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Home Energy Management System

A Home Energy Management System under Different Electricity Pricing Mechanisms

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Abstract

Peak demand is a severe problem in the electricity grid and it was solved by supply side management in the past. But nowadays the demand side management sources have drawn attention due to the economic and environmental constraints. Demand side management in the domestic sector can play an important role in reducing the peak demand on the power system network. It can help in reducing stress and overloading on the transmission and distribution lines. In many countries there are various demand response programs implemented for industrial and commercial loads. In these programs load control is primarily achieved by various types of pricing mechanisms. There are very few demand response programs in use for energy management in residential sector. Direct curtailment of the loads is the most popular method used to reduce the peak demand in the domestic sector. But by direct load control, customer comfort may be compromised. In contrast peak load reduction through load shifting can benefit both consumers and utilities.

In order to analyze demand response in the domestic sector, it is important to understand physical based power intensive load models with an emphasis on water heater units, air conditioner units, clothes dryers and electric vehicles. In this work, these load models are developed considering thermodynamic principles of buildings as well as their built in technical parameters. With the development of smart grid systems specially in the distribution network and possibility of load modeling, there is a requirement of a domestic intelligent energy management algorithm. In this work, power intensive non-critical loads are managed through developed energy management system algorithm and these loads are water heater, air conditioning unit, clothes dryer and electric vehicle. With the introduction of electric vehicles, demand responses can be performed within home for avoiding any overloading problems in the distribution network as well as on power generation. Additionally, the electricity bill saving which can be gained through proposed energy management system is analyzed by considering different electricity pricing mechanisms.

The highlight of the presented energy management system algorithm for home energy management is its capability to control the non-critical loads below specified peak demand limits by considering consumer behavior and priorities, giving consumers more flexibility in their operational time. Moreover, the results show that the electricity saving which can be gained through the proposed energy management system lies in a noticeably high range.

It is expected that the research findings of this work can be beneficial to utilities in providing information of limits and scope of domestic demand responses. And also it is anticipated that the cost analysis carried out can be used to motivate the consumers towards demand response through the developed energy management system.

Key words:

Domestic demand response, Home energy management system (EMS), demand limits, non-critical loads, load priority, Time of Use pricing, Real Time Pricing

Preface

First and foremost I would like to express my profound gratitude to my supervisor, Professor Mohan Lal Kolhe. You have been a constant motivator, giving indispensable guidance to me in reaching this goal. Without your priceless support I might not be able to complete this thesis successfully.

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Grimstad, Norway

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M.A.S.T. Ireshika

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Nomenclature

Symbols

ρ_{air}	Density of air	lb/ft^3
η_{WH}	Efficiency factor	
Δc	Energy needed to change the temperature of the air in the room by 1°F	$Btu/^{\circ}\mathrm{F}$
Δt	Duration of the time slot *i*	$hours$
ΔT_{AC}	Allowable temperature deviation/dead band of the AC unit	$^{\circ}\mathrm{F}$
ΔT_{WH}	Lower tolerance	$^{\circ}\mathrm{F}$
ACH	Air changes per hour	$changes/h$
$A_{ceiling}$	Area of the ceiling	ft^2
A_{tank}	Surface area of the tank	ft^2
A_{wall}	Area of the wall	ft^2
A_{window}	Area of the windows	ft^2
A_{window_south}	Area of the windows facing South	ft^2
C_{air}	Specific heat capacity of air for a typical room condition	$Btu\ /^{\circ}\mathrm{F}.ft^3$
$C_{battery}$	Rated capacity of the battery	kWh
C_s	Air sensible heat factor	$Btu\ /^{\circ}\mathrm{F}.ft^3$
$D_{AC,i}$	Control signal received by the AC unit from EMS in time slot *i*	
$D_{EV,i}$	Control signal received by the electric vehicle from EMS in time slot *i*	
$D_{WH,i}$	Control signal received by the water heater from EMS in time slot *i*	
E_{dr}	Energy used in driving	kWh
fr_i	Hot water flow rate in time slot *i*	gpm
G_i	Heat gain rate of the house during time slot *i*	Btu/h
H_p	Heat gain from one person	Btu/h
H_{solar}	Solar radiation power	W/m^2
k	Drying level	
M	Total number of drying levels	
n_p	Number of people	
P_{AC}	Rated power of the AC unit	kW
$P_{AC,i}$	Power consumption of the AC unit in time slot *i*	kW
$P_{CD,i}$	Power consumption of the cloth dryer in time slot *i*	kW
P_{EV}	Rated power of the electric vehicle	kW
$P_{EV,i}$	Power consumption of the electric vehicle in time slot *i*	kW
P_{hc}	Rated power of the heating coils of the cloth dryer	kW
P_m	Power consumption of the motor part of the cloth dryer	kW

P_{WH}	Rated power of the water heater	kW
$P_{WH,i}$	Power consumption of the water heater in time slot *i*	kW
R_{tank}	Heat resistance of the tank	$°F.ft^2.h/Btu$
$R_{ceiling}$	Heat resistance of the ceiling	$°F.ft^2.h/Btu$
R_{wall}	Heat resistance of the wall	$°F.ft^2.h/Btu$
R_{window}	Heat resistance of the window	$°F.ft^2.h/Btu$
$SHGC$	Solar heat gain coefficient of windows	
SOC_0	Initial charge state of the battery	
SOC_i	Charge state of the battery in time slot *i*	
SOC_{max}	Charge state of the battery at fully charged condition	
T_a	Ambient temperature	°F
$T_{AC,s}$	Thermostat set point of the AC unit	°F
$T_{Accumilated}$	Accumulated time of the drying operation	$minutes$
T_i	Room temperature in time slot *i*	°F
T_{inlet}	Inlet water temperature	°F
$T_{required}$	Required time/duration of the drying operation	$minutes$
$T_{out,i}$	Outdoor temperature in time slot *i*	°F
$T_{outlet,i}$	Outlet water temperature in the tank	°F
$T_{WH,s}$	Hot water temperature set point of the water heater	°F
V_{house}	Volume of the house	ft^3
V_{tank}	Volume of the tank	ft^3
$W_{AC,i}$	Status of the AC unit in time slot *i*	
$W_{CD,i}$	Status of the cloth dryer in time slot *i*	
$W_{EV,i}$	Status of the electric vehicle in time slot *i*	
$W_{WH,i}$	Status of the water heater in time slot *i*	

Abbreviations

AC	Air Conditioner
CD	Clothes Dryer
DL	Demand Limit
DLC	Direct Load Control
DR	Demand Response
EMS	Energy Management System
EV	Electric Vehicle
RTP	Real Time Pricing
THD	Total Household Demand
TOU	Time of Use
WH	Water Heater

Chapter 1

Introduction

This chapter provides background information of demand response systems emphasizing the need of reducing the of peak power demand. The role of the residential sector in managing the peak demand is explained in detail. Thereafter the problem statement with objectives, goals and limitations are discussed. Literature review and problem solutions are also included in this chapter. Finally an outline describing the structure of the upcoming chapters is provided.

1.1 Background

Peak power demand has caused adverse effects to the reliability and stability of the power system during the past decades. Reducing the peak demand can reduce the risk of transmission and distribution network failures thus the risk of outages. Demand response (DR) is a one way to deal with peak events and prevent network overloading because it provides the flexibility required to time shift loads [1], [2]. The operation of high cost generating units can be eliminated by reducing peak demand through DR programs which in turn will produce a significant cost saving.

A number of demand response systems have been developed during past especially for the commercial and industrial sector. DR in these sectors are achieved either by price based (indirect load control) or incentive base (Direct Load Control) techniques [3]. These DR systems are not widely implemented due to several reasons. In these systems, demand response participants have typically relied upon manual response strategies rather than using automation, although automated response technologies are slowly becoming more prominent, particularly in industrial and commercial buildings [4]. Although energy demand share of the residential sector accounts for a significant amount of the total energy demand, very few DR programs are currently used in the residential sector. Direct Load Control (DLC) is mostly used by the utility to manage the residential peak demand in which the customer loads are adjust and time shift during network peak events [5] –[7]. Consumers are paid for participating in DLC programs, but many residential consumers are not willing to participate in DLC programs as the consumer comfort has to be compromised. Time-of-Use (TOU), critical peak pricing and Real Time Pricing (RTP) are incentive based DR programs which are mostly used in commercial and industrial DR programs. Active participation of the consumer in scheduling the energy consumption is needed in most of these DR programs. But manual strategies are difficult to maintain due to significant volatility in real-time prices, requiring continual adjustments [8]. Moreover, it was also found that consumers are less likely to make active decisions about their load on an hourly basis under the real time pricing scheme [9].

However it is mandatory to assure the participation of all the sectors in DR programs since the all the consumers (ranging from residential to industrial manufacture) experience service interruptions if the peak demand is not managed properly. The participation of the industrial sector in DR is currently in an acceptable state, the level of participation of the residential sector is not satisfactory. Therefore in this work peak load management in the residential sector has emphasized and an efficient DR program for this sector is proposed.

An energy management system which can automatically shift the operation of the domestic appliances during peak hours can be used to manage the residential peak demand without compromising much of the consumer comfort. Many hardware applications for DR in residential sector are available in literature [10]. Most EMS focus on making the consumers more aware of their electrical power usage and/or providing methods to share this information with energy providers or third party application developers [11]. These researches focus on different graphical illustrations of data related to consume energy to ease consumer comprehension and on different tools and methodologies to share this data over the web [12].

In order to develop the energy management systems, physical based load models have to be used specially for power intensive residential loads. Physical based residential load models are developed in [13]. These models have been mostly used for DLC programs. But these load models can also be used to study the effects of energy management on the operational timing at an appliance level in residential DR programs. Electric vehicle load model has not considered in most of the previous works on DR. As the electric vehicles also have emerged in to the market and have a great impact on residential peak demand it also has to be considered in energy management systems.

1.2 Problem Description

This work proposes an algorithm for energy management in residential sector which can automatically shift the operational time of the non-critical power intensive loads from peak demand periods to off-peak periods, while assuring the consumer comfort levels. The proposed energy management algorithm is developed assuming that the demand limits are provided by the utility and the priority levels for the controllable power intensive appliances are specified by the consumer. The considered residential power intensive loads are water heater, air conditioner, clothes dryer and electric vehicle. The proposed energy management system can manage the operating times of these non-critical loads based on the load priorities given by the consumer, in such a way that the total household load is maintained below the demand limit specified by the utility. In this study, a Matlab simulation tool is developed to validate the developed algorithm in managing the operating times of the considered non-critical loads. The analysis is also carried out with the possible changes in the user behavior in response to the fluctuating energy prices. Different pricing mechanisms especially TOU and RTP with various demand charge configurations are considered in this project, to calculate the energy bill savings that can be gained by using the proposed energy management system. The developed simulation tool is extended and the considered pricing mechanisms are embedded to the Matlab program to evaluate the energy savings of the energy management system.

The findings show that the utility has to consider the possible changes in the consumer load profile in response to the price changes when deciding the demand limit levels in the energy management system. Also this work will provide import information for the utility in selecting the pricing mechanisms for the residential consumers to promote energy management system among the residential consumers. Also this work will provide evidence to the consumers about the effectiveness of the developed energy management system in reducing their electricity bill.

1.2.1 Goals

- To develop an algorithm for the optimum scheduling of the household appliances or residential loads in order to maintain the total power demand of the house below the demand limit level imposed by the utility without violating the consumer comfort levels or the supply to critical loads.
- To develop load models for power intensive non-critical loads and monitor the operation of these loads with the control strategy of the proposed energy management algorithm

1.2.2 Objectives

- To develop the power intensive non-critical residential load models
- To develop the energy management algorithm based on the time varying demand limits and load priorities of the power intensive loads
- To analyze the effect of the demand limit levels on the performance of non-critical power intensive residential loads
- To use the algorithm for analysis of the various configurations of power intensive non-critical load management
- To analyze the algorithm in finding the proper level of demand limits which will not cause violations in the operational parameters of the controlled loads
- To calculate the cost savings that can be gained by using the developed energy management system for different pricing mechanisms

1.3 Key Assumptions and Limitations

In developing this energy management system (EMS) following assumptions are taken in to account.

- Home energy management system will receive the information on the time varying demand limits are imposed by the utility and typical demand limits are assumed
- A typical household data and load profile have been considered
- The time of use and real time electrical energy pricing are assumed

Following limitations will be considered in developing the energy management system in the scope of the project.

- The limit of demand response will not cause high load compensation during off peak hours
- A typical seasonal home load profile will be selected and it may vary with real conditions and geographical location
- Considered load priority may vary from consumer to consumer
- The energy management system will be developed for selected key appliances in household. Introduction of wide variety of appliances with different characteristics may affect the working operation of home energy management system and is needed to consider them in the algorithm

1.4 Literature Review

1.4.1 Composition of Electricity Demand

In many countries the residential sector plays a major role in the electricity demand. Due to the improved life-style and the increased income level, the consumers tend to use more and more electrical appliances which will ease their daily activities.

Figure 1.1 shows the electricity consumption of Norway in 2011 with respect to different consumer groups.

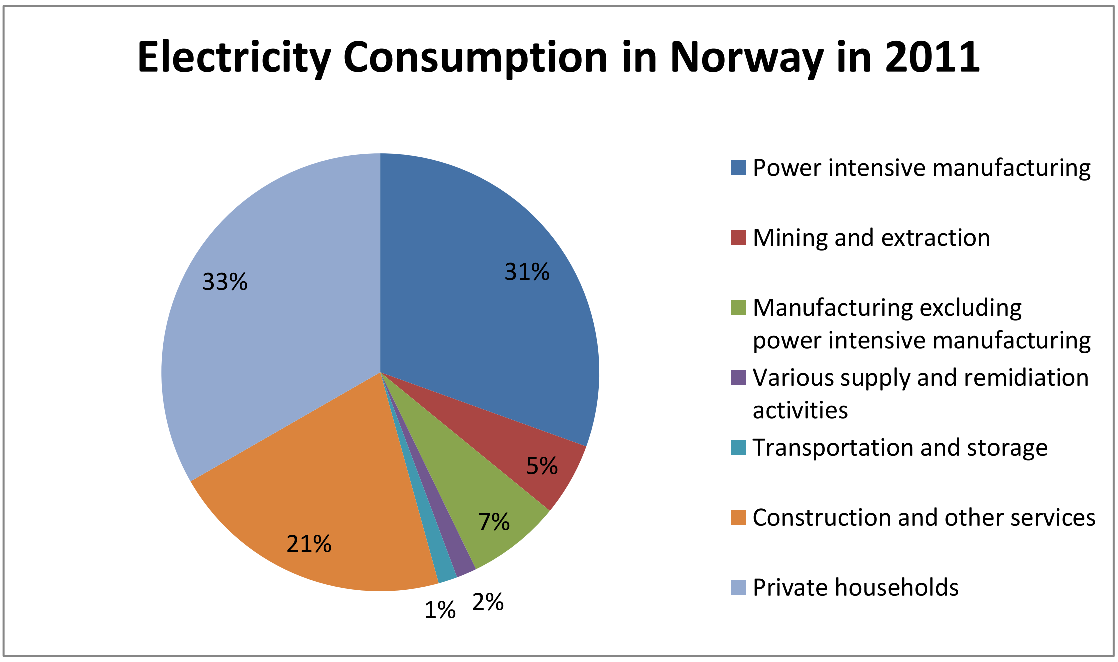


Figure 1.1: Electricity Consumption share of Norway in 2011 in which the energy demand of the household sector is 33 % [14]

According to Figure 1.1, the energy consumption in residential sector accounts 33 % which is a significant share of the total energy demand. It is clear that energy conservation in residential sector will affect to reduce the total power demand in the power system to a greater extent.

During the last decades, the residential electricity consumption has experienced a steep and a steady growth. The average size of a house has increased and the number of inhabitants has been decreased. In other words, there are more households per equal population. Each household needs at least the same basic apparatus, refrigerators, stoves, increasing the total household consumption [15]. Although the efficiency of the electric appliances has been improved, the electricity consumption has been increased as the number of appliances has been increased with rising standard of living. Figure 1.2 shows the growth of the household electricity from 1970 and the anticipated growth up to 2050.

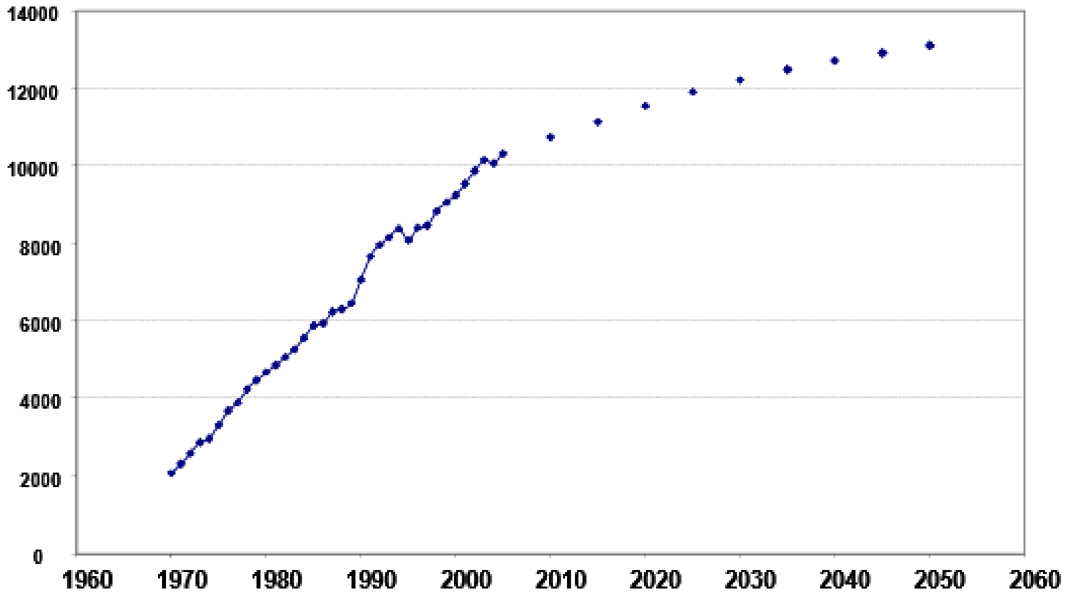


Figure 1.2: Annual Consumption of household electricity, excluding heating and domestic hot water. Historical development starting from 1970 and baseline future up to 2050 [Source: KTM 2007]

According to Figure 1.2, it can be seen that the demand for the electricity in domestic sector has increased steadily during last few decades. And also it is anticipated that this growth will continue in future as well. So the electricity providers must be able to meet this increasing demand and provide adequate network infrastructure.

1.4.2 Typical Daily Load Curve

The electricity consumption of an individual varies during the day and the combination of the energy demand of all the users produces a load pattern. The load pattern during a day is known as daily load curve and it has an irregular pattern. At some hours it has a very high value and at some periods it has a very low value. High demand periods are termed peak hours and low demand periods are known as off peak hours. Figure 1.3 shows a typical daily load curve for different electricity consumers. As shown in Figure 1.3, the residential demand during the middle of night (from 10 pm. - 6 a.m.) has a very low value. Demand in the residential sector during the middle of the day has not a very high value since many people are out. And the household demand has risen in the evening around 6 p.m. when people come home. In commercial buildings, demand has tailed off evenly from the middle of the day. It is clear that the aggregate demand of all the sectors has resulted an extended peak period from 2 p.m. – 6 p.m. as shown in Figure 1.3.

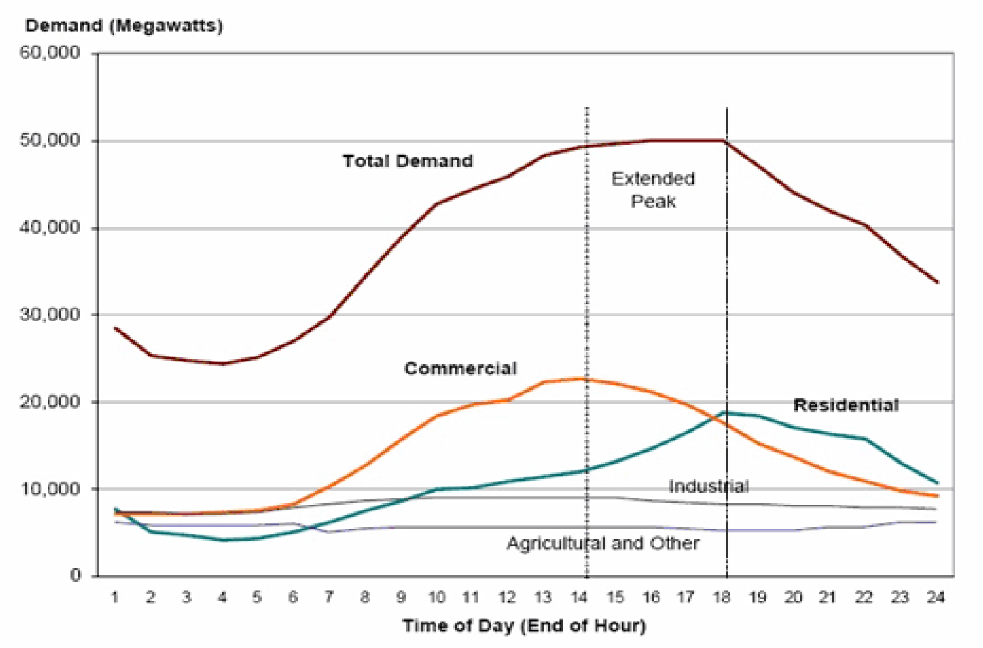


Figure 1.3: A typical load profile of different sectors [16]

Demand or energy use can be divided into “base load,” “intermediate load,” and “peak load” as shown in Figure 1.4.This helps to determine the type and quantity of power plants needed to produce the electricity at the right times. [17].

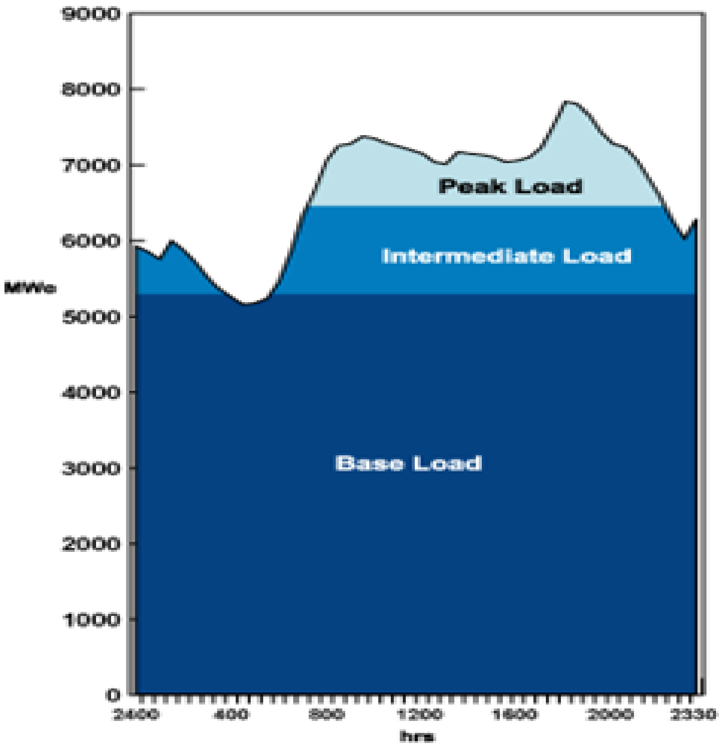


Figure 1.4: Different types of energy demand over the course of the day [18]

1.4.3 Peak Demand Growth

The peak demand of electricity has been increased during past decades and forecasts show that it will continue the growth in future as well.

