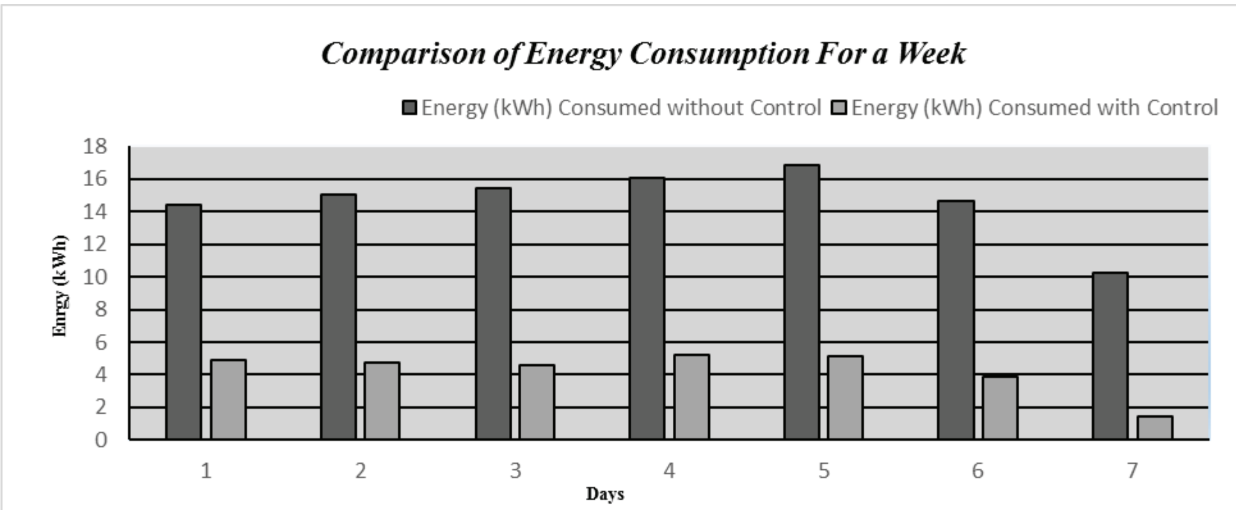

Fig. 13: The results comparison for one week

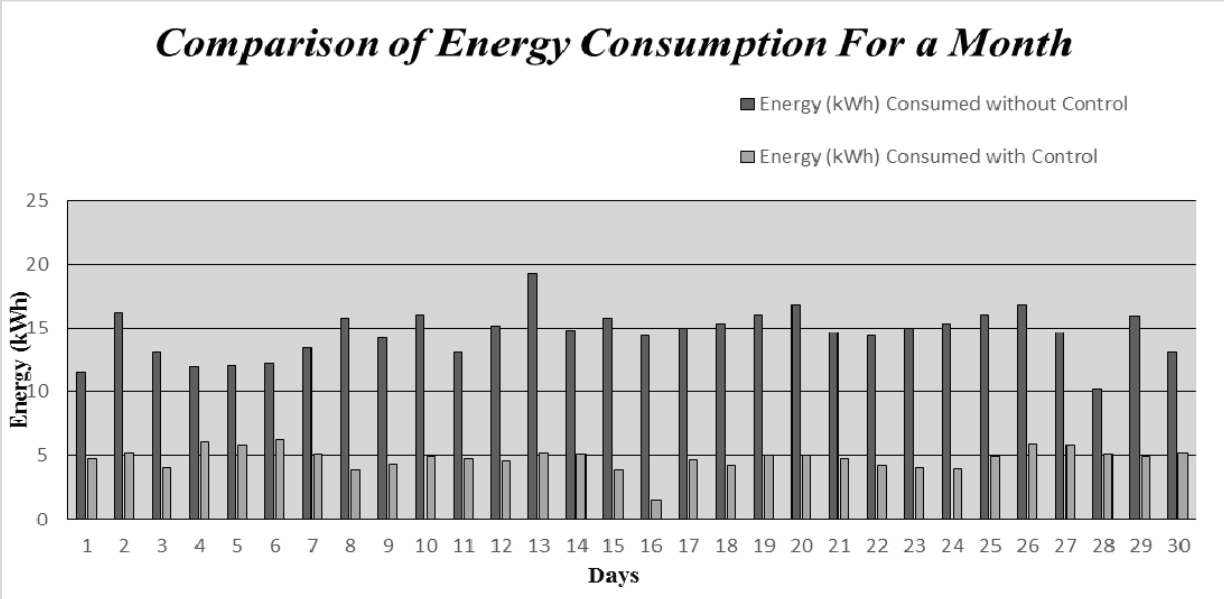

Fig. 14: The results comparison for one month

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