Smart Home Energy Management Technologies Based on Demand Side Management and A Review of Smart Plugs with Smart Thermostats

Onur Ayan[1], Belgin Emre Turkay[2],

[1]Department of Electrical Electronics Engineering, Istanbul Technical University, Turkey
ayanon15@itu.edu.tr
[2]Department of Electrical Electronics Engineering, Istanbul Technical University, Turkey
turkayb@itu.edu.tr

Abstract

The technology of Home Energy Management System (HEMS) has been developing for the purpose of increasing energy efficiency, reducing energy cost and reducing gas emissions. HEMS can allow consumers to provide load shifting using smart plugs and to provide energy efficiency using smart thermostats. Smart plugs and smart thermostats will enable the consumer to turn off devices that are large loads or let the Demand Side Management (DSM) system known as load management do its job such to reduce energy consumption in a given period with the premise of no consumers' comfort losses. This paper investigates the energy demand profiles for the residential sector. Investigations were out on residential energy consumption, energy conservation and the impacts of energy management systems on the residential load profile. This paper also aims to present an overview of the smart plugs and smart thermostats on the market and how consumers/users use them effectively. Finally, how people are going to save energy using smart plugs and smart thermostats was shown by experimental measurements in this study.

1. Introduction

Electricity consumption in the residential sector represents an significant part of the total electricity demand. A proper estimation of energy demand in housing sector is very important. Electricity use in residential area accounts for significant part of total energy consumption both in developing and western world[1]. Residential buildings currently account for large part of the total electricity demand[2]. Home Energy Management System (HEMS) is a significant part of the Smart Grid and has many benefits such as reduce the electricity bill, reduction of demand in peak hours and meeting the demand side requirements. Home Energy Management System is rapidly expanding alongside significant investment to improve energy efficiency and upgrade electricity infrastructure to a smart grid.One of the Home Energy Management System objectives is to decrease the peak demand of households by controlling power loads and take into account the comfort and priority at the same time. HEMS that is based on Zigbee and Zwave communication protocols allows the consumers/households to regulate power of smart devices after receiving a signal from the service provider. Time of Use (ToU) tariffs in Turkey apply different prices for electricity at different times of the day. Time is divided into on-peak period between 17:00-22:00, off-peak period between 22:00-06:00 and mid-peak period between 06:00-17:00. These periods reflect the level of demand on the electricity network. During off-peak period, electricity prices will be cheaper than at other times. The role of cost control is to change the load curve shape in such way that energy consumption peak decreases, although the total consumption for specific household is the same[3].

Home Energy Management System is basically a technology platform comprised of both software and hardware that allows the user/consumer to monitor energy usage and production and to manually control or/and automate the usage of energy within a household[4-5]. In other words, HEMS can be defined as those systems including both hardware and software linked via a network that enable households to manage their energy consumption[8]. Moreover, HEMS can provide the automatic interface the consumer needs to manage their consumption of electricity[6]. The specific characteristics of such systems are as follows. HEMS receives current and forecast information on electricity pricing. It can manage the settings of the smart appliances to manage their on-off times and record where the energy is being used. The consumer can develop their own energy usage profile and use data according to how it best benefits them. Consumers can override all previously programmed selections or instructions from the smart grid, while ensuring the appliance's safety functions remain active. HEMS incorporates features to target renewable energy allowing for the shifting of energy usage to an optimal time for renewable energy generation.

Home Energy Management System basically consists of two parts as software part and hardware part. HEMS' hardware generally consists of a hub device which relays communications between user and in some cases the local utility or electricity retailer. Hub can be installed on the home's electrical board as well as in cases where the HEMS operates purely on a wireless network. Software used in a Home Energy Management System is what moderates the ingoing and outgoing data and communications. From a user's perspective, the software is the interface that allows access to monitoring data and control functions of the system. The interface generally gets the form of an app or web portal. The software for some Home Energy Management System has the express goal of increasing the energy efficiency or effectiveness of the household, while the focus of others is simply to control devices remotely or automatically for convenience or security purposes[7].

HEMS can be done two ways. HEMS can provide energy consumers with information about how they use energy in the home and prompts to change consumption. HEMS can provide the households or third parties the ability to control energy consuming processes in residential area, either remotely via a smart phone or web service or based on a set of rules, which can be scheduled or optimized based on user behavior.