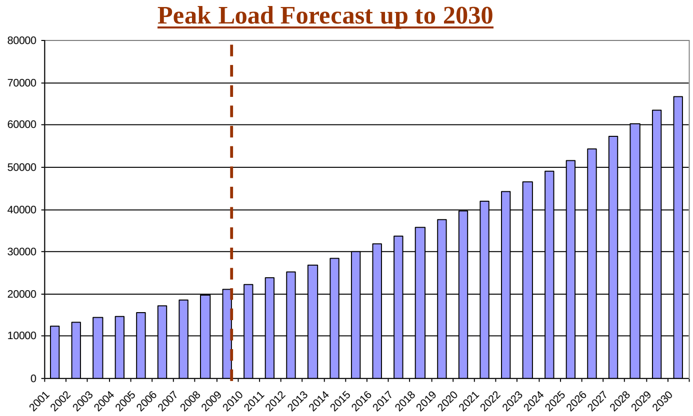


Figure 1.5: Growth of peak demand in electricity last decades and the forecasted growth [19]

According to Figure 1.5, the peak has increased intensely during the past and will increase even at a higher rate in future. The electrical power system should be able to meet this peak demand and if not it will result in blackouts. Although the average power demand is very much less than the peak demand, the transmission and distribution system should be designed to meet the peak demand.

1.4.4 Demand Response

As discussed in the above sections, the peak demand spikes in the grid occur for a very short period of time but regardless of that the utility must supply that demand to maintain the balance between the supply and the demand. To meet the peak demand, high cost generating stations are needed. Adding more generation was the solution strategy followed in the recent past to meet the rising electricity demand. But now the utility has paid their attention on demand side management to reduce the peak demand.

Demand response (DR) is a key concept in demand side management which helps to reduce the peak demand in critical situations. DR is 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 wholesale market prices or when system reliability is jeopardized” [20]. Load management is defined as “a set of objectives designed to control and/or directly or indirectly modify the patterns of electricity use of various customers of a utility to reduce peak demand”. This control and modification enables the supply system to meet the demand by making the best use of its available generation and transmission capacity [21].

To level the peak demand, three common load management strategies are used. Load shifting, peak clipping and valley filling are the load management strategies which are commonly used.

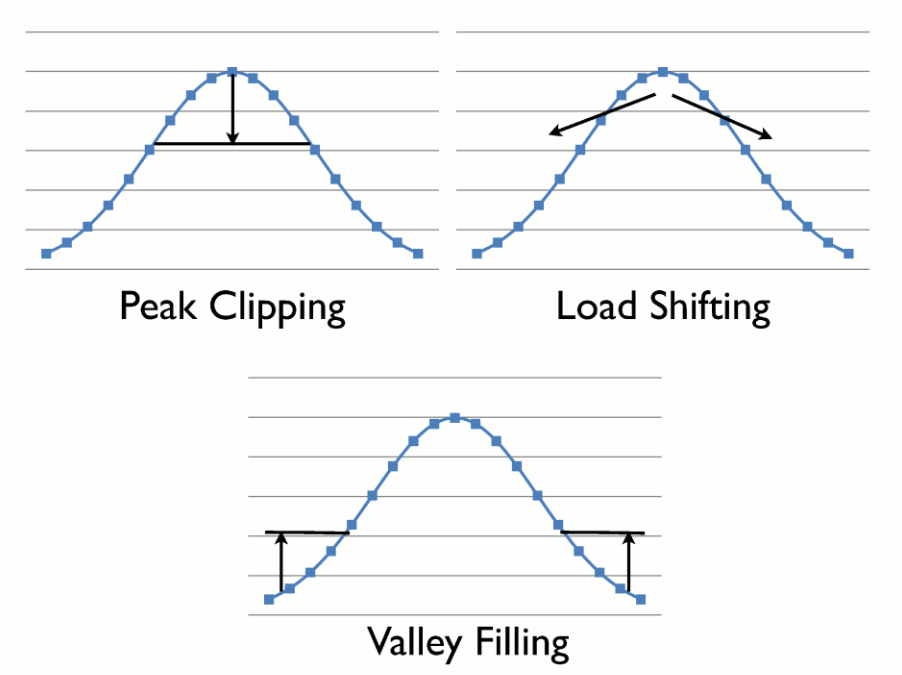


Figure 1.6: Load management strategies, peak clipping, load shifting and valley filling

Peak Clipping: Reduction of load during short usage peaks is known as peak clipping. Generally peak clipping is done by direct load control. In this method utility directly disconnects consumer appliances when a critical situation occurs. This direct control can be used to reduce capacity requirements, operating costs, and dependence on critical fuel [21].

Valley Filling: Building loads during off peak periods is known as valley filling. This will help to reduce the average price of electricity. One of the most promising methods of valley filling is off-peak industrial production, which displaces loads served by fossil fuels with electricity [21].

Load Shifting: Load shifting moves peak loads to off peak time periods without necessarily changing overall consumption. This method combines the benefit of peak clipping and valley filling by moving existing loads from on peak hours to off peak hours [21].

1.4.5 Benefits of Demand Response

In DR programs electricity consumers can play a major role in reducing peak demand during peak hours. The consumers can shift some of their loads to off peak hours and thereby help the suppliers to avoid power system failures and blackouts since it will reduce the probability of system stress conditions. Improving the energy security through DR will enhance the productivity of a country and increase customer satisfaction. DR will also help to eliminate the need of high cost peak generators and eventually reduce the electricity cost. Figure 1.7 shows the different plant mix used to provide the power demand based on their operating cost and the variation of average price with demand.

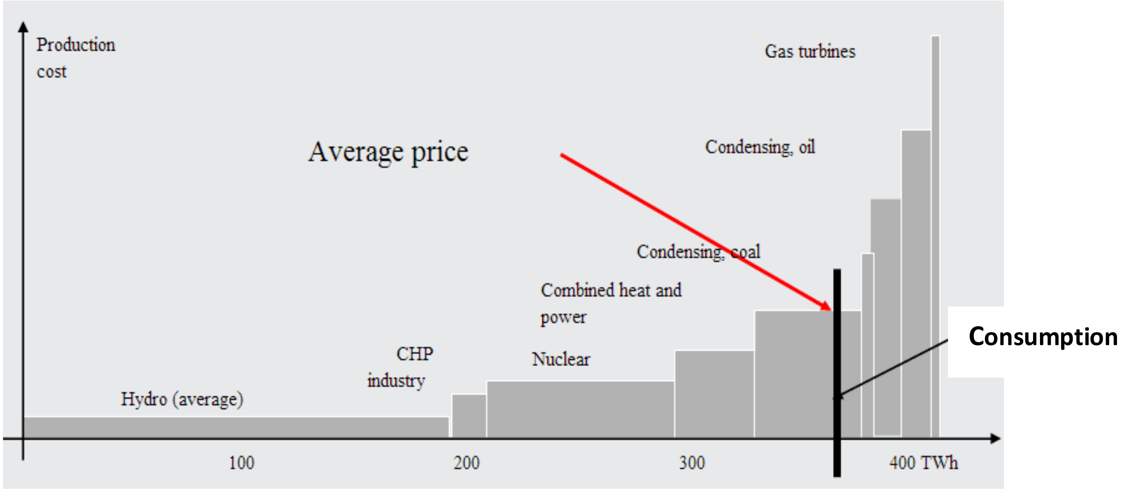


Figure 1.7: Determination of average price of electricity based on the production cost of plans in operation [22]

As shown in Figure 1.7, the average production cost is very low for base load power plants which operate almost 100% of the time. The production cost of gas turbines and other fossil fuel based power plants are very high and those plants are used only to meet the peak demand. It can be seen that with the growth of peak demand, the need of high cost peaking plants also increase and thus the average price of electricity. Reduction of fossil fuel based peak generating plants will also contribute to lower green-house gas emissions. To encourage the residential consumers to engage in DR programs, the utility can introduce time-based rates such as real time pricing, critical peak pricing and time-of-use pricing etc. which will change according in the cost of electricity production. To limit the demand level of the consumers, a method used earlier was direct load control (DLC) of selected appliances by the utility at critical situations. With DLC, the customers do not have any other option but to agree upon the grid operators decisions. But automated demand response allows the consumers to reduce their consumption during peak hours according to their preference, without compromising their comfort levels. Therefore in the consumer perspective and also in utility perspective DR have great benefits.

1.4.6 Challenges to Demand Response

In order to inform the consumers the real time data such as the demand curtailment request and the real time price, there should be a communication link between the utility and the consumers. With the possibility of two way communication in the smart grid concept, the real time data can be transmitted between the consumer and electric supplier. Consumers should be able to measure their demand in real time in order to respond during demand response events. Implementation of advance metering infrastructure (AMI) and other smart grid technologies will allow the user to measure real time power demand and further increase the use of DR resources in everyday operation [23]. And DR programs currently in use such as DLC does not provide flexibility in managing loads. Therefore, it is clear that there is a need of an automatic energy management system in DR programs which will provide consumers more flexibility.

1.5 Problem Solution

This work will develop an algorithm for managing the energy consumption of home appliances. To achieve this, power intensive residential loads will be modeled. The main focus of this work is to control selected power intensive load or appliances in order to maintain the power consumption below the demand limit levels imposed by the utility. The home energy management methodology will be developed by taking various load configuration in to account under Time of Use (TOU) and Real Time (RT) electrical energy pricing. This simulation tool will be developed in Matlab environment. Also it will analyze the impact of demand response on high off peak demand due to load management. The energy cost savings under TOU and RTP mechanisms which can be obtained through the developed EMS will also investigated.

1.6 Report Outline

This work is organized in to six chapters. The first chapter provides the background information on the selected problem and the motivation towards the selected problem. Problem statement, research objectives and goals followed by the literature review is also defined in this chapter.

In Chapter 2, the power intensive load models in the residential sector are explained with the technical parameters selected to develop these models.

The Chapter 3 is dedicated to the energy management algorithm in which the design requirements of the proposed algorithm are also included. Simulation tool used to validate the developed algorithm is also presented in this chapter.

The Chapter 4 describes the different electricity pricing mechanisms in the electricity market and provides the details of the typical pricing mechanisms used to evaluate the performance of the developed algorithm in electricity bill.

In Chapter 5, the simulation results obtained for the developed load models are presented and discussed. Then the scheduling of the operating time these loads to manage the household demand through the developed EMS is analyzed. Then a brief analysis is given to evaluate the electricity bill saving that can be gained through the EMS.

In Chapter 6, the main findings of this work are summarized and the relevance of the thesis work to the utility is pointed. Finally the important extension of the thesis is presented as future work.

In Appendix A, the developed simulation tool related to the work is attached. In appendix C, D, E and F, data referred in simulation is attached. Appendix G provides the enlarged referred graphs in Chapter 5.

Chapter 2

Domestic Power Intensive Load Models

In this chapter, domestic power intensive controllable load models are presented. The power intensive load models discussed in this chapter are water heater, air conditioner, clothes dryer and electric vehicle. And a typical random load profile which interprets the household critical loads is included.

2.1 Household Load Categorization

Electricity is used in household in many ways. Space heating/ cooling is the major consumer of household electricity. Water heating also plays a major role in household electricity consumption. Lighting has the third largest percentage of the electricity usage. Other electric appliances such as freezers, refrigerators, clothes dryers, kitchen appliances and entertainment devices account for the rest of the power consumption. A typical breakdown of electricity consumption in residential sector is shown in Figure 2.1. According to the figure, space heating accounts for 31% of the total household electricity usage and water heating accounts for 12%. Lighting and refrigeration account for 11% and 8% respectively. Clothes dryer also accounts for a considerable share of the total household electricity consumption. Although power consumption of the electric vehicle has not been included in this figure, it is included in this study as it will become a widespread application in the near future.

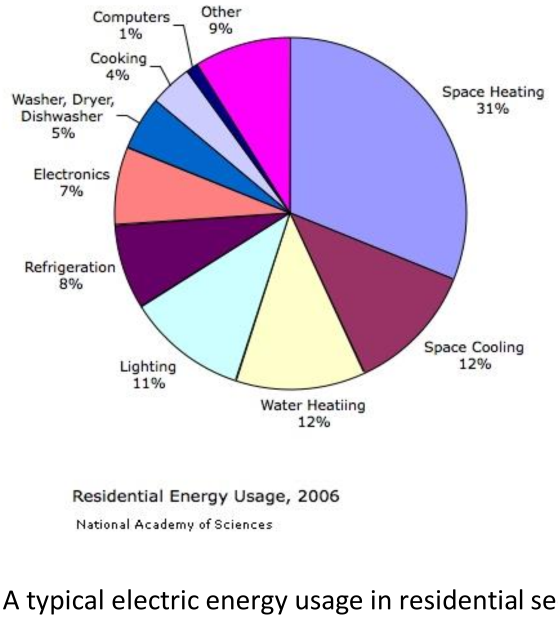


Figure 2.1: A typical electric energy usage in residential sector [24]

In this project, the household loads are divided in to two categories, non-critical or controllable loads and critical loads. Loads which are vital for the day today activities of the consumers such as cooking, refrigeration and lighting fall under critical loads. Controllable or non-critical power intensive loads can be interfered without noticeable effect to the consumer's lifestyle. The air conditioning (AC) unit, water heater, clothes dryer and the electric vehicle are the identified non-critical power intensive residential loads in this project. Since these power intensive loads account for a significant percentage of the total household demand, controlling these loads during peak hours will help to reduce the peak demand in the house.

In order to develop an algorithm to control the household electricity demand, first the power intensive non critical loads have to be modeled. The next sections describe how the considered power intensive non-critical loads are developed in accordance with [13].

2.2 Water Heater Load Model

In this work, water heater model is developed to determine the hot water temperature of the tank and power consumption of the water heater in each time slot *i (minutes)* .Flow chart of the water heater model is illustrated in Figure 2.2.

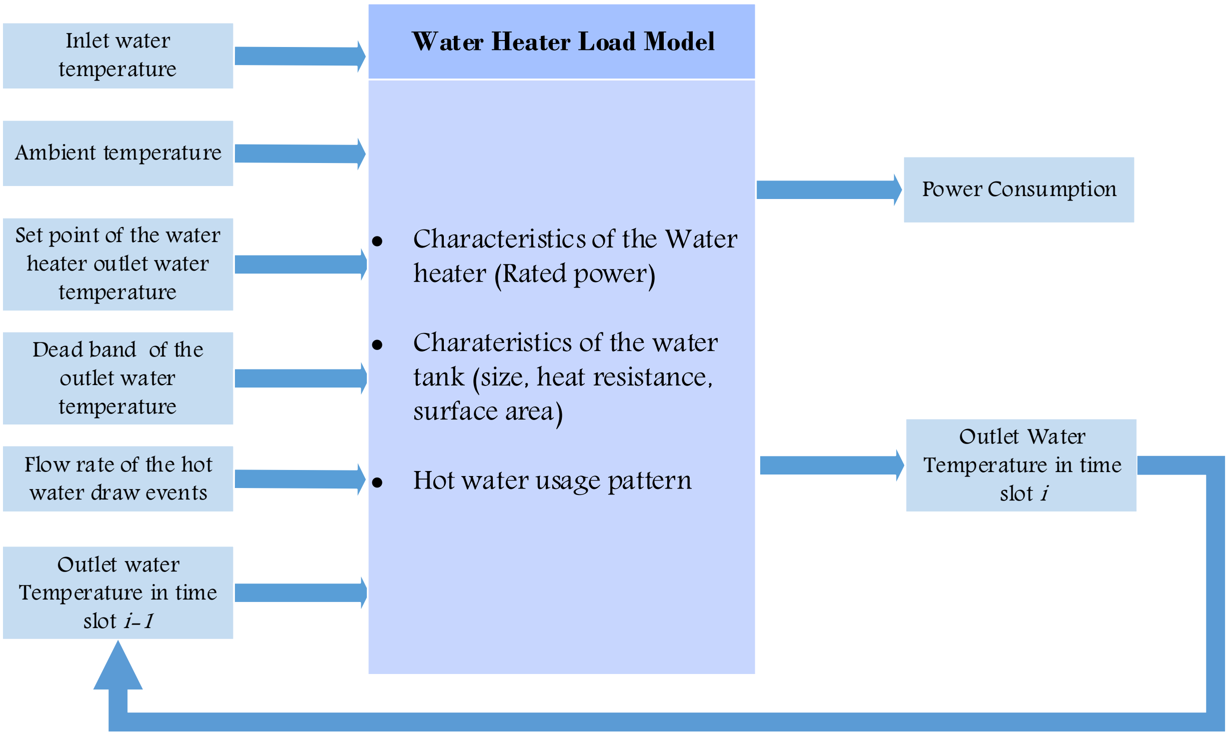


Figure 2.2: Flow chart of the water heater load model [13]

In the water heater, if the temperature of the water drops below the lower limit of the desired temperature range, then the heating coils are turned on and if the temperature of the water rises above the upper limit of the desired temperature range, the heating coils are turned off. If the temperature is within the desired range then the status of the coils are maintained as it is. This can be expressed as in (2.1).

$$W_{WH,i} = \begin{cases} 0 & T_{outlet,i} > T_{WH,s} \\ 1 & T_{outlet,i} > T_{WH,s} - \Delta T_{WH} \\ W_{WH,i-1} & T_{WH,s} - \Delta T_{WH} < T_{outlet,i} < T_{WH,s} \end{cases} \quad \textbf{(2.1)}$$

where,

$T_{WH,s}$	Hot water temperature set point of the water heater (°F)
$T_{outlet,i}$	Outlet water temperature in the tank (°F)
ΔT_{WH}	Lower tolerance of the hot water temperature (°F)
$W_{WH,i}$	Status of the water heater in the time slot *i*(minutes)

2.2.1 Power Demand of the Water Heater

Power consumption of the water heater in each time slot depends on the status of the water heater and the efficiency of the heater. It can be expressed as below [13].

$$P_{WH,i} = P_{WH} \times W_{WH,i} \times \eta_{WH} \quad \textbf{(2.2)}$$

where,

P_{WH}	Rated power of the water heater (kW)
$P_{WH,i}$	Power consumption of the water heater(kW) in time slot *i*
$W_{WH,i}$	Status of the water heater in time slot *i*
η_{WH}	Efficiency factor

2.2.2 Water Temperature of the Tank

Water temperature of the tank depends upon the hot water usage pattern, characteristics of the tank and characteristics of the water heating unit [13]. The outlet water temperature of the tank is determined from (2.2).

$$\begin{aligned} T_{outlet,i+1} = {} & \frac{T_{outlet,i}\,(V_{tank} - fr_i \times \Delta t)}{V_{tank}} + \frac{T_{inlet} \times fr_i \times \Delta t}{V_{tank}} \\ & + \frac{1\ gal}{8.34\ lb}\left[P_{WH,i} \times \frac{3412\ Btu}{kWh} - \frac{A_{tank} \times \left(T_{outlet,i} - T_a\right)}{R_{tank}}\right] \\ & \times \frac{\Delta t}{60\ \frac{min}{h}} \times \frac{1}{V_{tank}} \end{aligned} \tag{2.3}$$

where,

T_{inlet}	Inlet water temperature (°F)
T_a	Ambient temperature (°F)
fr_i	Hot water flow rate in time slot *i* (gpm)
A_{tank}	Surface area of the tank (ft^2)
V_{tank}	Volume of the tank (ft^3)
R_{tank}	Heat resistance of the tank (°F . $ft^2 . h/Btu$)
Δt	Duration of the time slot *i* ($hours$)
$P_{WH,i}$	Power consumption of the water heater(kW) in time slot *i*

2.2.3 Development of the Model

In this project, the data for the water heater model is selected referring a storage tank water heater for a typical house with three people. One minute time intervals are used in the implementation. Table 2.1 summarizes the data of water heater model which includes details of the water tank, water temperatures, power consumption and water usage patterns.

Table 2.1: Parameters for the water heater load model

Parameter	**Value**
$\boldsymbol{T_{WH,s}}$	118 °F [25]
$\Delta \boldsymbol{T_{WH}}$	10 °F
$\boldsymbol{T_{inlet}}$	68 °F (Assumed to be same as ground temperature) [26]
$\boldsymbol{T_a}$	T_i (Assumed to be same as the room temperature)
$\boldsymbol{fr_i}$	Appendix D1
$\boldsymbol{A_{tank}}$	14 ft^2
$\boldsymbol{V_{tank}}$	80 $gallons$ [27]
$\boldsymbol{R_{tank}}$	16 °F $. ft^2 . h/Btu$ [27]
$\Delta \boldsymbol{t}$	1 $minute$
$\boldsymbol{P_{WH,i}}$	4 kW
$\boldsymbol{\eta_{WH}}$	0.85

The ambient temperature is assumed to be same as room temperature is referred from air conditioning load model which is presented in Section 2.3.

2.3 Air Conditioning (AC) Load Model

AC unit load model is developed to determine the room temperature and the power consumption of the air conditioning load at each time slot. In order to determine the room temperature and power consumption in a given time slot, certain input parameters must be provided to the model and it depends upon built in parameters of the AC unit. The air conditioning model [13] flow chart with its inputs, outputs and model parameters are shown in Figure 2.3.

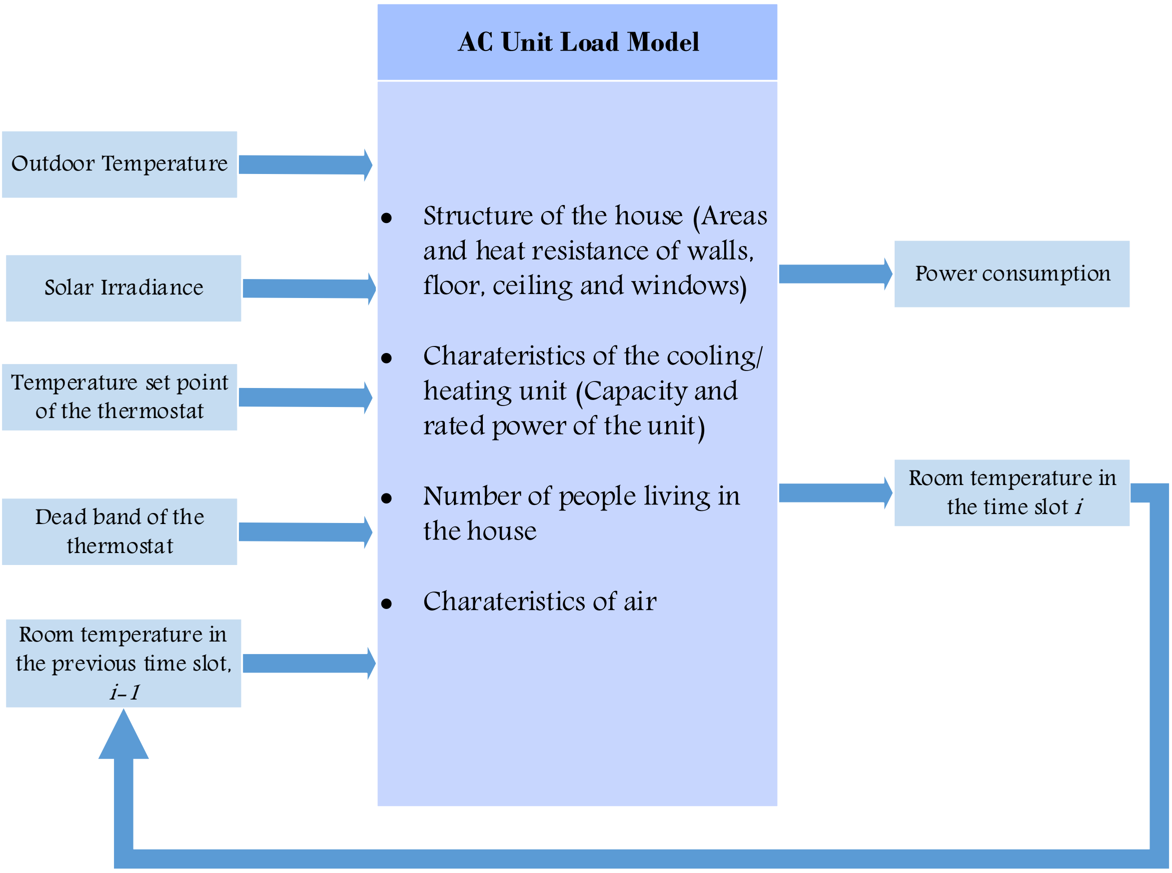


Figure 2.3: Flow chart of AC unit load model [13]

In an AC unit, a thermostat is used to maintain the temperature of the room within the predefined range. It controls the heat energy flowing in to or out of the unit to keep the temperature in the preferred range. In order to regulate the temperature, first it senses the room temperature and compares it with the set point. And then cooling or heating coils are switched on or off accordingly. A thermostat may switch on and off at temperatures either side of the set point .The difference between the upper or lower limit of the allowable temperature and the set point is called as the dead band or temperature deviation/differential. The set points and the temperature differential of an AC unit used for space heating are shown in Figure 2.4.

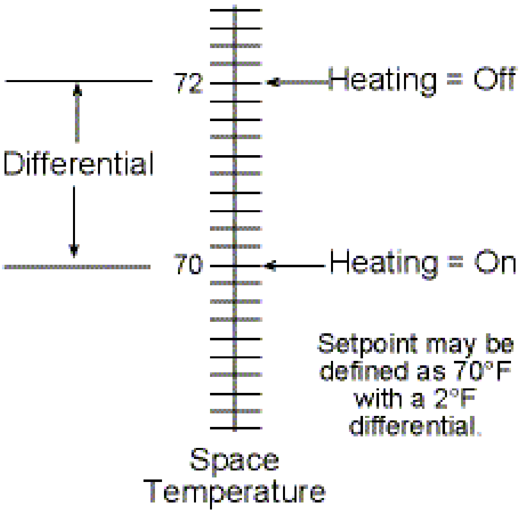


Figure 2.4: Thermostat set points and the temperature differential
in an AC unit used for space heating [28]

For an example in case of space cooling, if the room temperature sensed is above the upper limit of the allowable temperature range then the space cooling unit is switched on. So the room temperature drops and when it reaches the lower limit of the allowable temperature range, the cooling unit is switched off. Then the room temperature rises again and this cycle repeats. The status of the coils, $W_{AC,i}$ remain unchanged if it is within the allowable range.

When an AC unit is used for space cooling, the status of the cooling coils can be expressed as in (2.4).

$$W_{AC,i} = \begin{cases} 0 & T_i < T_{AC,s} - \Delta T_{AC} \\ 1 & T_i > T_{AC,s} + \Delta T_{AC} \\ W_{AC,i-1} & T_{AC,s} - \Delta T_{AC} < T_i < T_{AC,s} + \Delta T_{AC} \end{cases} \tag{2.4}$$

Similarly the status of the heating coils of an AC unit when it is used for space heating can be represented as in (2.5).

$$W_{AC,i} = \begin{cases} 1 & T_i < T_{AC,s} - \Delta T_{AC} \\ 0 & T_i > T_{AC,s} + \Delta T_{AC} \\ W_{AC,i-1} & T_{AC,s} - \Delta T_{AC} < T_i < T_{AC,s} + \Delta T_{AC} \end{cases} \tag{2.5}$$

where,

$W_{AC,i}$	Status of the AC unit in time slot *i*
T_i	Room temperature in time slot *i* (°F)
$T_{AC,s}$	Thermostat set point of the AC unit (°F)
ΔT_{AC}	Allowable temperature deviation/dead band of the AC unit (°F)

2.3.1 Power Demand of the AC Unit

The AC unit has two states either on or off. So when the unit is in the on status it consumes the rated power and when it is in the off state it does not consume any power. The electricity demand of the AC unit for any time slot, *i* can be expressed as in (2.6).

$$P_{AC,i} = P_{AC} \times W_{AC,i} \tag{2.6}$$

where,

P_{AC}	Rated power of the AC unit (kW)
$W_{AC,i}$	Status of the AC unit in time slot *i*
$P_{AC,i}$	Power consumption of the AC unit(kW) in time slot *i*

2.3.2 Room Temperature

The temperature of the room in each time slot depends on the capacity of the AC unit, heat gains or losses of the room and the temperature of the room in the previous time slot [13]. Equation (2.7) is used to calculate the room temperature, by taking these factors in to consideration.

$$T_{i+1} = T_i + \ \Delta t.\ \frac{G_i}{\Delta c} + \Delta t.\frac{C_{HV,AC}}{\Delta c}.W_{AC,i} \tag{2.7}$$

where,

T_i	Room temperature in time slot *i* (°F)
Δt	Length of the time slot *i* ($hours$)
G_i	Heat gain rate of the house during time slot *i* , positive value results in an increase in room temperature and negative value results in a decrease in room temperature (Btu/h)
$C_{HV,AC}$	Cooling/ heating capacity, positive for heating and negative for cooling (Btu/h)
Δc	Energy needed to change the temperature of the air in the room by 1°F ($Btu/$°F)
$W_{AC,i}$	Status of the AC unit in time slot *i*

Heat gain rate of the house, G_i depends mostly upon the air infiltration, solar irradiance and heating losses through walls, windows and ceiling [13]. Heat gain rate can be calculated as in (2.8).

$$G_i = \left(\frac{A_{wall}}{R_{wall}} + \frac{A_{ceiling}}{R_{ceiling}} + \frac{A_{window}}{R_{window}} + C_s \times \frac{ACH}{60} \times V_{house}\right) \times \left(T_{out,i} - T_i\right) + SHGC \times A_{window\_south} \times H_{solar} \times \frac{3.412\,\frac{Btu}{Wh}}{10.76\,\frac{ft^2}{m^2}} + H_p \times n_p \qquad \textbf{(2.8)}$$

where,

A_{wall}	Area of the wall (ft^2)
R_{wall}	Heat resistance of the wall ($°\mathrm{F}\,.ft^2.h/Btu$)
$A_{ceiling}$	Area of the ceiling (ft^2)
$R_{ceiling}$	Heat resistance of the ceiling ($°\mathrm{F}\,.ft^2.h/Btu$)
A_{window}	Area of the windows (ft^2)
R_{window}	Heat resistance of the window ($°\mathrm{F}\,.ft^2.h/Btu$)
C_s	Air sensible heat factor (Btu /$°\mathrm{F}.ft^3$)
ACH	Air changes per hour ($changes/h$)
V_{house}	Volume of the house (ft^3)
$T_{out,i}$	Outdoor temperature in time slot *i* (°F)
$SHGC$	Solar heat gain coefficient of windows
A_{window_south}	Area of the windows facing South (ft^2)
H_{solar}	Solar radiation power (W/m^2)
H_p	Heat gain from one person (Btu/h)
n_p	Number of people

Energy required to change the house temperature by 1 °F , Δc is calculated as below.

$$\Delta c = C_{air} \times \rho_{air} \times V_{house} \qquad \textbf{(2.9)}$$

where,

C_{air}	Specific heat capacity of air for a typical room condition (Btu /$°\mathrm{F}.ft^3$)
ρ_{air}	Density of air (lb/ft^3)
V_{house}	Volume of the house (ft^3)
Δc	Energy required to change the house temperature by 1 °F

2.3.3 Development of the Model

A typical single family house with dimensions of 76 ft *36 ft is considered in this study. The data in the Table 2.2 give a summary of a typical housing structure data, climatic data of a typical geographic location and AC unit characteristics which are cited from ASHRAE handbook [29]. A typical day in May is considered for this study and used in the developed model.

Table 2.2: Parameters for the AC unit load model

Parameter	Value
Δt	1/60 $hours$
$C_{HV,AC}$	33 000 Btu/h
A_{wall}	1564 ft^2
R_{wall}	12 °F . $ft^2 . h/Btu$
$A_{ceiling}$	2664 ft^2
$R_{ceiling}$	32 °F . $ft^2 . h/Btu$
A_{window}	228 ft^2
R_{window}	2 °F . $ft^2 . h/Btu$
C_s	1.177 Btu /°F. ft^3
ACH	0.5 $changes/h$
V_{house}	21312 ft^3
$T_{out,i}$	93 °F
$SHGC$	0.67
A_{window_south}	32 ft^2
H_{solar}	Appendix C
H_p	392.38 Btu/h
n_p	3
T_s	68 °F
ΔT	4 °F
C_{air}	0.24 Btu /lb. °F
ρ_{air}	0.075 lb/ft^3
P_{AC}	2.352 kW

2.4 Clothes Dryer Load Model

The inputs, outputs and the built in parameters for the clothes dryer model [13] are illustrated in Figure 2.5.

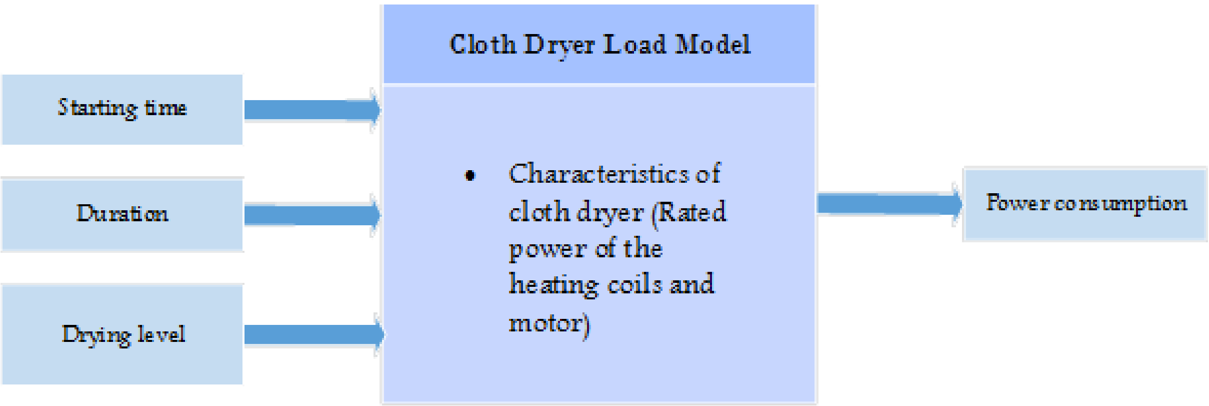


Figure 2.5: Flow chart of the clothes dryer load model [13]

For the clothes dryer model, the user inputs the required time for the drying operation. The clothes dryer operates until the accumulated time is less than the required duration.

$$W_{CD,i} = \begin{cases} 1 & T_{Accumilated} < T_{required} \\ 0 & otherwise \end{cases} \tag{2.10}$$

where,

$W_{CD,i}$	Status of the clothes dryer in time slot *i*
$T_{Accumilated}$	Accumulated time of the drying operation ($minutes$)
$T_{required}$	Required time/duration of the drying operation ($minutes$)

2.4.1 Power Demand of the Clothes Dryer

The clothes dryer consists of two parts, motor and heating coils. The power consumption of the dryer can be divided in to two as power consumption of the motor part and the power consumption of the heating coils. Power consumption of the clothes dryer in each time slot *i,* can be expressed as in the following equation.

$$P_{CD,i} = k \times P_{hc} \times W_{CD,i} + P_m \times W_{CD,i} \tag{2.11}$$

where,

$P_{CD,i}$	Power consumption of the clothes dryer (kW) in time slot *i*
P_{hc}	Rated power of the heating coils of the clothes dryer (kW)
k	Drying level (k= 1/M, 2/M,…., M/M)
M	Total number of drying levels
P_m	Power consumption of the motor part of the clothes dryer (kW)
$W_{CD,i}$	Status of the clothes dryer in time slot *i*

2.4.2 Development of the Model

A typical clothes dryer with total power consumption of 4 kW has been selected in this study and Table 2.3 summarizes the data used in the considered clothes dryer model.

Table 2.3: Parameters for the clothes dryer load model

Parameter	Value
$\boldsymbol{P_{hc}}$	3.7 kW [30]
$\boldsymbol{M}$	5
$\boldsymbol{P_m}$	0.3 kW [30]
$\boldsymbol{Start\ time}$	6 $p.m.$
$\boldsymbol{Duration}$	90 $minutes$

2.5 Electric Vehicle Load Model

With the electric vehicle load model, the charge state and the power consumption of the battery in each time slot *i,* can be determined [13]. The flow chart of the electric vehicle with inputs, outputs and built in parameters are shown in Figure 2.6.

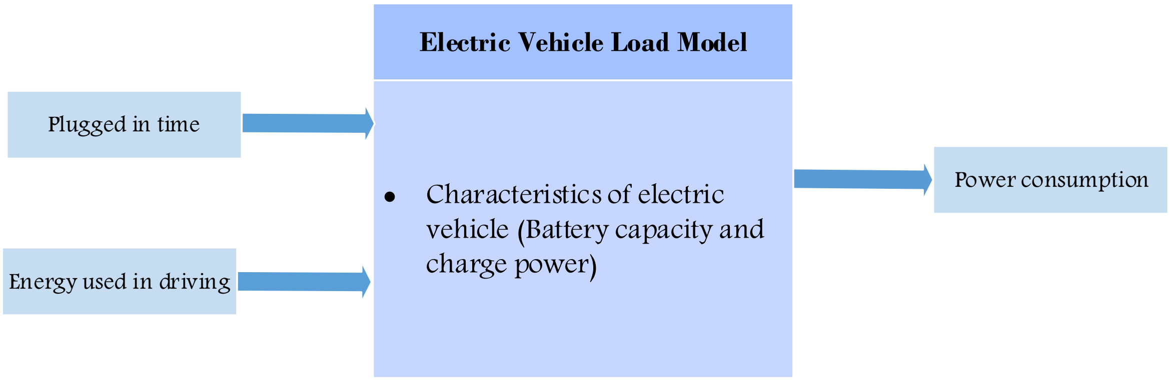


Figure 2.6: Flow chart of the electric vehicle load model

The status of the electric vehicle is determined as follow.

$$W_{EV,i} = \begin{cases} 1 & SOC_i < SOC_{max} \\ 0 & SOC_i \geq SOC_{max} \end{cases} \tag{2.12}$$

where,

$W_{EV,i}$	Status of the electric vehicle in time slot *i*
SOC_i	Charge state of the battery in time slot *i*
SOC_{max}	Charge state of the battery at fully charged condition

2.5.1 Power Demand of the Electric Vehicle

The power consumption of the electric vehicle can be obtained as in (2.13).

$$P_{EV,i} = P_{EV} \times W_{EV,i} \tag{2.13}$$

where,

$W_{EV,i}$	Status of the electric vehicle in time slot *i*
$P_{EV,i}$	Power consumption of the electric vehicle (kW) in time slot *i*
P_{EV}	Rated power of the electric vehicle (kW)

2.5.2 Electric Vehicle Charge State

Charge state of the battery in any time slot depends upon the charge state of the battery in the previous time slot, battery capacity and the charging rate. Initial charge state of the battery (i.e. battery state when the electric vehicle is plugged in), depends on the energy used for driving. Initial charge state can be obtained in accordance with the (2.14).

$$SOC_0 = 1 - \frac{E_{dr}}{C_{battery}} \tag{2.14}$$

Charge state of the battery at any time slot *i* can be determined as follow.

$$SOC_i = SOC_{i-1} + P_{EV} \times \frac{\Delta t}{C_{battery}} \tag{2.15}$$

where,

SOC_0	Initial charge state of the battery
SOC_i	Charge state of the battery in time slot *i*
SOC_{i-1}	Charge state of the battery in time slot *i-1*
E_{dr}	Energy used in driving (kWh)
$C_{battery}$	Rated capacity of the battery (kWh)
P_{EV}	Charge power of the electric vehicle (kW)
Δt	Length of the time slot *i* ($minutes$)

2.5.3 Development of the Model

It is assumed that the home owner has a Nissan Leaf electric vehicle and the data required for electric vehicle [30], [31] are tabulated in Table 2.4.

Table 2.4: Parameters for electric vehicle load model

Parameter	Value
$\boldsymbol{C_{battery}}$	24 kWh [31]
$\boldsymbol{P_{EV}}$	3.6 kW [32]
$\boldsymbol{\Delta t}$	1 $minute$
$\boldsymbol{Start\ time}$	6 $p.m.$

The energy used for driving is assumed as 15 kWh and the initial charge state is calculated with (2.14) as below.

$$SOC_0 = 1 - \frac{15\ kWh}{24kWh}$$

$$SOC_0 = 0.375$$

The initial charge state of battery is obtained as 37.5 % for the considered case.

2.6 Critical Loads

The critical loads of the household may include refrigeration, freezing, cooking, lighting and other electric appliances. A random profile which has a maximum value of 2 kW and a minimum value of 1 kW is selected in the simulation program. A typical load profile for the critical loads considered in this work is attached in Appendix B and the variation of the critical loads with time is shown graphically in Figure 2.7.

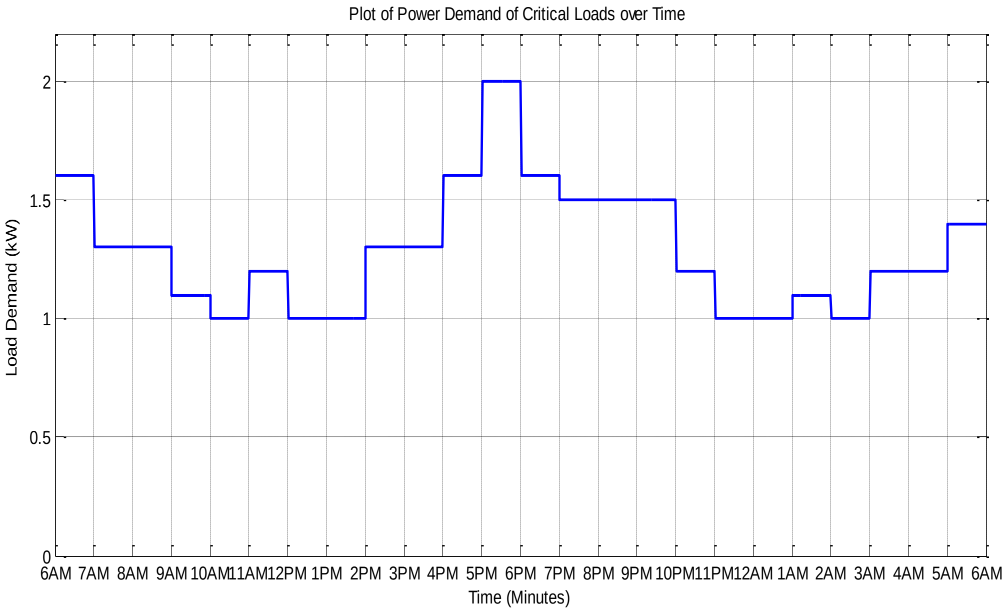


Figure 2.7: A typical variation of the critical loads in the household during a day with a maximum value of 2 kW and a minimum value of 1 kW

By referring the Figure 2.7, it can be seen that for the selected critical load profile, the maximum value of the critical load demand of 2 kW has occurred at 5 p.m. – 6 p.m. where everybody return home and start their household work. During the night where everybody is in bed and in the day time where most of them are out, a low value is selected for the critical load demand.

To obtain the optimum scheduling of power intensive non-critical during a DR event, EMS algorithms is developed by considering the time varying demand limits and load priorities. In the next chapter, the developed algorithm for the EMS is presented.

Chapter 3

Home Energy Management System Algorithm

This chapter mainly focuses on development of the energy management algorithm for reducing the household power demand. Power intensive non-critical load models which are presented in Chapter 2 are modified for demand response system. Development of the Matlab simulation tool to validate the power intensive non-critical load models and the EMS is also discussed in this chapter.

3.1 Design Requirements

The main focus of this project is to develop an algorithm for keeping the household energy consumption below a limit specified by the utility, during peak hours. By shifting the household energy consumption to off peak hours, the total demand of the power grid can be reduced during peak hours and thereby the probability of power grid failures as well as overloading of the network elements can be reduced. As a result, the electricity cost can also be reduced.

It is assumed that the demand limit levels imposed by the utility which may vary with time will receive by the energy management system through the smart meter installed in the house. The energy management system can manage only the controllable power intensive appliances which have a significant impact on household total energy consumption. The controllable loads considered in this project are AC unit, water heater, clothes dryer and electric vehicle. Although the electric vehicle is currently little widespread, it may have major impact on overloading of the distribution network as well as power generation in future as it is an emerging appliance. Therefore it also has been included in this project. Any critical load will not be controlled by the system and will operate without intervention.

In order to keep the household total demand below the demand limit levels, the household loads should be scheduled such that the total demand is below the specified limit at any time. To achieve this, operating time of some loads must be shifted to low demand periods without a demand limit level or a high demand limit. In shifting the loads the impact to customer lifestyle also has to be considered. So priority levels have to be assigned for the non-critical loads, according to the consumer preferences. During a demand response event, the loads will be shifted starting with the lowest priority load. Then the customers have more flexibility in operation of the electric appliances according to their preference while gaining electricity bill saving. Compared to direct load control methods, which are used to shed loads during peak hours, shifting household loads to off peak hours through energy management systems give consumers higher reliability and more flexibility.

3.2 Demand Response Enabled Load Models

If there is a demand response situation, the energy management system will set the demand response signal for each non-critical power intensive load by comparing the priority levels and the demand limit level. Consequently, the power consumption of the non-critical loads which are controlled depends on the demand response signal issued from the energy management system. When determining power demand of the controllable electric loads in each time slot, the energy management system's control signal will also be considered. The load models described in Chapter 2 are modified to enable them to operate in accordance with the home energy management control signals. The modified load models are summarized in the following sections.

3.2.1 Water Heater

The water heater model is described in Section 2.2. It is modified to incorporate with the developed EMS. If the water heater is needed to turn on to maintain the water temperature within the desirable range, a turn on request is sent to the EMS. When the EMS receives the request, it checks whether there is a demand limit imposed by the utility. If there is a demand limit, then it checks whether the total household power demand is below the demand limit. If it is below the demand limit, the EMS decides to turn on the water heater and sends the control signal to the water heater. If the total household power is greater than the demand limit, the EMS checks the status of controllable loads starting with the lowest the priority load. Then, starting from the lowest priority load, the EMS turns off of the controllable appliances which have lower priorities than the water heater, until the total power is below the demand limit level. And as soon as the total household power becomes less than the limit, the EMS decides to turn on the water heater and sends the corresponding control signal.