2. Demand Side Management Strategies

Even though often used interchangeably, Demand Side Management and Demand Response are essentially different. Demand Response programs are designed to encourage end users/consumers to make short term reductions in energy demand in response to a control signal. This control signal can be defined as price. However, Demand Side Management programs are medium to long term measures to stimulate end-users/consumers towards energy efficiency[9]. While Demand Side Management programs extend to any system that uses energy, Demand Response programs are virtually limited to electricity users. Load profile can be changed and load curve can be adjusted with Demand Side Management(DSM) techniques as described by Gellings and Chamberling in 1993[10]. Six applied DSM strategies to reshaped load pattern are described below and shown in Fig. 1.

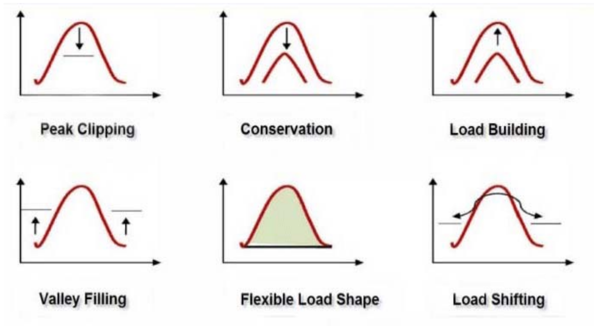

Fig. 1. DSM strategies

- Peak Clipping/Reduction: Peak clipping refers to the reduction of utility loads during peak demand periods. This can defer the need for additional generation capacity. The net effect is a reduction in both peak demand and total energy consumption. The method usually used for peak reduction is by direct utility control of consumer appliances or end-use equipment[11].
- Load Shifting: Load shifting involves shifting load from on-peak periods to off-peak periods. The net effect is a decrease in peak demand, but no change in total energy consumption. Typical methods used for load shifting are Time of Use (ToU) rates and/or the use of storage devices.
- Conservation: Conservation refers to the reduction in end-use consumption. There are net reductions in both peak demand and total energy consumption. Examples of conservation efforts are appliances efficiency improvement and building energy conservation.
- Valley Filling: Valley filling is a form of load management that entails building of off-peak loads. This is often the case when there is underutilized capacity that can operate on low cost fuels. The net effect is an increase in total energy consumption, but no increase in peak demand. A typical example for the creation of valley filling is the energy thermal storage.
- Load Building/Growth: Load building consists of an increase in overall sales. The net effect is an increase in both peak demand and total energy consumption. Examples of load building include electrification commercial and industrial process heating and other means for increase in energy intensity in industrial and commercial sectors.
- Flexible Load Shape: Flexible load shape refers to variations in reliability or quantity of service. Instead of influencing load shape on permanent basis, the utility has the option to interrupt loads when necessary. There may be a net reduction in peak demand and little if any change in total energy consumption.

3. Residential Loads

Residential loads can be grouped based on multiple factors. Some studies broadly divide the loads into two categories with the respect to energy management possibilities such as deferrable and non-deferrable loads where the former refers to devices whose operation can be shifted to later times of the day, and the later implies those whose operation cannot be shifted. Other studies use flexible and non-flexible loads to virtually refer to same category of loads[12]. The residential loads can be divided along the ability to control the devices either locally or remotely via automatic actions, hence the terms controllable and uncontrollable loads. Other categorization can be represented based on appliances' rated power consumption such as heavy loads, normal loads and light loads.

Flexibility is defined as the ability of devices to increase, decrease or postpone their power consumption or generation in time without impacting on the services they provide[13].

3.1. Inflexible Loads

Inflexible loads are refer to domestic appliances whose operation cannot be shifted or interrupted to later periods. There are two types of inflexible loads. Firstly, there are appliances that are "always on" or on "stand-by" most part of the day such as modems, telephones, and internet gateways. The second group is appliances that must be in operation at the desired period and cannot be shifted such as television, laptop, personal computer, and lighting. They are regarded as inflexible loads because they are incapable of adapting and/or changing their operations to meet circumstances without impacting on the service provide.

3.2. Shiftable Loads

They are defined as loads with fixed time periods of operational cycles and which are not time dependent[13]. Dishwasher, tumbler and washing machine loads can be shown as examples of shiftable loads. Their energy consumptions are determined by such factor as frequency of operation, selected program, ambient conditions and machine efficiency. Shiftability potentials of these appliances depend on the behavior and needs of the users.

3.3. Thermal Loads

Thermal loads refer to thermostatically controlled devices that supply cold or heat. Heat pumps, refrigerators, freezers and air-conditions are common example of thermal loads[14].