The demand response enabled load model for the water heater is as follows.

$$P_{WH,i} = P_{WH} \times W_{WH,i} \times \eta_{WH} \times D_{WH,i} \qquad \textbf{(3.1)}$$

where,

$P_{WH,i}$	Power consumption of the water heater in time slot *i* (kW)
P_{WH}	Rated power of the water heater (kW)
$W_{WH,i}$	Status of the water heater in time slot *i*
η_{WH}	Efficiency factor
$D_{WH,i}$	Control signal received by the water heater from EMS in time slot *i*

$$D_{WH,i} = \begin{cases} 1 & If\ EMS\ decides\ to\ turn\ on\ the\ water\ heater \\ 0 & If\ EMS\ decides\ to\ turn\ off\ the\ water\ heater \end{cases} \qquad \textbf{(3.2)}$$

3.2.2 AC Unit

Detailed AC model is presented in Section 2.3. If the AC unit has to be turned on to keep the room temperature within the user specified limits, accordingly a request is sent to EMS. Then the EMS decides whether to turn on or off the AC unit based on the defined operational priorities and demand limits to maintain the total power demand of the household below the considered demand limit levels. The demand response enabled AC unit model can be expressed as in (3.3).

$$P_{AC,i} = P_{AC} \times W_{AC,i} \times D_{AC,i} \tag{3.3}$$

where,

$P_{AC,i}$	Power consumption of the AC unit (kW) in time slot *i*
P_{AC}	Rated power of the AC unit (kW)
$W_{AC,i}$	Status of the AC unit in time slot *i*
$D_{AC,i}$	Control signal received by the AC unit from EMS in time slot *i*

$$D_{AC,i} = \begin{cases} 1 & If\ EMS\ decides\ to\ turn\ on\ the\ AC\ unit \\ 0 & If\ EMS\ decides\ to\ turn\ off\ the\ AC\ unit \end{cases} \tag{3.4}$$

3.2.3 Clothes Dryer

The cloth dryer model is discussed in detail in Section 2.4. If the user switches on the clothes dryer, a request is sent to the EMS and the EMS issues a control signal as based on the defined priorities and the considered demand limits. But in the clothes dryer model, only the heating coils are controlled by the EMS control signal. It is assumed that the motor is not controlled by the EMS as it cannot be turned on without human intervention once it is turned off. If the clothes dryer is switched on, the motor will continuously operate until the job is completely finished. As the motor consumes less power compared to the heating coils, the effect of not controlling the motor does not significantly impact the total household power demand. The modified demand response enabled clothes dryer model is as follows.

$$P_{CD,i} = k \times P_{hc} \times W_{CD,i} \times D_{CD,i} + P_m \times W_{CD,i} \tag{3.5}$$

where,

$P_{CD,i}$	Power consumption of the clothes dryer (kW) in time slot *i*
P_{hc}	Rated power of the heating coils of the clothes dryer (kW)
P_m	Power consumption of the motor part of the clothes dryer (kW)
$W_{CD,i}$	Status of the clothes dryer in time slot *i*
$D_{CD,i}$	Control signal received by the clothes dryer from EMS in time slot *i*
k	Drying level

$$D_{CD,i} = \begin{cases} 1 & If\ EMS\ decides\ to\ turn\ on\ the\ clothes\ dryer \\ 0 & If\ EMS\ decides\ to\ turn\ off\ the\ clothes\ dryer \end{cases} \quad \textbf{(3.6)}$$

3.2.4 Electric Vehicle

The electric vehicle load model is described in Section 2.5. The home energy management system will control the charging of electric vehicle when as per the priority and the modified demand response enabled electric vehicle power demand is as follows.

$$P_{EV,i} = P_{EV} \times W_{EV,i} \times D_{EV,i} \quad \textbf{(3.7)}$$

where,

$P_{EV,i}$	Power consumption of the electric vehicle *(kW)*in time slot *i*
P_{EV}	Rated power of the electric vehicle *(kW)*
$W_{EV,i}$	Status of the electric vehicle in time slot *i*
$D_{EV,i}$	Control signal received by the electric vehicle from EMS in time slot *i*

$$D_{EV,i} = \begin{cases} 1 & If\ EMS\ decides\ to\ turn\ on\ the\ electric\ vehicle \\ 0 & If\ EMS\ decides\ to\ turn\ off\ the\ electric\ vehicle \end{cases} \quad \textbf{(3.8)}$$

If the charging of the electric vehicle has to be set on hold due to a demand response event, then the EMS sends a control signal to electric vehicle and charging stops. If there is no violation in the demand limit, the EMS sends the control signal allowing the electric vehicle to charge.

3.3 Home Energy Management System Algorithm

The first step in home energy management is to establish the status of the household appliances. This means that, data received from the appliance monitoring and control units of each appliance are compared with set points or requirements. If it is not required to switch on any appliance, then no action is performed. If any appliance has to be switched on and if there is no demand limit level imposed by the utility, then the EMS decides to turn on the relevant appliance and issues a control signal. If there is a request from any power intensive controllable load and if the total household load is below the demand limit level imposed by the utility and then the EMS issues the control signal for turning on the appliance.

If the total household load is greater than the demand limit level at any given time, then the EMS will force the controllable loads to shift their operating time. The appliances are interfered starting with the lowest priority appliance until the total household load is lower than the demand limit imposed by the utility.

If any appliance has to be turned on and the total household power consumption is greater than the demand limit level, then the priority of that appliance will be checked with the appliances which are in on status, starting from the lowest priority load. If the priority of the appliance which needs to be turned on is greater than any appliance which is in on status then the lower priority load will be forced to shift its operating time. Checking the priority and forcing to delay the operating times of lower priority loads are continued until the appliance which has to turn on can be turned on without making the total household power consumption greater than the demand limit level.

So at a demand response event, the high priority loads will be allowed to operate if there is a request for operation, given that the total household power is less than the demand limit level. When such events occur, lower priority loads will be shifted to later time periods where the demand limit levels are high. In this way, the EMS will optimize the scheduling of the selected household loads while maintaining the total household power below the demand limit level imposed by the utility.

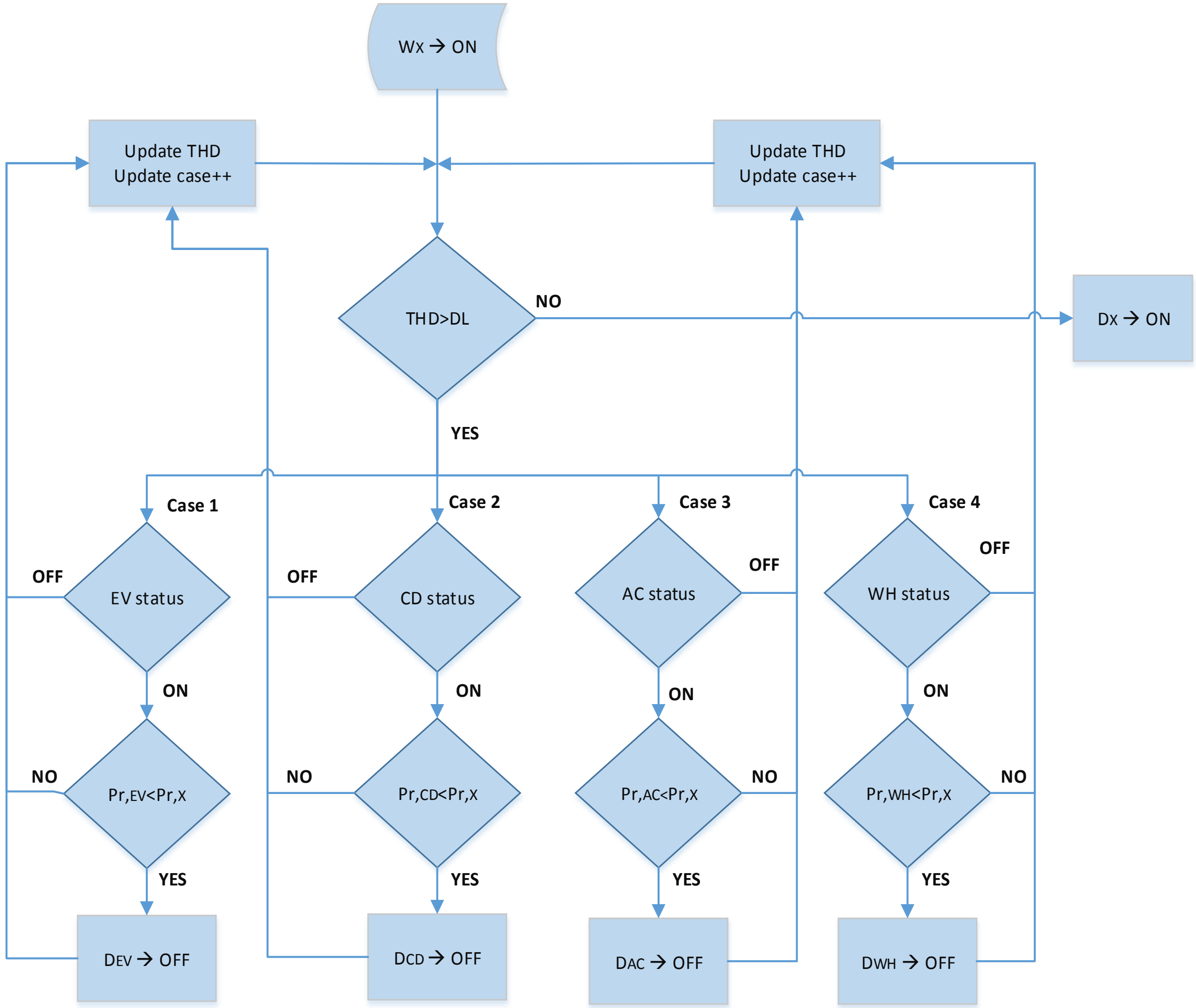
3.4 Development of the EMS Algorithm

The first step in developing the EMS is to model the power intensive non-critical loads. The controllable (non-critical) and critical load models are developed as described in Chapter 2 in Matlab environment. In order to develop the EMS, the priorities of the appliances must be defined and the priorities of the controllable loads used in this work are defined as in Table 3.1. The flow chart of the proposed EMS for the load priorities in Table 3.1 is shown in Figure 3.1.

Table 3.1: Controllable load priorities selected for the developed EMS

Controllable Loads	**Priority**
AC unit	1
Water heater	2
Cloth dryer	3
Electric vehicle	4

A Matlab program is developed for the proposed EMS algorithm by considering the operation of non-critical power intensive load models discussed in Chapter 2 and load priorities in Table 3.1. In this simulation tool, 24 hour period is taken in to consideration and the reference starting time is taken as 6 a.m. The operation of non-critical loads and the total household power demand with the control strategy of the EMS based on demand limits and priorities of the loads are observed and the obtained results are presented in Chapter 5.The complete Matlab program is attached in Appendix A.



Wx : Request to change status of non-critical appliance, x
THD : Total Household Demand
DL : Demand Limit
Pr,x : Priority of the non-critical appliance, x
Dx : EMS control signal to non-critical appliance, x
EV : Electric Vehicle
CD : Clothes Dryer
AC : Air Conditioning Unit
WH : Water Heater

Figure 3.1: Flow chart of the EMS algorithm assuming the load priorities as WH >AC >CD>EV (Table 3.1)

To promote the developed EMS easily among the domestic consumers there should be cost benefits which can be obtained by using this system. The developed algorithm can be used to reduce the electricity bill of the domestic consumers by using proper electricity tariff systems. Different electricity pricing mechanisms which can be used to emphasize the benefits of the developed EMS in electricity savings are discussed in the next chapter.

Chapter 4

Electricity Pricing Mechanisms

In this chapter, different electricity pricing mechanisms specially time of use and real time pricing are described. Various demand charging scenarios are used along with these pricing mechanisms. Typical energy prices are considered in doing the cost saving analysis on use of the developed energy management system.

4.1 Different Electricity Pricing Mechanisms

The wholesale electricity prices vary significantly from hour to hour. Since the cost to generate electricity is different for each power plant, the cost for generation of one kilowatt-hour (kWh) of electricity varies constantly, depending on the plants which operate and how cost effective those plants are [17]. At any given time, there are many generators in operation. The plants are operated according to an economic dispatch basis i.e. during low demand periods the power plants which have lowest operational cost will operate and with the increase of power demand other plants with low operational cost will operate. During very high peak periods the fossil fuel based power plants which has a high production cost have to be used to balance demand and supply. Therefore spikes in the wholesale electricity price occur during peak demand periods. As the production cost of electricity varies hour to hour, the cost of consuming electricity should vary accordingly. However, almost all end users nowadays are charged some flat-rate retail electricity price [33], [34], which does not reflect the actual wholesale price. Therefore the consumers use much more electricity during peak hours. The domestic consumers also use much higher amount of electricity during late afternoon where the demand of the power grid is high. The high peak-hour demand not only induces high cost to the retailers due to the high wholesale prices in those hours, but also has a negative impact on the reliability of the power grid [35]. Therefore it is needed to distribute the electricity consumption evenly during the day by demand response programs. The developed EMS algorithm can manage the household peak demand during peak hours. But to promote this algorithm, there should be a motivation and some cost savings for the domestic consumers.

Researchers have introduced electricity pricing mechanisms which reflect the actual electricity market prices, such as Time of Use (TOU) and Real Time Pricing (RTP). These schemes will encourage the users to shift their electricity consumption to off peak hours. Under the TOU tariff system, the electricity prices vary with the time of the day, the day of the week and season of the year. Usually a higher price is used for peak demand periods and a lower price for the off peak demand periods. And sometimes a third price which is between the high and lower prices is used for moderate demand periods. These prices are fixed for a few months mostly for a season, either for winter or summer. With the TOU pricing, as the consumers know the electricity prices for each time period during a day, they can shift some of their loads to off peak hours which has a low electricity price per kWh. Power intensive appliances such as air conditioners, dishwashers, cloth dryers and electric vehicles can be shifted to off peak periods and they will be able to reduce their electricity bill. But they should monitor their electricity consumption regularly and schedule the operation of these appliances which is not an easy task due to the complex life style. With the algorithms developed in this thesis less priority power intensive non-critical loads are automatically shifted to periods where the demand limit level imposed by the utility is high. The demand limits are selected by the utility based on the electricity prices. So the proposed EMS will help the consumer in reducing their bill.

The most accurate method of billing the electricity consumers is to use the retail electricity prices which fluctuate according to the marginal cost of producing electricity. This mechanism is known as Real Time Pricing (RTP). A comparison of TOU and RTP indicates that high resolution real-time pricing signals will carry on more real-time operation information of power systems, which would bring more benefits to power systems in terms of flattening the system load profile and reducing the peak demand as compared to TOU rates [36], [37]. Due to the potential benefits the real-time electricity pricing could bring to the demand side, consumers can optimally adjust their energy consumptions by participating into the demand response (DR) program for minimizing the electricity bill [37]. And with the two way communication backbone in smart grids, it is possible for consumers to communicate with the power provider and vice versa. The utility will inform of fluctuating hourly pricing data through the two way communication link or it is also possible to send these data through email or mobile phones to the consumer. The consumers have to monitor the fluctuating energy prices and schedule the electricity consumption. But the developed EMS can be used to automatically schedule the power intensive non-critical appliances based on the demand limit levels given by the utility and priorities specified by the consumer to reduce the electricity bill of the consumers if RTP is used for energy pricing.

The most severe problem that the electricity providers facing is the high value of peak demand. So aiming at reducing the peak demand, the utility has introduced a demand charge which measures the maximum value of the demand occurred during the billing period and charge for that value. So in addition to the energy cost, a demand charge also has to be paid by the consumer in such schemes. Even though peak demand in the household occurred for just few minutes, if the value of the peak demand is so high the consumer has to pay a high value of demand charge. In such schemes, the consumers tend to reduce their peak demand in order to reduce the electricity bill. This will eventually reduce the peak demand in the power system and reduce the risk of overloading transmission and distribution lines and also reduce the need of high-cost capacity increases. With the program developed in this project, the peak demand of the household can be maintained below the demand limits specified by the utility. Therefore, the demand charge will be constrained to a low value. So the consumers can reduce their expenditure on electricity bill by using the EMS where demand charge is also imposed in electricity tariff systems.

4.2 Inclusion of Pricing Mechanism in the Developed EMS

A typical TOU and RTP energy pricing mechanism are considered and included in the Matlab program developed for the EMS algorithm. The total household energy consumptions of the house with and without energy management system and the peak demand during the specified day are estimated in the Matlab program (Appendix A). The energy prices with considered electricity tariff systems are calculated with and without energy management system. The electricity prices are compared for the two cases and the electricity cost saving is calculated considering the various demand charge scenarios with TOU and RTP mechanisms.

4.2.1 Time of Use Energy Pricing

To calculate the energy prices under TOU energy pricing, a typical TOU tariff system is considered [38]. In the considered TOU pricing mechanism, 24 hours of the day is divided into three time periods and three different energy prices are used for these time periods. The peak demand period is defined from 2 p.m. to 7 p.m. and a high value of energy price is used during this period. Time between 7 a.m. - 2 p.m. and 7 p.m. - 11 p.m. are termed as off peak periods and an average price per unit of energy is used for this time period. During the super off period which starts from 11 p.m. and ends at 7 a.m. the energy prices are very low. The energy prices during each of these time period are illustrated in Figure 4.1.

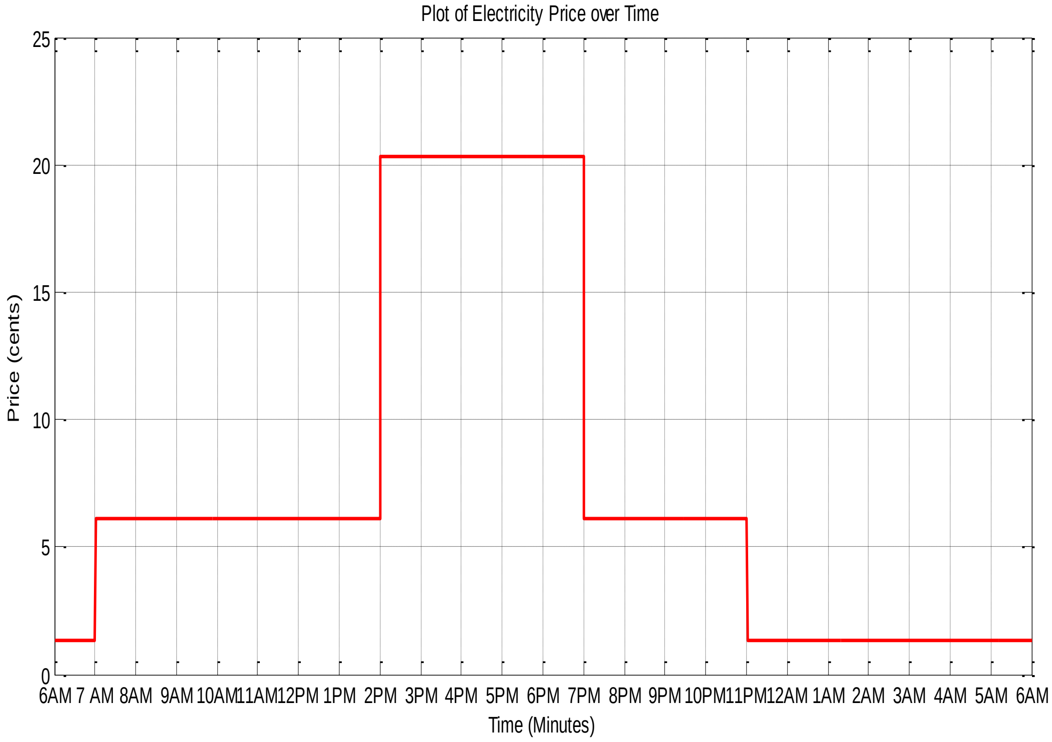


Figure 4.1: Variation of electricity prices with Time of Use energy prices tariff system

Table 4.1: Time of Use energy prices [28]

Period	**Time interval**	**Energy Price** (¢ per kWh)
On-peak period	2 p.m. – 7 p.m.	20.3217
Off-peak period	7 a.m. – 2 p.m. & 7 p.m.-11p.m.	6.1132
Super off-peak period	11 p.m.-7 a.m.	1.3063

4.2.2 Real Time Pricing

A typical hourly electric energy prices for a day are considered in estimating the energy saving that can be gained from the developed EMS. The considered hourly real time energy prices are attached in Appendix E and are illustrated in Figure 4.2[38].

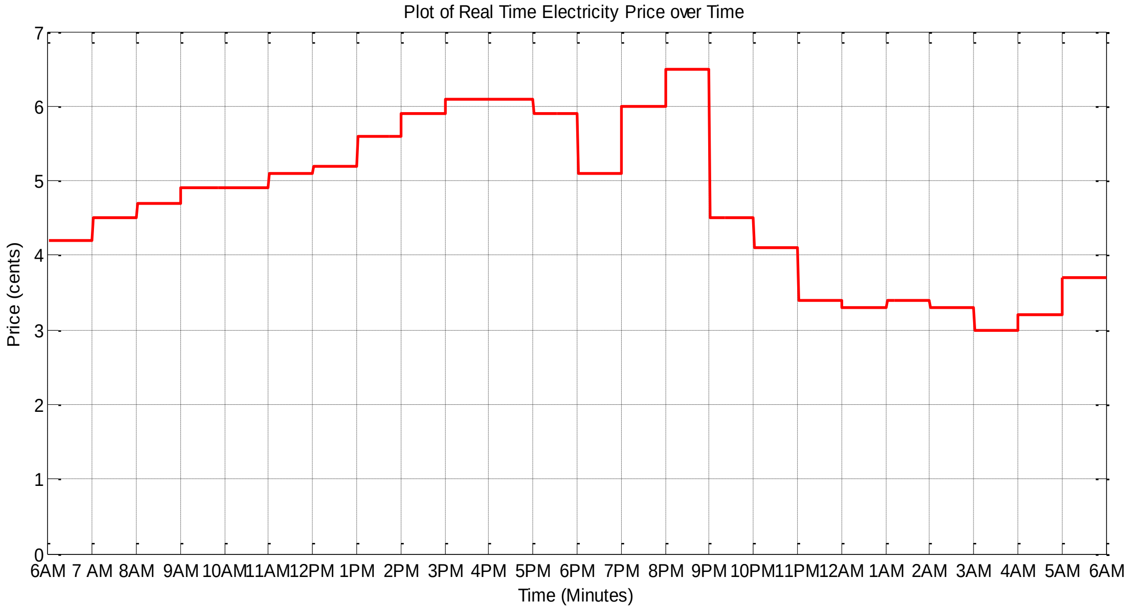


Figure 4.2: Real time electricity price variation [38]

According to Figure 4.2, the highest energy price occurs during 8 p.m. - 9 p.m. and energy prices are very low during 11p.m. - 6 a.m. It is quite clear that the there is a large gap between the highest energy price and the lowest energy price. So if the consumers tend to shift their energy usage to lower energy price periods they may gain a large electricity saving.

4.2.3 Peak Demand Charge

The peak value of the power consumed during the billing period is measured in kW and the demand charge is charged accordingly. In order to compare the results, it is assumed that the selected day has the peak demand in the chosen billing period. Three different demand charge scenarios are considered as below.

1. No demand charge
2. A fixed demand charge throughout the day
3. Time varying demand charges

A typical demand charge has been considered and for the fixed demand charge case it is 18.09 $ per kW [38]. In time varying demand charge profile, for the on peak hours 18.09 $ per kW is used and for the off peak period, 75% of the on peak demand charge is used. For the super off peak time period, the demand charge is assumed to be 50% of the on peak demand charge. By introducing three different demand charge values, the consumer will be motivated more to shift their peak demand power to off peak periods. The varying demand charge profile is shown in Figure 4.3.