3.4. Buffer Loads

These are loads with incorporated storage systems. Electric vehicles and electricity and heat storage systems are example of buffer loads[15].

3.5. Energy Storage Systems

Energy storage systems are enabling technologies for transport and grid application. Flywheel, compressed air energy storage, pumped hydropower, superconducting magnetic energy storage and thermal energy storage are examples of energy storage technologies[15].

4. Home Energy Management Systems

HEMS can be defined as in-home devices or systems that control, monitor and analyze home energy use and provide information to the occupants. These systems are to conserve energy, reduce cost and improve comfort using intelligent monitoring and control systems. In this study, the effects of smart plugs and smart thermostats for HEMS were examined.

4.1. Smart Plugs

Smart plug (SP) is an electronic device which helps users to control their electrical appliances from a smart phone or tablet. Smart plugs (SPs) can be inserted between plug and power socket and they provide real time measurement and communication. They play an important role in converting existing electrical appliances into smart electrical appliances with the purpose of controlling remotely[16].

4.1.1. Implementation of SPs in a HEMS for Load Shifting

The energy consumed in residential area needs to be control to reduce the peak load on the network. Operating and duration time can be shifted from peak hours to off-peak hours by load shifting and thus the power consumption in residential area can be reduced. Smart plugs are an alternative way of controlling electrical appliances and load shifting. In this paper, a simulation study was carried out to show effect of controlling the deferrable loads. Energy consumptions of electrical devices that can be used at home were measured over a month through smart plugs. A monthly household load profile was obtained with these measurements. The obtained load profile is shown in Fig.2.

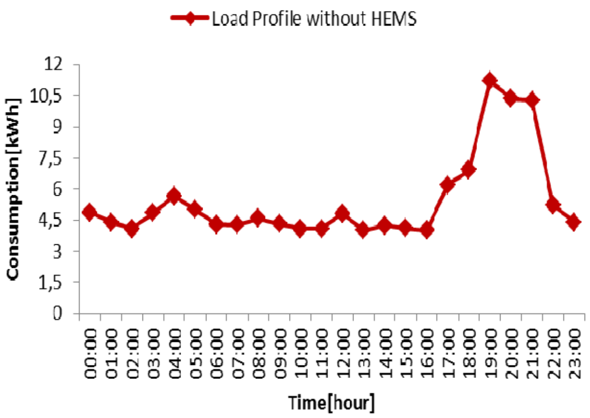

Fig. 2. Monthly load profile

It has seen that the peak loads in the given monthly load profile occur more in the evening hours. Three-tier tariff applied in the evening between 17:00-22:00 hours is determined as the most expensive time interval. For this reason, it is advantageous to shift certain electrical devices out of this time interval and deferrable loads such as washing machine, dishwasher and tumbler were shifted from peak hours to off-peak hours using smart plugs. The change in the load profile after load shifting using smart plugs is shown in Fig.3.

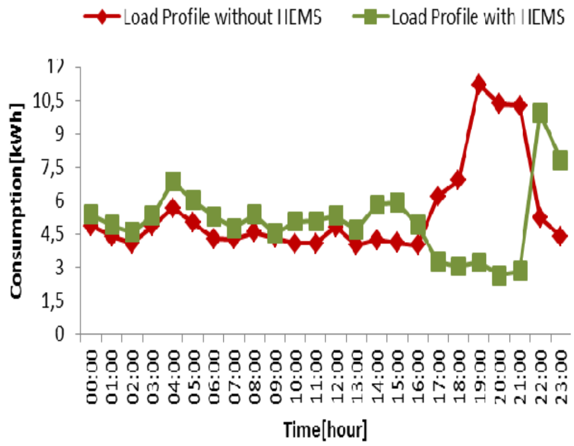

Fig. 3. Monthly load profile before and after load shifting

It is seen from the Fig.3 that power consumption has been improved by shifting deferrable loads from peak hours to off-peak hours. A reduction in peak demand up to %33,24 was achieved with load shifting in the evening hours when the price of electricity was expensive. In this paper, the change in the load profile of a house was studied. Taking into account the number of houses in Turkey, extensive studies about power consumption will contribute significantly to relieve distribution network.

When choosing smart plugs, consumers need to consider what they want to use it for and different smart plug brands have different features. The implementations of smart plugs can reduce energy use in residential area. Brief information about the features that some of the most popular smart plugs is shown in Table 1.