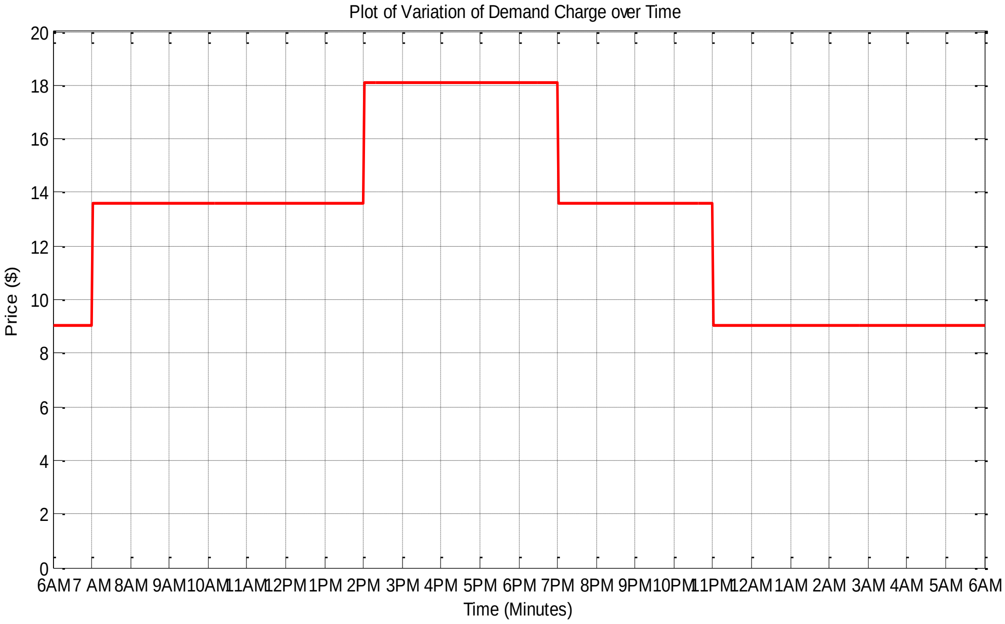


Figure 4 .3: Variation of peak demand charge over a day, a high demand charge during on peak hours and a moderate demand charge in off peak periods

4.2.4 Calculating the Electricity Bill

A Matlab code is developed and embedded in the developed simulation tool (Appendix A) for EMS to calculate the energy prices for the considered day. In the TOU energy pricing mechanism, energy used during each time period are calculated and is multiplied by the corresponding energy price for that time period. The values obtained for the considered three time periods are added together to find the energy cost for the considered day. In RTP, the energy used at each time slot is multiplied by the per unit price of the electricity at that time slot and added together. The Matlab program is developed considering one minute time intervals. Therefore RTP which vary for one minute time intervals can also be used in the developed simulation tool. If demand charges are also included in the bill, the peak demand during the day is found and if the demand charges are fixed then the peak demand is multiplied by the per unit demand charge. If the demand charge varies with time, then the time at which the peak demand has occurred is found and it is multiplied by the corresponding peak demand charge. It is assumed that the energy prices are same for each day throughout the billing period and the peak demand has occurred on the selected date. Other fixed electricity charges are excluded. The electricity bill for the month is as follows.

$$Bill = Energy\ Price\ per\ day * number\ of\ days\ in\ billing\ period + Peak\ demand * peak\ demand\ charge$$

The normal billing period is one month, so the number of days in the billing period is taken as 30 days.

The developed EMS in the Chapter 3 is used to manage the operating time of the power intensive non-critical loads discussed in Chapter 2, based on the time varying demand limits and load priorities of the consumer. The operational behavior of the non-critical loads due to the control strategy of proposed EMS is presented in the next chapter. The cost savings that can be obtained by using the developed EMS in the household are also discussed considering the electricity pricing mechanisms discussed in Chapter 4.

Chapter 5

Results and Discussion

This chapter provides the operational times of power intensive non-critical loads managed by the developed EMS considering time varying demand limits and load priorities for TOU and RTP mechanisms. The possible changes in the user behavior due to the RTP are also taken in to account. Five cases are analyzed and the energy cost saving that can be achieved through the developed EMS for these cases are also presented in this chapter.

5.1 Residential Controllable Loads

The power intensive controllable load models are presented in Chapter 2 and they are modeled in Matlab. The operation of these power intensive controllable loads is discussed in the following sections.

5.1.1 Water Heater

The water heater model is presented in Section 2.2. The various operational parameters of the water heater load model are given in Figure 2.2 and relevant values used in this thesis work are included in Table 2.1.In this water heater model, if the temperature of the water drops below the lower limit of the desired temperature value, then the heating coils are turned on. If the temperature of the water rises above the upper limit of the desired temperature, then the heating coils are turned off. If the water temperature is within the desired range, then the status of the water heating coils are maintained as they are.

The 24 hours operation of the water heater unit for the defined minimum and maximum limits of the water temperature are considered in this work. To illustrate the typical operation of the water heater load model, the time period from 6 p.m. to 12 midnight is considered and presented in Figure 5.1 In this work, it is assumed that a hot water draw event of 5 gpm occurs for a duration of 15 minutes at 7 p.m. and at 8 p.m. Around 9 p.m., 3 gpm of hot water usage with 10 minutes duration occurs. The water heater usage profile is given in Appendix D1. In this work, it is assumed that consumers will use hot water during the stated time periods due to availability of energy at relatively low cost.

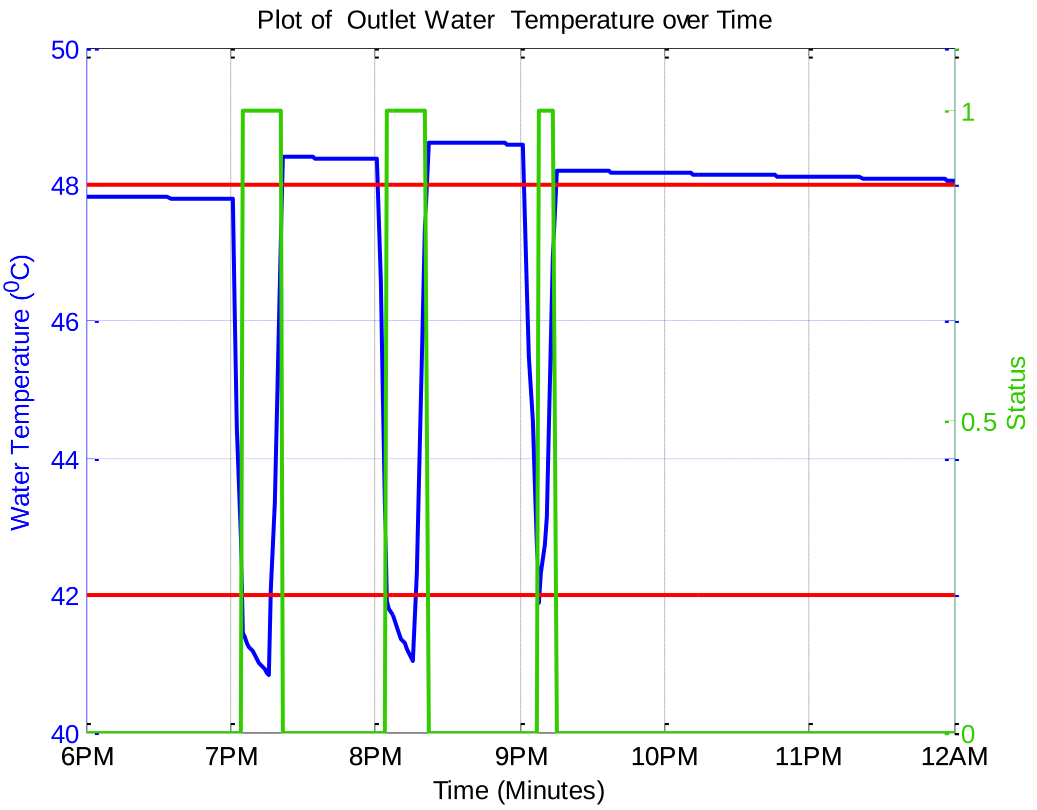


Figure 5.1: Outlet water temperature of the water heater with large water draw events at 7 p.m. & 8 p.m. and a moderate water draw event at 9 p.m.

When a water draw event occurs at 7 p.m., the outlet water temperature drops and reaches to its lower limit. As soon as the outlet water temperature reaches to the lower limit of the desired temperature range, the water heater is switched on to bring the outlet water temperature to the desired value. As a result, the outlet water temperature increases and when it reaches to the upper limit of the outlet water temperature (specified by the consumer), the water heater is switched off. At 7 p.m. and 8 p.m., the outlet water temperature drops dramatically due to mentioned large water draw events as in Figure 5.1. When the water temperature reaches to the lower limit of the preferred temperature, the water heater is switched on. But the water temperature drops further due to the high rate of water usage. At the end of the high water draw event the water heater controller has been able to bring the water temperature to the desired temperature range. The water temperature profile for the selected case is shown in Figure 5.1 in blue and the upper and lower limits of the customer specified water temperatures are shown in red. The green color graph shows the operational status of the water heater.

5.1.2 AC Unit

The AC model is presented in Section 2.3. The different parameters of this model are described in Figure 2.3. Typical values for these parameters used in this work are given in Table 2.2.The power consumption of the AC unit is managed by regulating the temperature. The 24 hours operation of the AC unit for the maximum and minimum limits of the temperature is considered and the typical operation of AC unit for the time period from 6 a.m. - 2 p.m. is given in Figure 5.2.

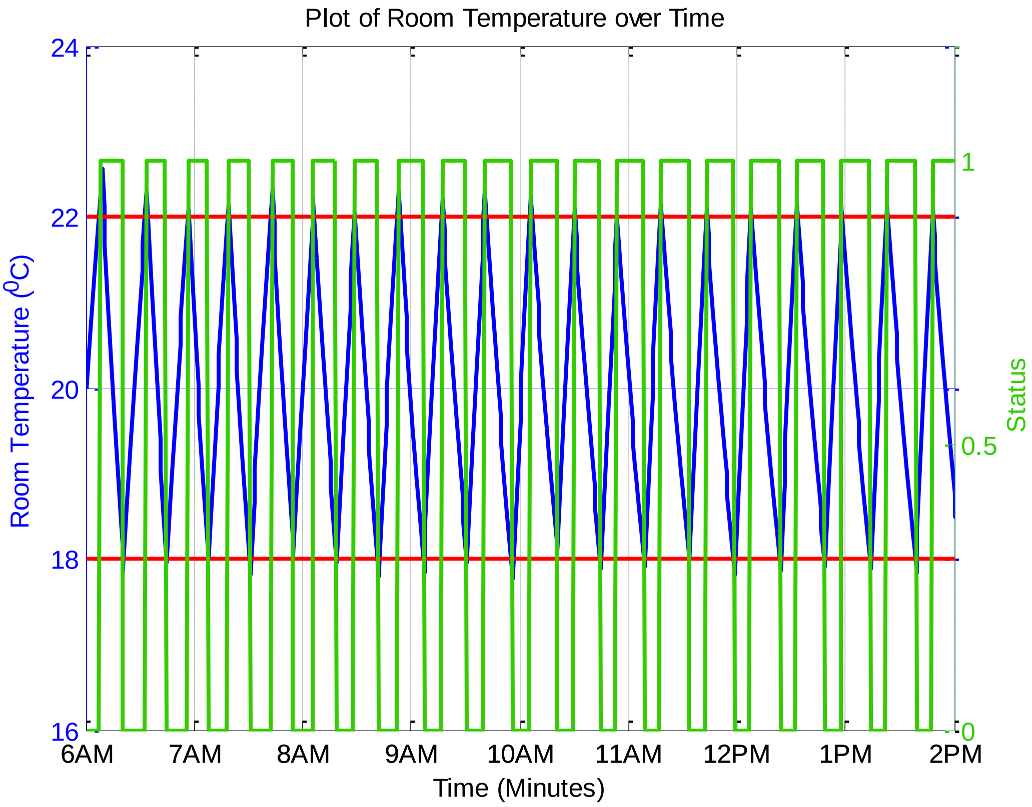


Figure 5.2: Regulation of the room temperature within the limits by the AC unit

For this AC unit, the set point of the room temperature is taken as 20 °C and the upper limit of the room temperature is kept at 22 °C whereas the lower limit of the desired temperature is kept at 18°C.These two limits of the room temperature has to be maintained during the operation of AC unit (shown in red lines in Figure 5.2).The variation of the room temperature is shown in blue in the Figure 5.2 and it can be seen that the room temperature is maintained within the preferred limits. In Figure 5.2, it can be seen that as soon as the room temperature reaches to the upper temperature limit, the AC unit is switched on and then the room temperature drops. When the temperature drops below the lower temperature limit, the AC unit is switched off again. This cycle is repeated throughout the day to maintain the room temperature within the desired limits. The operational status of the AC unit is shown with green in Figure 5.2.

5.1.3 Clothes Dryer

The clothes dryer model is explained in Section 2.4. The various operational parameters of the clothes dryer load model are given in Figure 2.5. As discussed, the power consumption of the clothes dryer is divided in to two parts as power consumption of the motor and power consumption of the heating coils. The technical parameters of the clothes dryer load are given in Table 2.3. In this work, it is assumed that the homeowner operates the clothes dryer at 6 p.m. in the evening and he specifies the duration of the drying job as 90 minutes (Table 2.3). The load demand curve of the clothes dryer is shown in Figure 5.3.

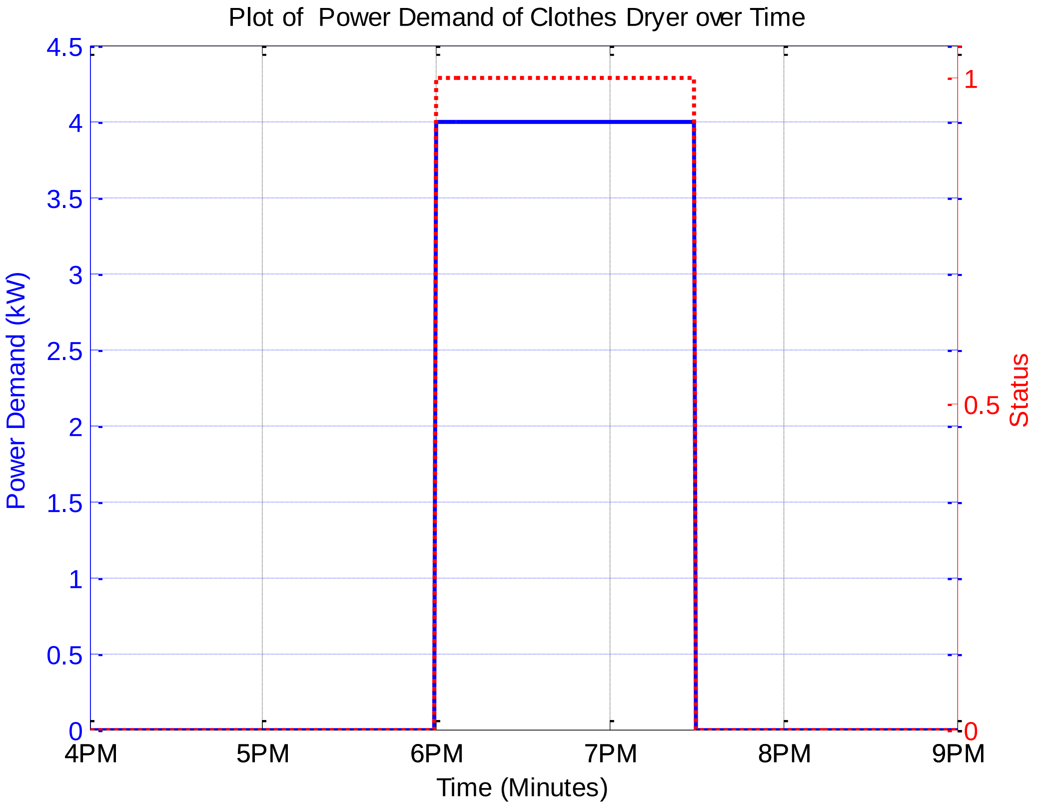


Figure 5.3: Power demand and status of the clothes dryer when a 90 minutes duration job occurs at 6 p.m.

When the homeowner switches on the clothes dryer and specifies the required time, the cloth dryer operates until the job is completed. In this study case, the clothes dryer has started at 6 p.m. and has completed its job at 7.30 p.m. The power demand of the clothes dryer during this event is shown in blue and the status of the operation of clothes dryer is shown in red dotted line in Figure 5.3.

5.1.4 Electric Vehicle

The electric vehicle load model is presented in Section 2.5. The various operational parameters of the electric vehicle load model are given in Figure 2.6. The technical parameters of the electric vehicle is given in Table 2.4.In this work, it is considered that the electric vehicle is plugged in at $6\ \mathrm{p.m}$ in the evening by assuming that it has an initial state of charge of 37.5% as specified in Chapter 2 (described in Section 2.5.3). The electric vehicle load curve with its charging profile is shown in Figure 5.4.

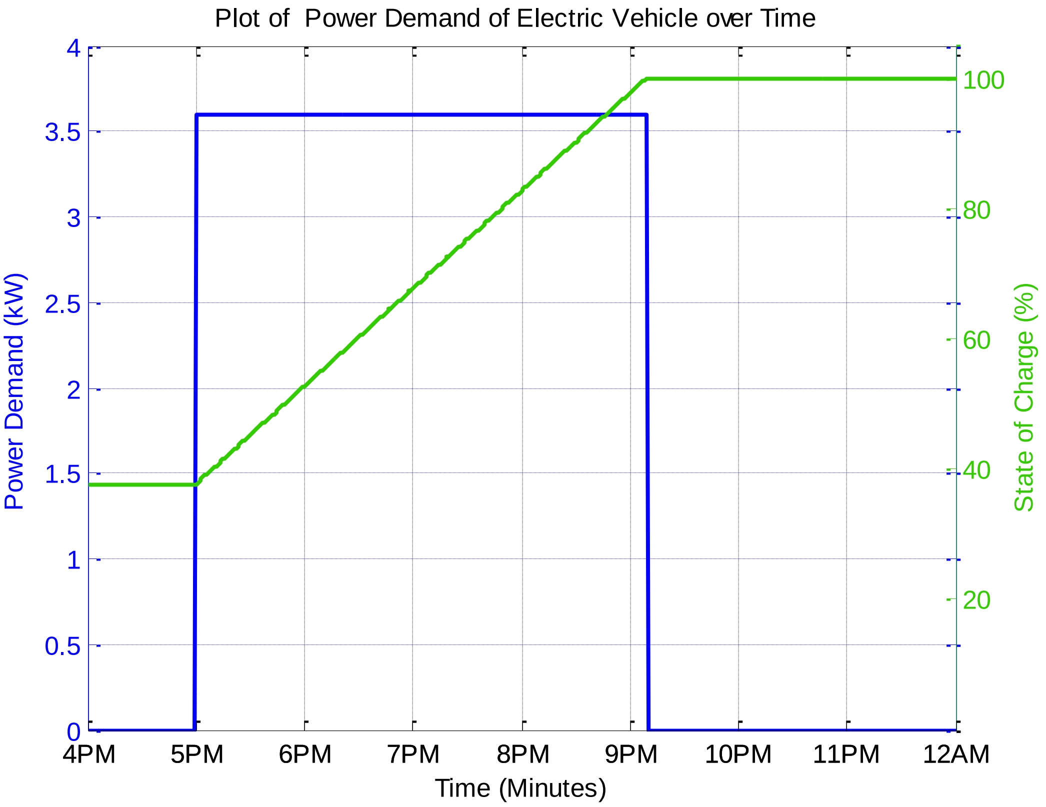


Figure 5.4: Charge state of the electric vehicle with 37.5% initial state of charge and plugged in at $6\ \mathrm{p.m.}$

It can be seen from Figure 5.4, that it has taken 4 hours and 10 minutes to fully charge the electric vehicle with 37.5% initial state of charge. In Figure 5.4, the power demand of the electric vehicle at each time interval is indicated in blue and the state of charge is shown in green.

5.2 Operation of the Non-Critical Loads with TOU Pricing (Case A)

In this section, the operations of power intensive non-critical loads with and without demand limits for various energy pricing mechanisms are considered. The operations of the non-critical loads are controlled by using the presented home energy management algorithm in Chapter 3. The home energy management algorithm has been given in Figure 3.1 for the selected load priorities. Various electricity pricing mechanisms (given in Chapter 4) has been considered in this EMS algorithm for finding the proper operational time of the controllable loads. The critical load profile for the all cases discussed in this section is shown in Figure 2.7.

5.2.1 Operation of the Non-Critical Loads without EMS for TOU Energy Pricing

In the following sections the operations of the non- critical loads are presented for TOU energy pricing without taking EMS control over these loads. The total household load profile obtained without EMS control over the controllable loads is also presented.

Water Heater

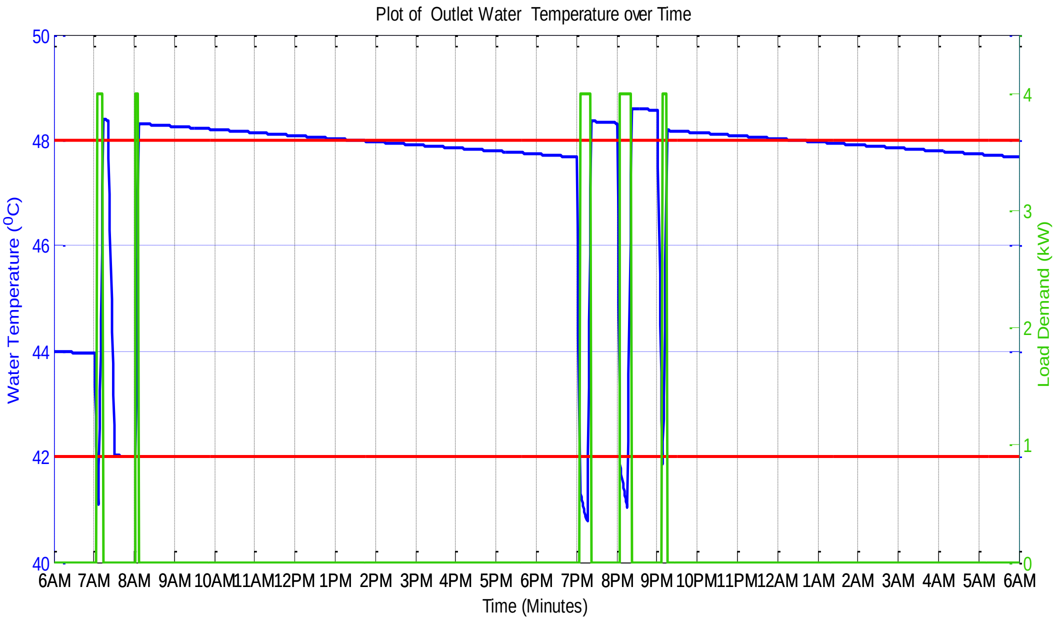


Figure 5.5: Outlet water temperature of the water heater without EMS control for TOU pricing

The operation of the water heater is described in Section 5.1.1 The 24 hours operation of the water heater for the defined minimum and maximum limits of the outlet water temperature is considered and the operation of the water heater during this time period is shown in Figure 5.5. In this figure, the desired limits of the outlet water temperature used in this work are shown in red and the variation of the outlet water temperature is shown in blue. Also the power demand of the water heater is shown in green.