4.2. Smart Thermostats

Heating, cooling, ventilating and air conditioning systems known as HVAC systems are considerably energy consuming systems and HVAC automation, which takes into account the characteristics of the living environment(house, shopping center, industrial facilities, etc.) allows significant energy savings. The energy consumed in HVAC systems varies between 15% and 60% depending on characteristics of the building and intended use. Applications to be made in HVAC systems can provide up to 40% energy saving in operating costs. Average households spends 1900$ a year on energy costs with half going toward heating and cooling. Similarly, average household spends well over 1,000£ a year on heating and powering for UK families.

There are three main types of thermostats used in residential area. These are manual (dumb), programmable and smart thermostats. Manual thermostats remained one of the simplest components of a home heating system for a long time. While manual thermostats are easy to use, they have lots of disadvantages like limited accuracy and inability to perform automatic temperature changes. Programmable thermostats allow consumers to enter a heating and cooling temperature set point, setup temperature for each day of the week or give the thermostat schedule to operate by.

4.2.1. Implementation of Smart Thermostat in a HEMS for Energy Efficiency

Since consumers do not have full control over programmable thermostats, smart thermostats provide a good solution in flexibility and type of controlling for consumers. Consumers can arrange their schedules remotely using smart thermostats[17]. This process gives consumers complete control over when their home's heating and cooling equipment runs. Since smart thermostats Wi-Fi enabled, consumers can use smartphones and tablets to remotely monitor them and make changes. Electricity and natural gas consumption of the combi boiler used for heating between January 23 and January 29 are shown in Table 2. Consumption values were measured for a house.

Table 2. Electricity and natural gas consumption of combi boiler

Date	Electricity Consumption (kWh)	Natural Gas Consumption (m^3)
23.01.2017	1,555	5,816
24.01.2017	1,548	6,232
25.01.2017	1,552	6,358
26.01.2017	1,503	5,392
27.01.2017	1,533	6,838
28.01.2017	1,528	5,787
29.01.2017	1,559	5,59

According to the measurements shown on the Table.2, the combi boiler causes 1,539 kWh electricity consumption and 6,001 m^3 natural gas consumption per week.

- The most efficient use of a combi boiler when households are at home all day long: To our knowledge, there are not many alternatives to efficient use of combi boiler when the households stay at home all day long. When the people are at home all day, the temperature of the house must be kept constant. The most economical way for the households is to program the combi boiler at a certain value.
- The most efficient use of a combi boiler when households are not at home: When the households work at a job, meaning they are out of their house at some specific hours, reducing the temperature of combi boiler to a certain value or shutting it down completely leads to decrease in the electric bills.

On January 30, 2017 the combi boiler was off between 07:35 and 17:05, meaning no electricity or natural gas consumption occurs. At 17:05, the internal temperature of the house was 15.6 °C. After turning the combi boiler on, it took 1 hour and 21 minutes for combi boiler of the house used in the experiments to reach desired temperature from 15.6 °C to 18 °C. On January 30, 2017 total daily electricity and natural gas consumption were 0,95 kWh and 4,853 m^3 respectively. After shutting combi boiler down on January 30,2017 the average energy savings for natural gas and electricity consumption were calculated as 19,13% and 38,2% respectively. The time required to reach the desired temperature of the house (1 hour 21 minutes) can also be set remotely by smart thermostats. If the households set smart thermostats using smartphones 1,5 hours before arriving home, the house will be at the desired temperature. Thus, good satisfaction in comfort will be provided. The Honeywell Y87RFC2090 smart thermostat was used to remotely control the combi boiler in this study. The change in natural gas on January 30, 2017 was shown in Fig.4.

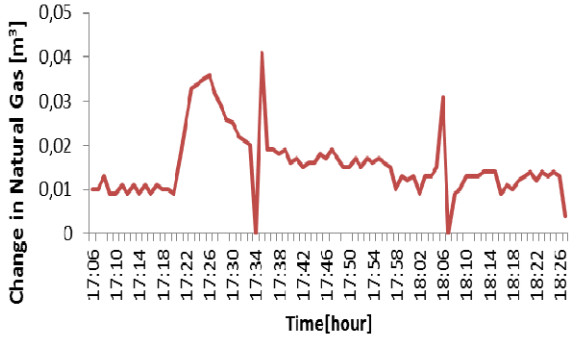

Fig. 4. Change in natural gas consumption dated January 30

A similar study was conducted again on February 1, 2017. The combi boiler was off between 07:23 and 17:02. At 17:02, the internal temperature of the house was 15.5 °C. On February 1, 2017 total daily electricity and natural gas consumption were 0,976 kWh and 4,982 m^3 respectively. After shutting combi boiler down on February 1,2017 the average energy savings for natural gas and electricity consumption were calculated as 16,98% and 36,58% respectively. Similar results were obtained on January 30 and 1 February,2017. The change in natural gas on February 1, 2017 was shown in Fig.5.