AC Unit

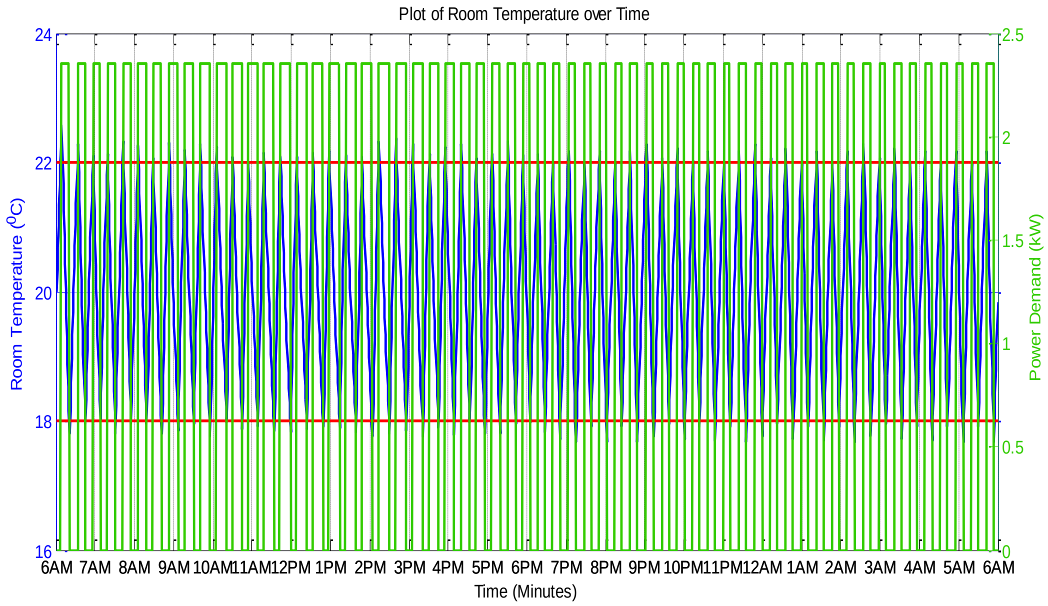


Figure 5.6: Operation of the AC unit without EMS for TOU pricing

The operation of the AC unit is described in Section 5.1.2. The 24 hours operation of the AC unit in a typical summer day for the defined minimum and maximum limits of the operating temperature and for the selected parameters is given in Figure 5.6.

Clothes Dryer

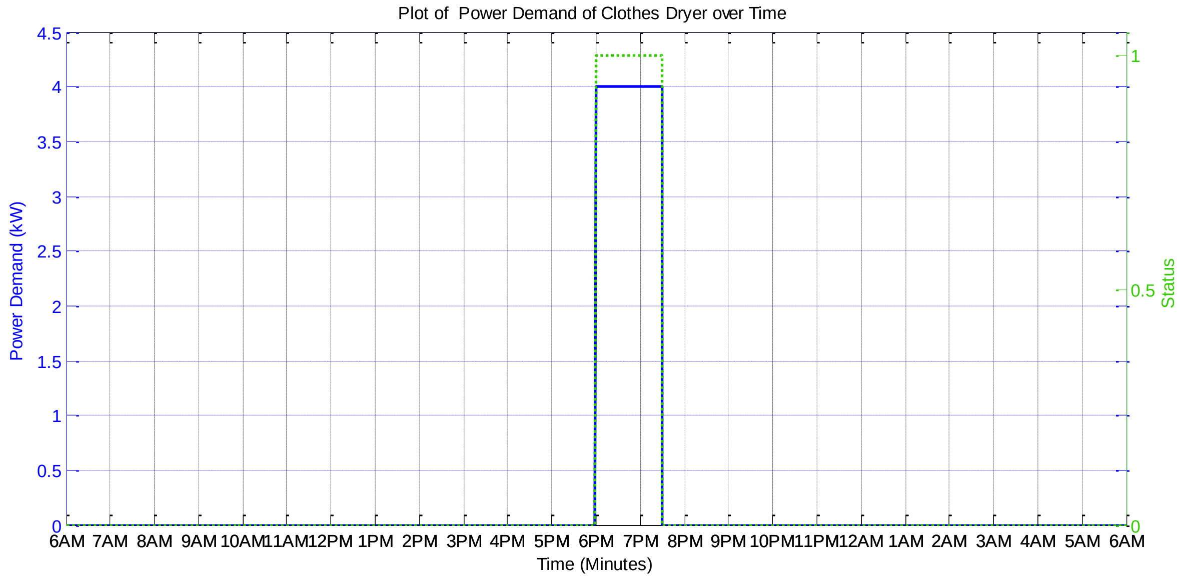


Figure 5.7: Operation of the clothes dryer without EMS control for TOU pricing

The operation of the clothes dryer is described in Section 5.1.3. The operation of the dryer for 24 hours is considered and is given in Figure 5.7. The power demand of the dryer is shown in blue and its operational status is shown in green in the Figure 5.7. As required by the consumer it will start operating at 6 p.m. and complete the job after 90 minutes.

Electric Vehicle

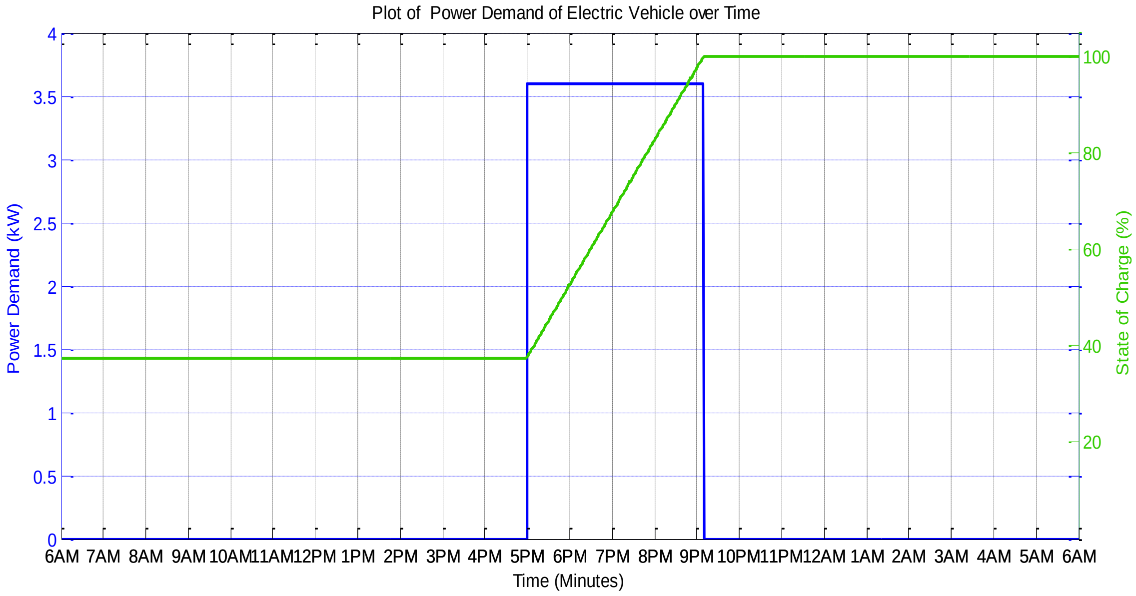


Figure 5.8: Operation of the electric vehicle without EMS for TOU pricing

The operation of the electric vehicle is described in Section 5.1.4 The 24 hours operation of electric vehicle considered is given in Figure 5.8. The power demand of the electric vehicle is shown in blue and the state of charge of the electric vehicle is shown in green in the Figure 5.8.

Total Household Load

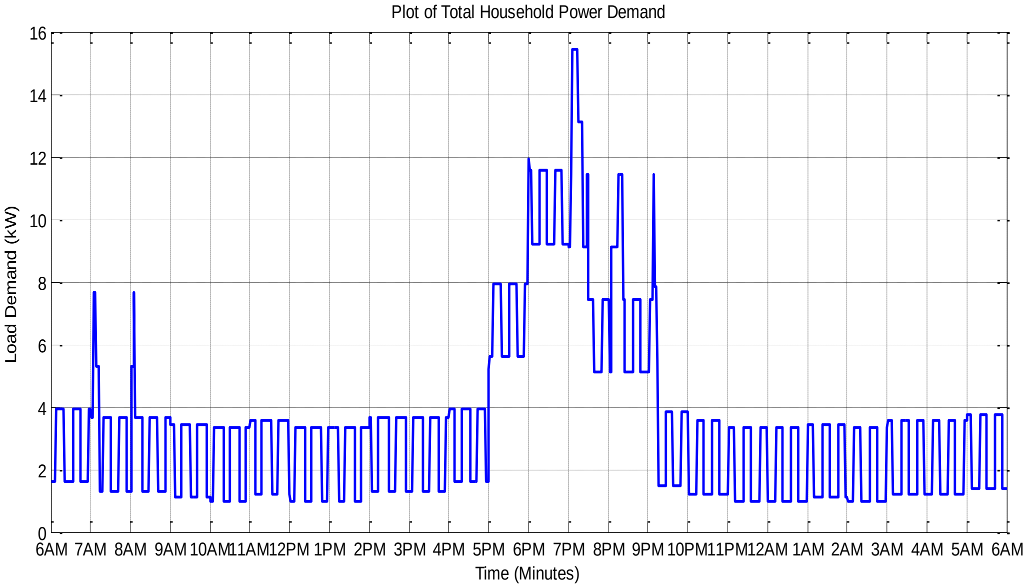


Figure 5.9: Total household load for 24 hours without EMS for TOU pricing

The total load curve for the household which includes the critical and non-critical loads without EMS for TOU pricing is shown in Figure 5.9. As shown in Figure 5.9, the maximum power demand of the household is 15.45 kW and it occurs during 7.05 p.m. – 7.14 p.m. The total energy consumption of the selected day which is obtained using the graph in Figure 5.9 is 84.53 kWh. Typical average electricity energy consumption of the household in this case is 3.52 kWh and the load factor is 22.8%.

5.2.2 Operation of the Non-Critical Loads for TOU Energy Pricing with EMS

The operations of the non-critical loads which are controlled by the developed EMS with the demand limits in Table 5.1 are discussed in the next section. The demand limits are selected based on the TOU pricing explained in Section 4.2.1. The load curve of the house with EMS is also discussed in the next section.

Table 5.1: Demand limit levels used in EMS for different time intervals in TOU tariff system

Time Duration	Demand limit level (kW)
7 a.m. – 2 p.m.	8
2 p.m. -7 p.m.	5
7 p.m. -11 p.m.	8.5
11 p.m.-7 a.m.	-

The time period from 2 p.m. - 7 p.m. is considered as on-peak period where the peak demand of the electricity in the grid is high. As a result, the cost of electricity is also high during that period. Therefore, utility expects domestic consumers to lower their electricity consumption during that period. Therefore, a lower demand level is used for that period which will not violate the desired operating limits of the non-critical loads. As the peak demand as well as the cost of electricity during the night time is low, no demand limit is imposed after 11 p.m. until 7 a.m.

Water Heater

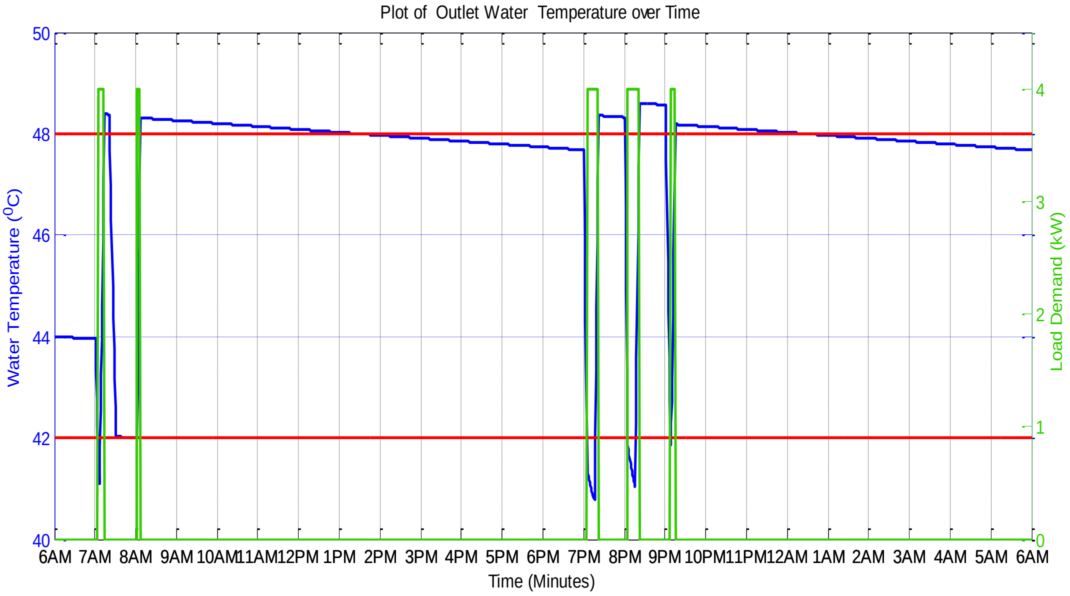


Figure 5.10: Operation of the water heater with EMS for TOU energy pricing mechanism

In this case of TOU energy pricing with stated time varying demand limits, the operation of water heater is given in Figure 5.10. This figure gives the operational time of the water heater as specified in Section 2.2 and the variation of hot water temperature due to hot water consumptions within considered hot water temperature limits.

AC Unit

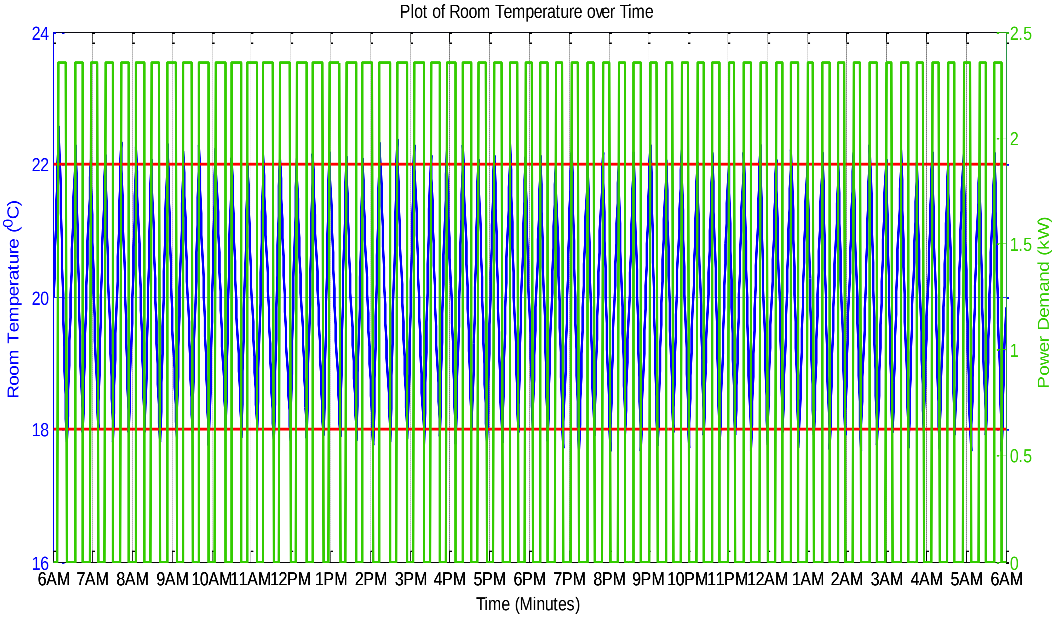


Figure 5.11: Operation of the AC unit with EMS for TOU pricing

The operation of the AC unit after imposing demand limits in EMS algorithm is given in Figure 5.11.It shows that the on and off operation of the AC unit and the temperature variation which is managed within the desired temperature limits.

Clothes Dryer

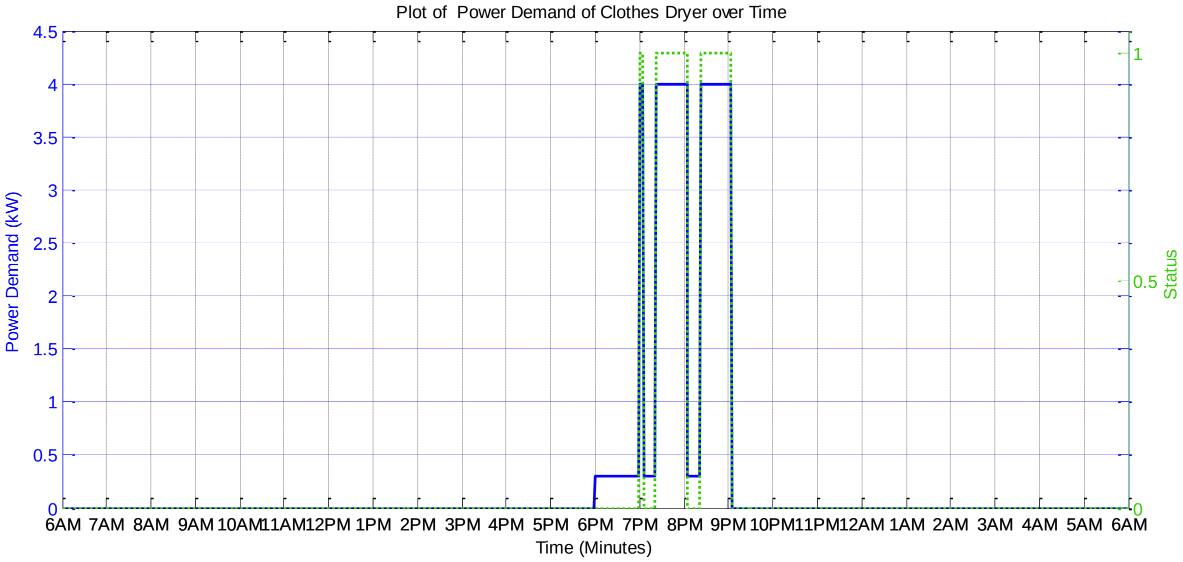


Figure 5.12: Operation of the clothes dryer with EMS for TOU pricing

The clothes dryer operation for considered TOU energy pricing with mentioned time varying demand limits are given in Figure 5.12. The clothes dryer parameters and operational time are discussed in Section 2.4. The operation of the dryer has been started at 6 p.m. as specified by the user but due to demand limit, the heating coils of the clothes dryer are started (The operation of the electric motor has started but not the heating coils). Operation of the heating coils has been controlled through EMS algorithm by considering the demand limits as well as load priorities (refer Table 3.1 & Figure 3.1).It is observed through Figure 5.12 that the heating coils of the clothes dryer are started at 7 p.m. for a short time as the total household load demand is less than the corresponding demand limit at time. Then in the next few minutes heating coils of the clothes dryer are paused allowing the water heater to operate. In the next two hours clothes dryer heating coils with motor are operated when the water heater is not in operation and finishes its job around 9 p.m.

Electric Vehicle

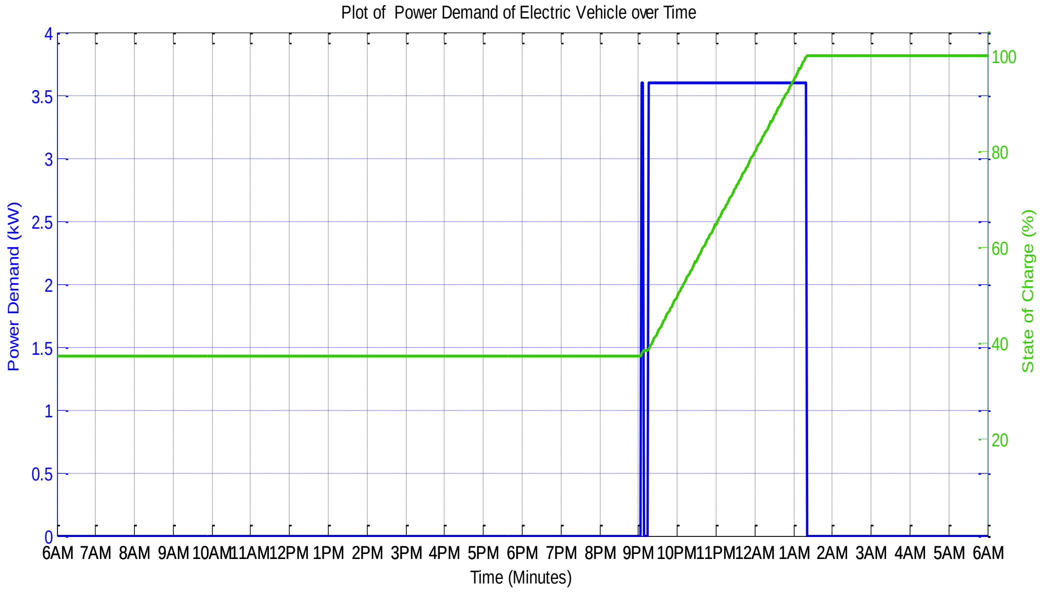


Figure 5.13: Operation of the electric vehicle with EMS for TOU pricing

The operation of the electric vehicle for this case is presented in Figure 5.13. The technical parameters of the electric vehicle are given in Section 2.5. The charging of the electric vehicle has to be started at 6 p.m. but by considering the EMS algorithm with demand limits and priorities of the loads it has started charging around 9 p.m. It is observed in Figure 5.13, at 9.04 p.m. when the clothes dryer completes its job, the electric vehicle starts charging. But after a few minutes as water heater has to be turned on, the charging of the electric vehicle is paused. After the water heater is turned off, the charging operation commences and completes charging around 1.30 a.m.

Total Household Load

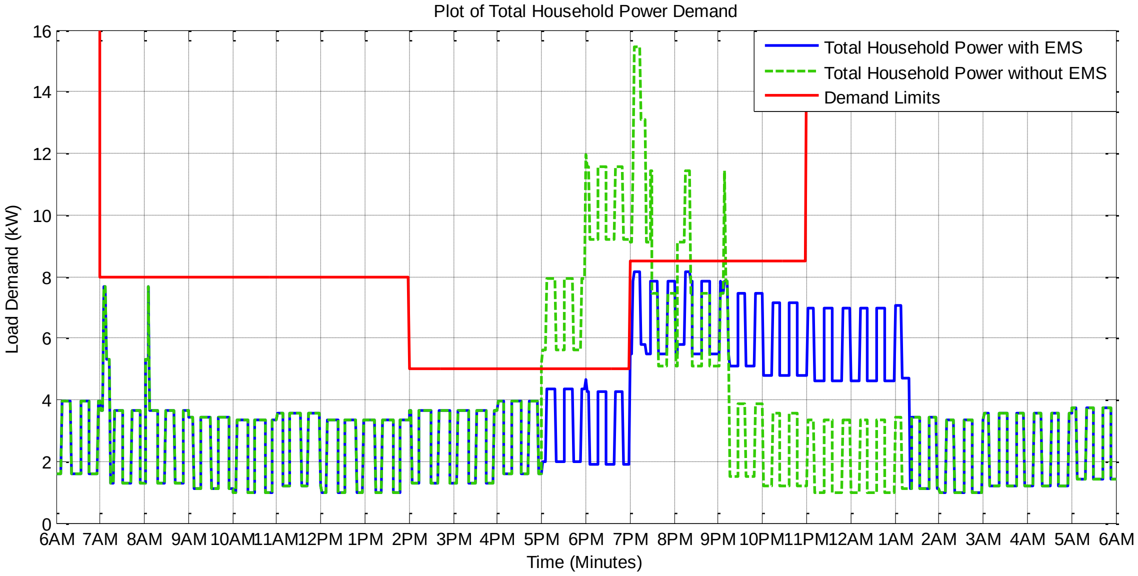


Figure 5.14: Total household load with EMS for TOU pricing

The daily load curves with and without demand limits are given in Figure 5.14. The demand limits for different time periods are also given in this figure. It is observed that by putting demand limits in the EMS algorithm, the operation of the non-critical loads are scheduled in such a way that the total household load is always lower that the demand limits during the corresponding time period. With demand limits in the developed EMS algorithm, the peak load of the household has been reduced from 15.45 kW to 8.15 kW. In both cases the daily energy consumption is the same. The daily load factor has been improved to 43.45% with the EMS which is 22.8 % without EMS. By considering the TOU energy pricing and fixed demand charges the daily energy cost for this typical daily load consumption is 17.23 $ in case of without EMS. With EMS using the same energy pricing mechanism, the total daily energy cost for this typical daily energy consumption is 10.89 $. It is observed that for this energy pricing mechanism with EMS, the daily saving is 36.75%.

5.3 Operation of the Non-Critical Loads with RTP (Case B)

The RTP is explained in Section 4.2.2. A typical RTP which has been used in this study is given Figure 4.2. The operation of non-critical loads with the developed EMS and without EMS is discussed in this section.

5.3.1 Operation of the Non Critical Loads for RTP Energy Pricing without EMS

The combined operational load curve of all the critical and non- critical loads under RTP without EMS is the same as given in Figure 5.9. The operational load curves for water heater, AC unit, clothes dryer and electric vehicle are same as in Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8 respectively. And the total load curve without EMS for RTP is same as the load curve for TOU pricing without EMS as in Figure 5.9.

5.3.2 Operation of the Non Critical Loads for RTP Energy Pricing with EMS

In the proposed EMS algorithm, the demand limits with RTP are considered for finding the proper daily operational time of the non-critical loads. Typical demand limit levels which are used in this case are tabulated in Table 5.2.

Table 5.2: Demand limit levels used in EMS for different time intervals in RTP tariff system

Time Duration	Demand limit level (kW)
2 p.m. -5 p.m.	4
5 p.m. -7 p.m.	5
7 p.m.-9 p.m.	8.5
9 p.m.- 10 p.m.	6
10 p.m. – 11 p.m.	4
11 p.m. -2 p.m.	8

During 2 p.m. - 7 p.m. as the peak demand in the grid is so high, a low value for the demand limit is selected. And during 7 p.m. - 9 p.m. the demand in the household is high whereas the total demand in the grid is not very high as the industrial load is low during that period. Therefore, in order to preserve the consumer comfort level a high value of demand limit is maintained during that time period.

Water Heater

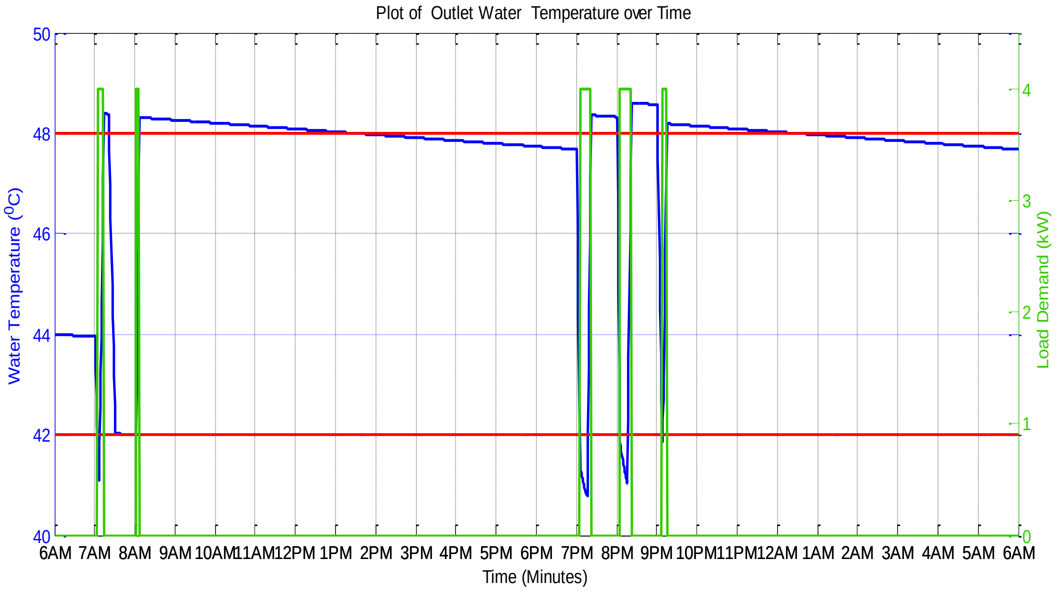


Figure 5.15: Operation of the water heater with EMS for RTP mechanism

The operation of the water heater for RTP with mentioned demand limits and priorities of the loads are given in Figure 5.15 for a typical day. This figure shows the power consumption of the water heater at different time periods based on hot water consumption and the temperature is maintained within desired temperature limits by taking the load priorities in to account.

AC Unit

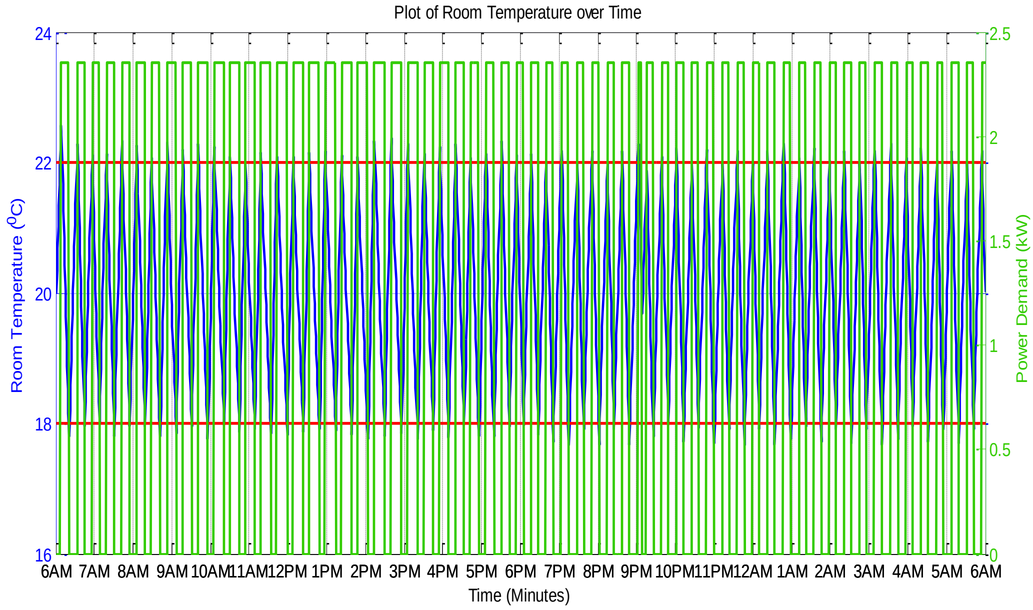


Figure 5.16: Operation of the AC unit with EMS for RTP mechanism

The operation of the AC unit for RTP with stated demand limits and priorities of the loads is given in Figure 5.16 for a typical day. Although there is a forced switch off in the AC unit by the EMS control signal around 9 p.m. due to the demand limits, the temperature has been managed within the user specified limits.

Clothes Dryer

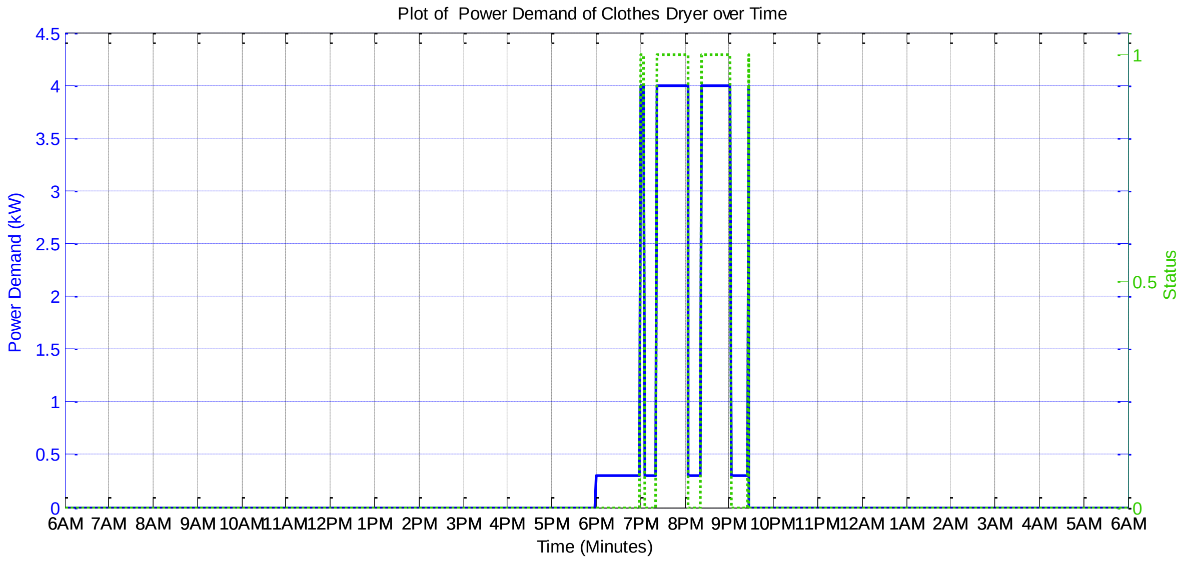


Figure 5.17: Operation of the clothes dryer with EMS for RTP mechanism

For RTP with demand limits, the clothes dryer operation has presented in Figure 5.17. The clothes dryer parameters and its operational time are explained in Section 2.4. The clothes dryer has to start its operation at 6 p.m. But due to the demand limit imposed by EMS, the heating coils are turned off until 7 p.m. allowing higher priority loads to operate. During that time, only the motor part is operated. Based on the demand limits and the load priorities, the operation of the heating coils are started around 7 p.m. Then there are some on-off cycles of the heating coils due to the control of EMS, and it has completed the job around 9.30 p.m.

Electric Vehicle

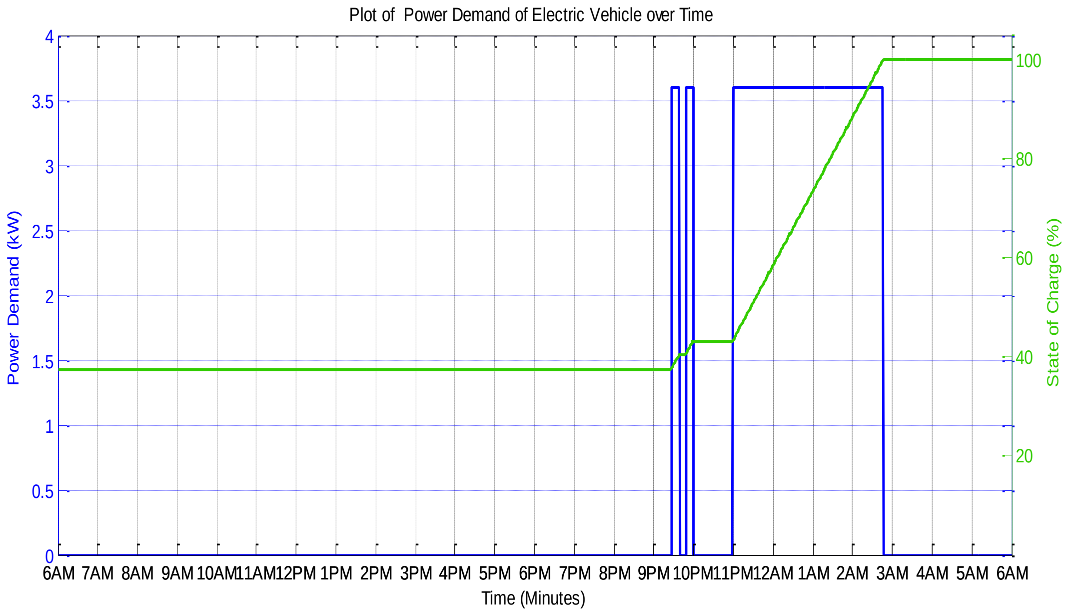


Figure 5.18: Operation of the electric vehicle with EMS for RTP mechanism

The electric vehicle charging operation for RTP with specified demand limits has been given in Figure 5.18. The electric vehicle charging parameters are given in Section 2.5. In considered non-critical loads, the electric vehicle has the lowest priority. By considering the priorities of the loads as well as demand limits in the EMS algorithm, the electric vehicle has started charging relatively late in this case with compared to operation of electric vehicle charging in RTP without demand limits. It is observed that due to lower priority of electric vehicle, the charging operation has started around 9.30 p.m. with two short duration on-off cycles. Then around 10 p.m. its charging has paused due to the low value of demand limit allowing AC unit and critical loads to operate. But after 11 p.m. the continuous charging of the electric vehicle is commenced until it gets fully charged around 3 a.m. This electric vehicle charging operation has been shifted due to lower priority and specified time varying demand limits (Figure 5.18). The variation in electric vehicle battery state of charge due to this switching pattern is also given in Figure 5.18.

Total Household Load

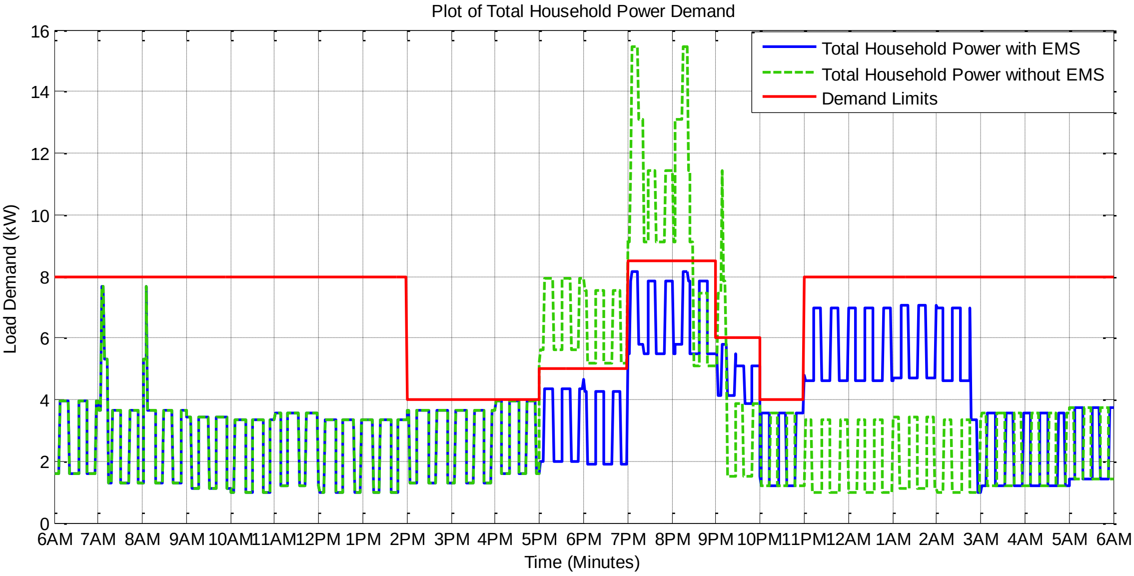


Figure 5.19: Total household energy consumption with EMS for RTP mechanism

The daily load curve without EMS has been given in Figure 5.19 in green dashed lines. The RT energy pricing with specified demand limits have been considered for finding out the optimum operational time of the non-critical loads. The typical daily demand limits under this case are given in Figure 5.19. The EMS algorithm with demand limits has managed the non-critical load operation in such a way that the peak load does not exceed the demand limits and the total daily energy consumption is the same as without EMS. With specified demand limits in the developed EMS algorithm, the peak load of the household has been reduced from 15.45 kW to 8.15 kW. It has been observed that through Figure 5.19, the energy consumption of non-critical loads during peak period has been shifted to off peak period due to the EMS algorithm. With EMS, the load factor has been improved to 43.51% which is 22.8% without EMS.

By considering the RT energy pricing with fixed demand charges, the monthly energy cost for this typical daily load consumption is 408.83 $. By using the developed EMS with considered demand limits and load priorities, the daily load profile is given in Figure 5.19. For this load profile the cost of electricity with fixed demand charges is 266.67 $. So it is clear that the daily energy cost has been reduced by 34.77% with the help of the EMS.

5.4 Possible Changes of User Energy Consumption Behavior due to RTP (Case C)

It is assumed that the user may possibly change the energy consumption of some loads (e.g. hot water consumption for shower, starting time of the cloth dryer and electric vehicle) based on available daily RTP. A typical daily real time energy pricing is shown in Figure 4.2 and based on that it is assumed that the consumer will start water consumption at 6 p.m. and similarly the clothes dryer is started at 7 p.m. (hot water usage for case C is attached in Appendix D2). In the next sections, operation of the EMS with demand limits and load priorities in managing the operation of non-critical loads due to these changes in consumer behavior are discussed.

5.4.1 Operation of the Non-Critical Loads for RTP with EMS

Based on RTP the consumer may change the electricity usage pattern and it is assumed that the user may change the operation of non-critical loads in the following manner.

Water Heater

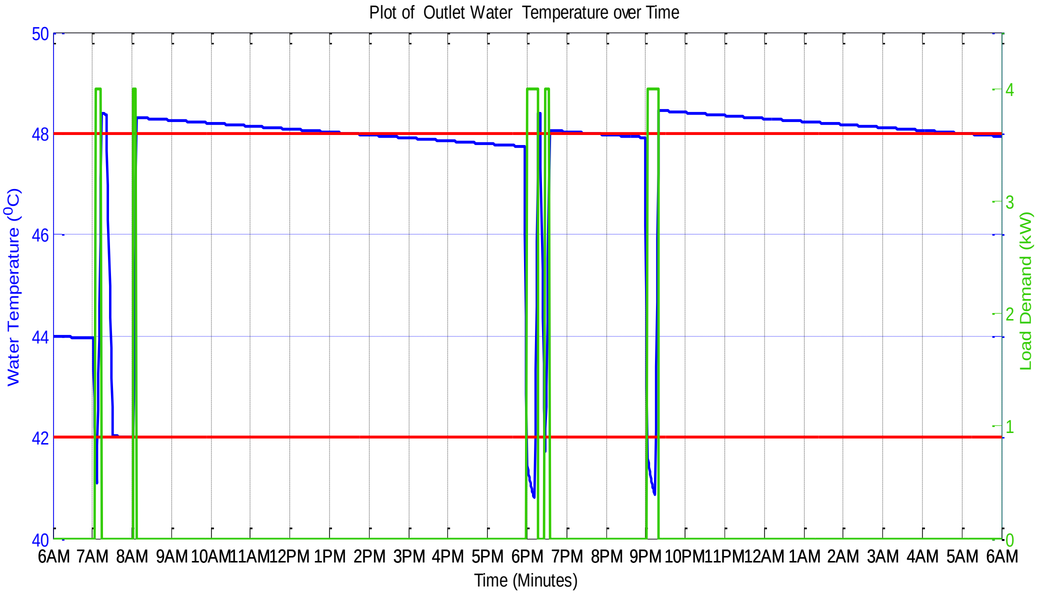


Figure 5.20: Operation of the water heater without EMS for RTP mechanism

By observing the daily RTP the consumer can shift the hot water consumption .The user can shift the hot water consumption to 6 p.m. and 9 p.m. as the prices during that period are relatively low. The 24 hours operation of the water heater for the defined minimum and maximum limits of the outlet water temperature is considered and the operation of the water heater during this time period is shown in Figure 5.20.

AC Unit

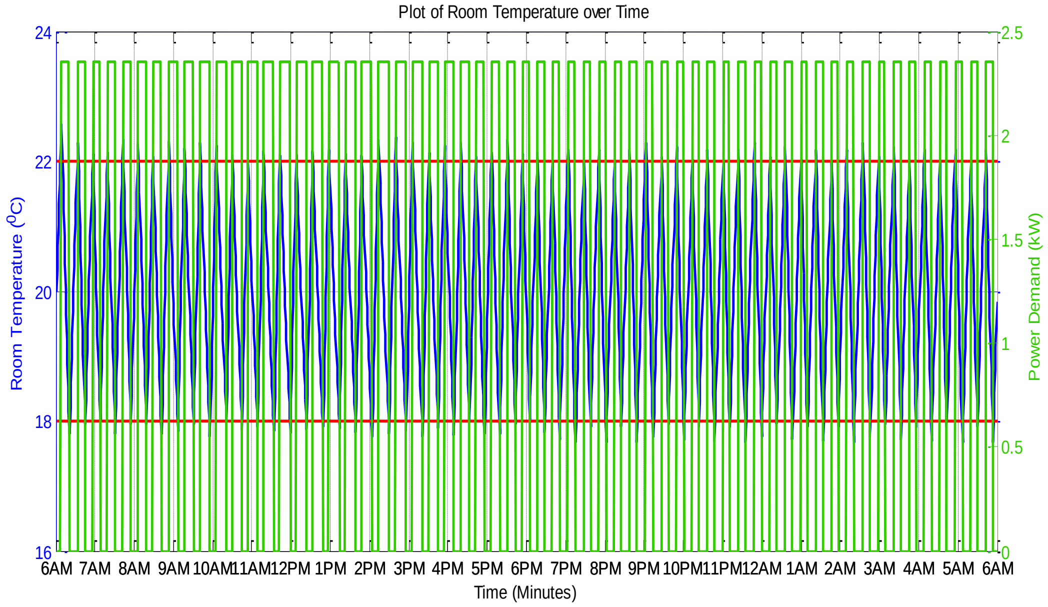


Figure 5.21: Operation of the AC unit without EMS for RTP mechanism

The operation of the AC unit for 24 hours period for the defined minimum and maximum limits of the operating temperature and for the selected parameters is given in Figure 5.21. It is assumed that the user has not changed any set points in the AC unit with the change in electricity price and demand limits.

Clothes Dryer

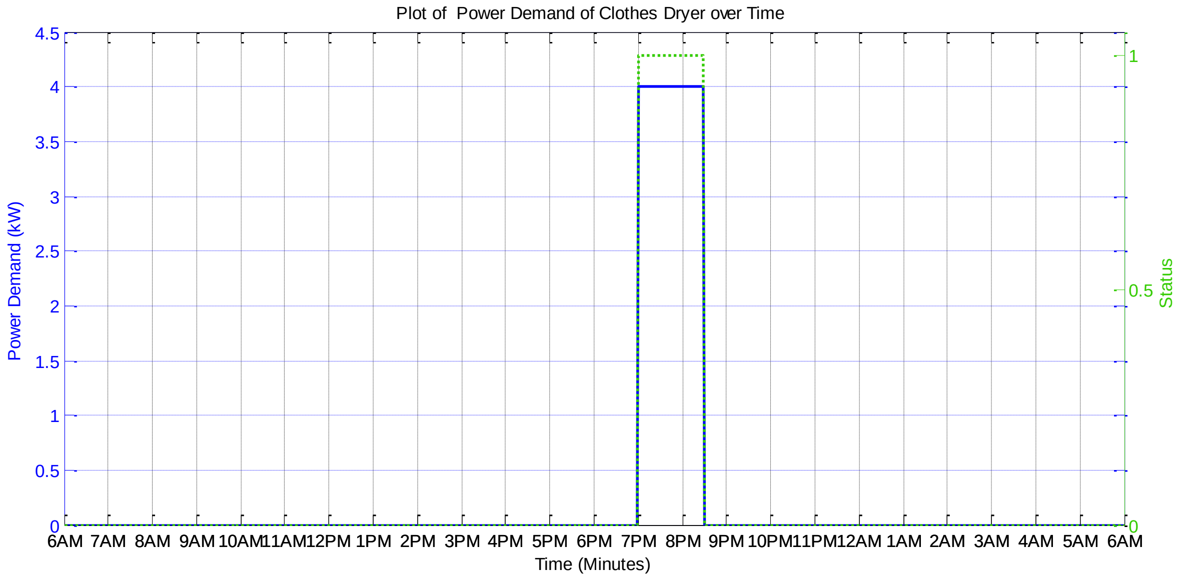


Figure 5.22: Operation of the clothes dryer without EMS for RTP mechanism

The consumer can change the starting time of clothes dryer to 7 p.m. as the hot water consumption has changed to 6 p.m.