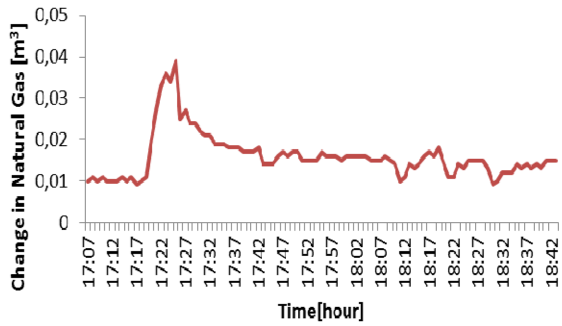

Fig. 5. Change in natural gas consumption dated February 1

The most well-known smart thermostats products in terms of functionality were shown in Table 3.

5. Conclusions

Peak loads have been increasing in recent years due to increase in population, new technologies and incorrect use of electrical appliances. DSM is proposed for peak load management. Loads can be delayed, controlled or shifted with DSM techniques. Smart plugs can be used for load shifting and controlling of the deferrable loads. In this paper some residential loads were shifted from peak hours to off-peak hours for 30 days and there was a reduction in peak demand of up to 33,24%. Another study in this paper is about how the combi boiler can be used economically. If people are out of their house at some specific hours, reducing the temperature of combi boiler or shutting it down completely provides energy efficiency on a large scale and decrease in consumer's electric bills. Although there was no significant difference in natural gas consumption by shutting the combi boiler down between certain hours, 37,59% energy saving was achieved in electricity consumption.

Table 1. The most well-known smart plug products

Function / Products	Amazon Echo Support	Power Usage Monitoring	Android & IOS Compatible	Pros	Cons	Price
Edimax Wi-Fi Smart Plug	×	✓	✓	Limit Usage, Monitor Usage, Schedules, Easy and fast setup	Doesn't support Nest, Remains off after a power outage, Some Connectivity Issues	$27.90
TP-Link Smart Plug	✓	✓	✓	Quick and easy setup, Away Mode, Power Usage Tracking	No Dimming, Not Compatible with IFTTT	$26.99
Koogek Wi-Fi Smart Plug	×	✓	IOS only	Supports Siri, Supports Apple Homekit	Doesn't support Android, Nest and IFTTT, Unit blocks other sockets	$29.99
Wemo Insight Switch Smart Plug	✓	✓	✓	Quick and easy setup, Supports IFTTT and Nest, Power Usage Tracking	Large Plug, May not be fit in smaller sockets	$47.29
Wemo Mini Smart Plug	✓	×	✓	Supports IFTTT and Nest, Doesn't block other sockets	Doesn't Track Power Usage	$34.99
Orvibo Wi-Fi Smart Socket Outlet Plug	×	×	✓	Quick and easy setup, Timers and Schedules can be set,	Doesn't support Nest and IFTTT, No Away Mode	$17.12
iHOME ISP5 Home Control Smart Plug	✓	×	✓	Works with Nest, Apple Homekit and SmartThings	Connectivity Issues with Apple Homekit, No power Usage Indicators	$23.00

Table 3. The most well-known smart thermostat products

Function / Products		Learning	Geolocation	Motion Detection	Weather Monitoring	Home Automation	Smartphone App Control	IFTTT Integration
Nest Learning		✓	×	✓	✓	Nest, Alexa, Wink, Google Home, SmartThings	✓	✓
Ecobee3		×	✓	✓	✓	Alexa, HomeKit, SmartThings, Wink	✓	✓
Honeywell	Lyric T5	×	✓	✓	✓	Alexa, Wink, Google Home HomeKit	✓	✓
Honeywell	Evohome	×	✓	×	×	Alexa, Wink, Google Home	✓	✓
Honeywell	Wi-Fi Smart	×	Via IFTTT	×	✓	Alexa, Wink, Google Home	✓	✓
Hive		×	✓	×	×	Alexa, Wink Google Home	✓	✓
Tado		✓	✓	×	✓	Alexa, Wink Google Home	✓	✓
Heat Genius		✓	×	✓	✓	Alexa, Wink Google Home	✓	✓

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