Electric Vehicle

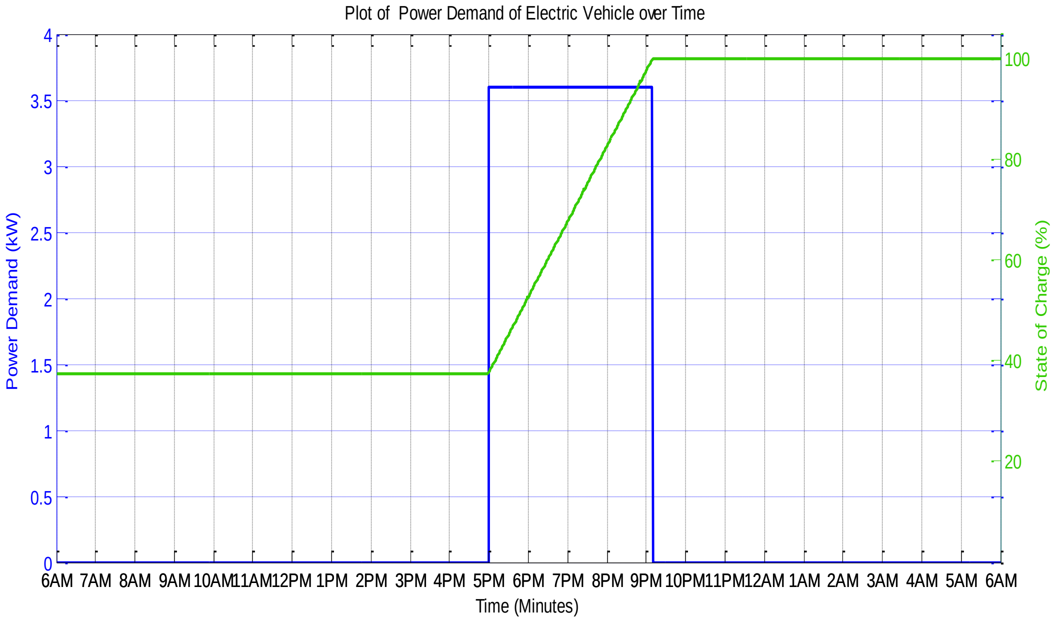


Figure 5.23: Operation of the electric vehicle without EMS for RTP mechanism

The consumer can plug the electric vehicle for charging around 5 p.m. as before by monitoring daily RTP. The charging operation of the electric vehicle for the 24 hours period is given in Figure 5.23.

Total Household Load

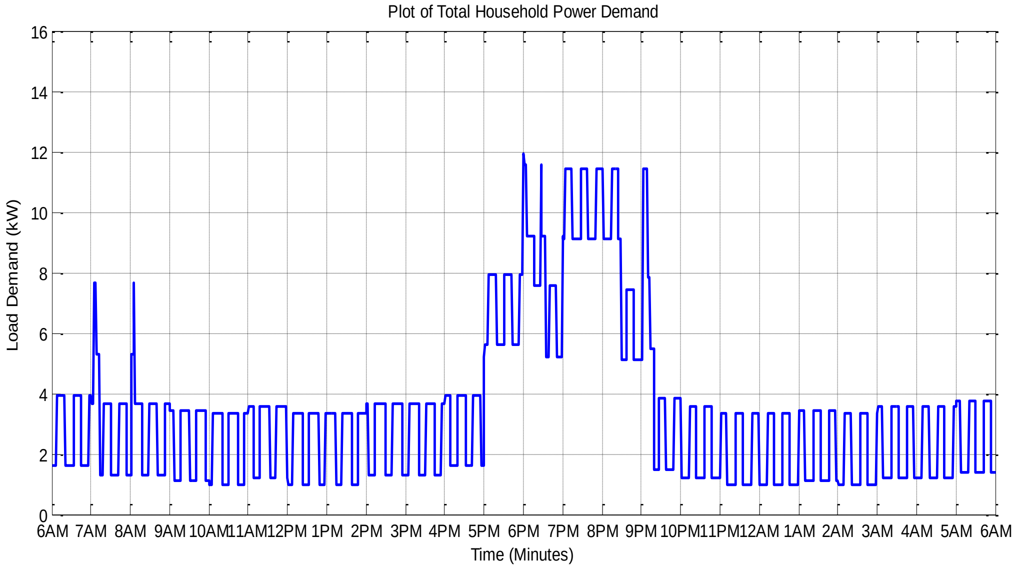


Figure 5.24: Total household energy consumption without EMS for RTP mechanism

By considering the operational time of non-critical loads due to change in user behavior and the critical load operation, the combined daily load curve without EMS has been given in Figure 5.24. It is observed that due to change in consumer behavior the peak demand has been dropped from 15.45 kW to 11.95 kW and peak load time also has been shifted to 6 p.m. It can be seen that in this case the load factor also has been improved to 29.47% which would be 22.8% if there is no user behavior change.

5.4.2. Operation of the Non-Critical Loads for RTP with EMS

In this consumer behavior change case, if the EMS algorithm is developed with RTP (Figure 4.2) and time specified demand limits (Table 5.2) the operational behavior of non-critical loads are analyzed and explained in the following section.

Water Heater

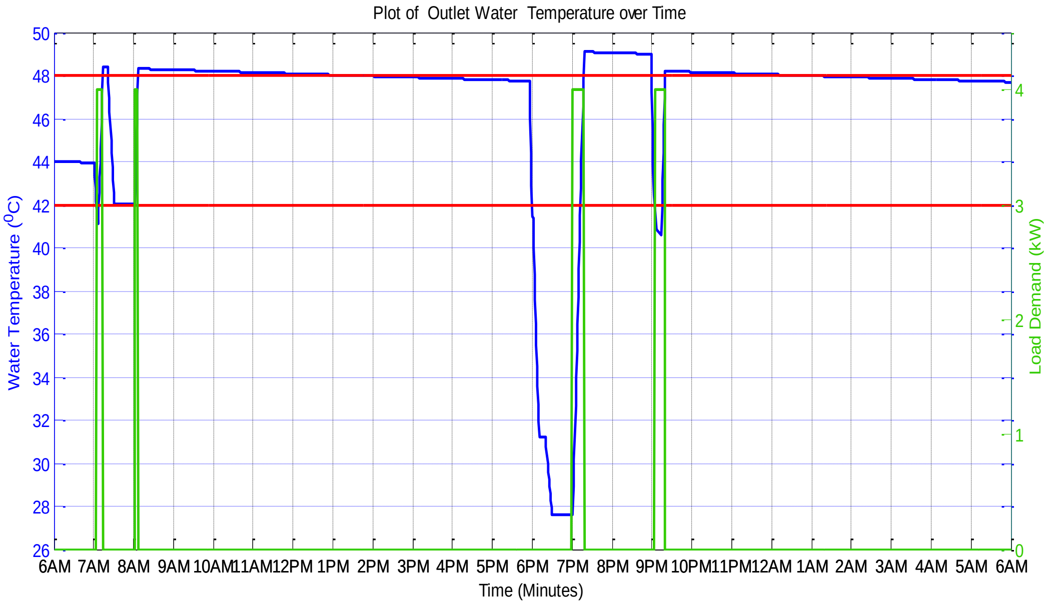


Figure 5.25: Operation of the water heater with EMS for RTP mechanism with load pattern changes due to change in user behavior

With user behavior change, the hot water consumption timing has been changed and the EMS algorithm with demand limits tries to manage the operational time of water heater as shown in Figure 5.25. It is observed that around 6 p.m. the user has started the hot water consumption due to the low electricity price during that hour. Although the price is low, the demand limit used in this case around that period is quite low. Even though the water temperature has dropped below the lower limit, the water heater is not switched on during water draw event around 6 p.m. due to the control signal received from the EMS. The EMS decides to turn off the water heating coils based on the demand limits and the load priorities. The outlet temperature of the water heater has dropped significantly to 25.5 ^{0}C at that instance. Due to the increase of demand limit at 7 p.m. the EMS has decided to switch on the water heater at that time and then it has been manage the water temperature within the limits.

AC Unit

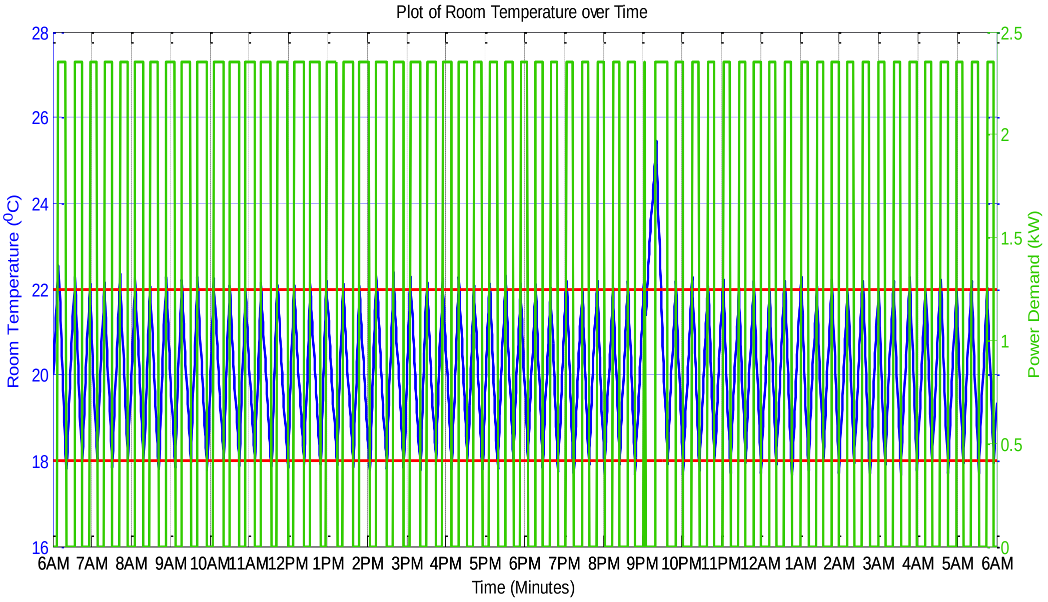


Figure 5.26: Operation of the AC unit with EMS for RTP mechanism with load pattern changes due to change in user behavior

In this condition, daily operation of the AC unit is given in Figure 5.26. It is observed that the AC unit operates within the defined temperature limits. But from 9.07 p.m.-9.21 p.m. it has violated the temperature limits. Due to the operational priorities of other non-critical loads and demand limits, the AC unit is off during that period and room temperature has increased to 25.5 ^{0}C.

Clothes Dryer

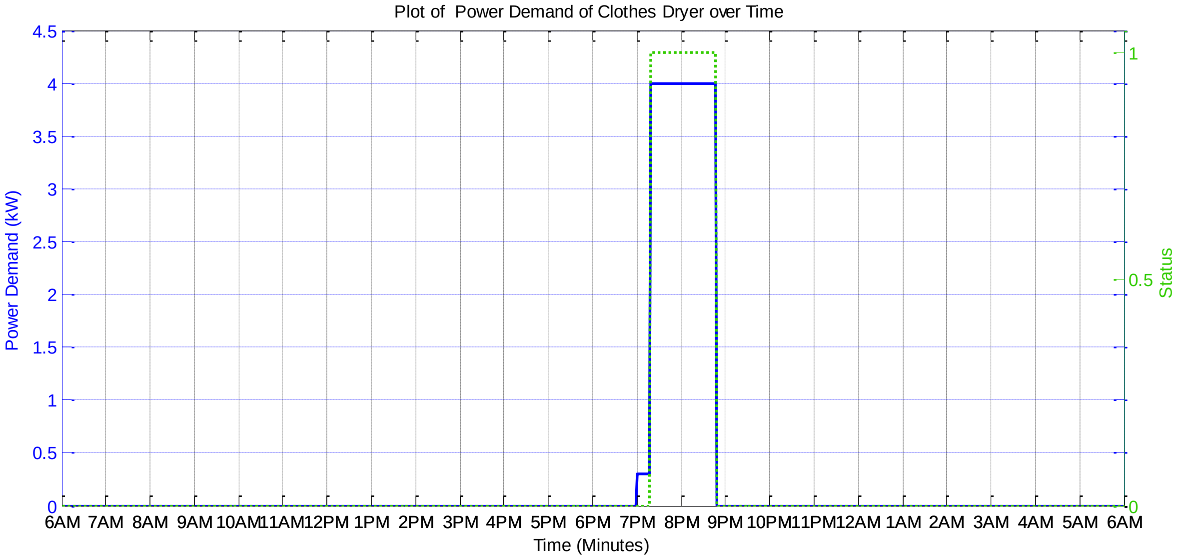


Figure 5.27: Operation of the clothes dryer with EMS for RTP mechanism with load pattern changes due to change in user behavior

Similarly the clothes dryer operation in this change in user behavior case with EMS algorithm is given in Figure 5.27. Considering the user behavior, the clothes dryer motor starts operation at 7 p.m. but the heating coil operation is delayed until 7.15 p.m. allowing the water heater to operate. The clothes dryer then operates continuously until 9.45 p.m.

Electric Vehicle

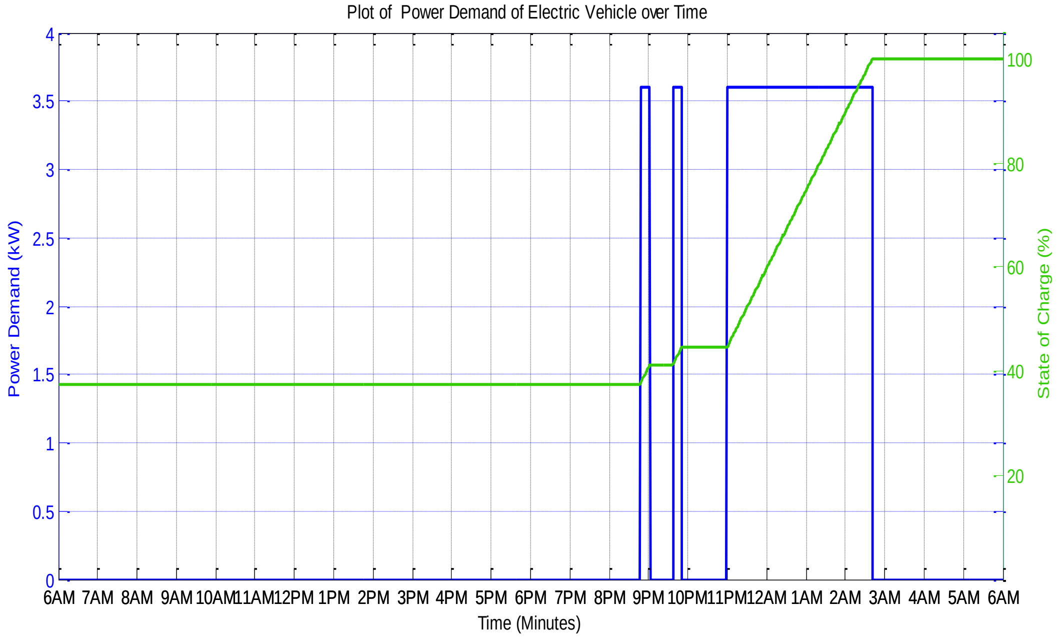


Figure 5.28: Operation of the electric vehicle with EMS for RT pricing mechanism with load pattern changes due to change in user behavior

The operation of the electric vehicle in the case of change in user behavior is also delayed until 8.45 p.m. although it is planned to start at 5 p.m., due to the EMS algorithm where the demand limits and load priorities are considered. The operational status and the charging profile of electric vehicle for this case are shown in Figure 5.28. Charging has started around 9 p.m. but after few minutes, the operation of the electric vehicle is again paused as the water heater has to be turned on. Then again it is charged for several minutes around 9.45 p.m. During 10 p.m. - 11 p.m. due to the lower demand limits, only critical loads and AC unit are operated. After 11 p.m. with the increase of demand limit, the electric vehicle has started to charge continuously. It is observed that with the demand limits and load priorities, the EMS has managed to charge the electric vehicle and finish charging around 2.45 a.m.

Total Household Load

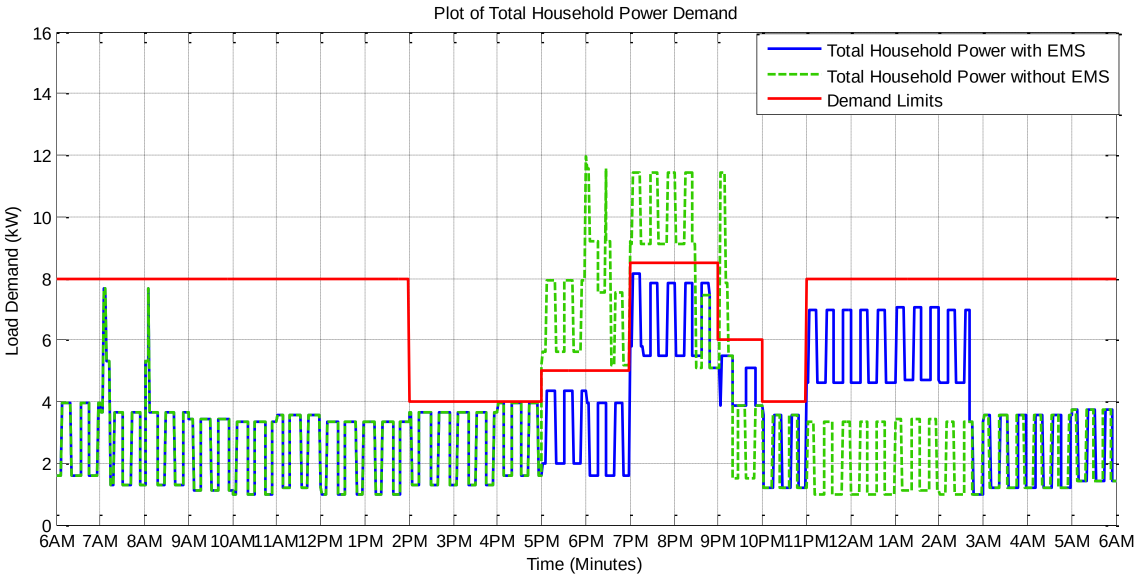


Figure 5.29: Total household load with EMS for RTP mechanism with load pattern changes due to change in user behavior

The combined load profiles for critical loads and optimized load profile for non-critical loads in changing user behavior case with and without EMS algorithm are given Figure 5.29. In this case, the EMS algorithm has reduced peak demand from 11.95 kW to 8.15 kW. But there are some cases for the AC unit and water heater where defined limits of the temperature are violated due to change in the operating time managed by EMS.

It is noted that if the EMS algorithm with demand limits has to be implemented in the case of change in user behavior, then non-critical load operations are not optimized based on the customer comfort level within the prescribed time varying demand limits.

5.5 Impact of User Behavior Change on Putting Time Defined Demand Limits in EMS Algorithm

In the previous section, it is observed that the prescribed demand limits in the EMS may not be sensible for operating non-critical loads in such a way that the consumer comfort levels are not compromised. Therefore if the EMS algorithm has to be analyzed in the change in user behavior case, then the demand limits has to be arranged in such a way that the non-critical load operations do not violate consumer comfort levels. In this user behavior change case, two sets of time period demand limits are considered and analyzed.

5.5.1 Impact of User Behavior Change on Putting Time Defined Demand Limits in EMS Algorithm with Demand Limit Set 1 (Case D)

A typical time period depended demand limits as in Table 5.3 are considered with RTP (Figure 4.2). In this discussion, this set of demand limits is referred as demand limit set 1 for the analysis purpose.

Table 5.3: Demand limit set 1 used in EMS for different time intervals in RTP tariff system in user behavior change case

Time Duration	Demand limit level (kW)
7 a.m. -2 p.m.	8
2 p.m. -6 p.m.	5
6 p.m.-6.30 p.m.	8
6.30 p.m.- 9 p.m.	5
9p.m. – 10 p.m.	8.5
10 p.m. -11 p.m.	4
11 p.m. – 7 a.m.	-

Since the peak demand in the industrial sector increases during 2 p.m. to 6 p.m. a low value of demand limit has been used during that period. And as the price around 6 p.m.is a low value in the RTP mechanism, user tends to use more power during that period. Therefore a high value of demand limit is used for that period.

Water Heater

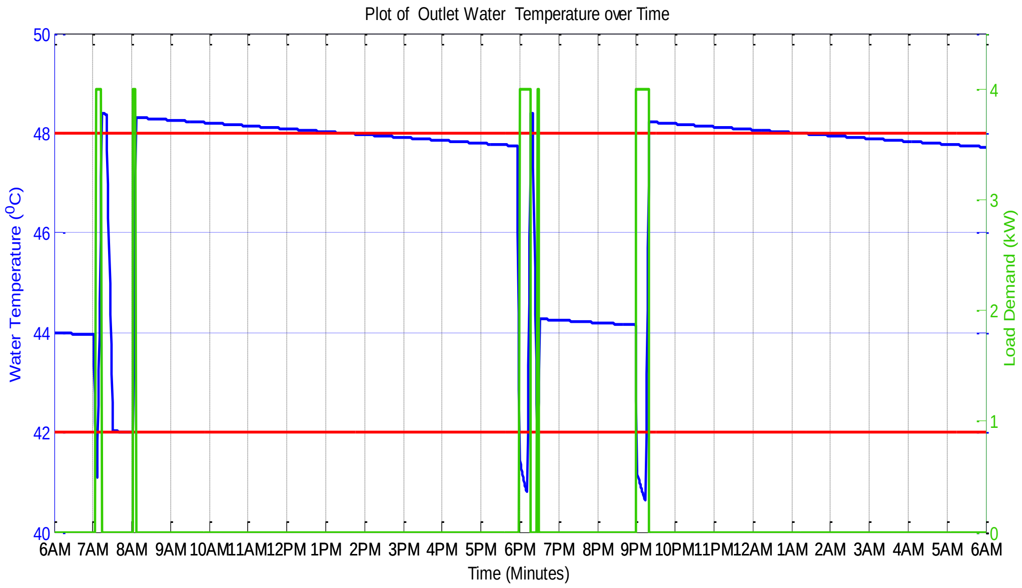


Figure 5.30: Operation of the water heater with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

The operational behavior under the case of user behavior change with revised demand limits in Table 5.3 is given in Figure 5.30. Around 6.30 p.m. the water heater has turned on but before the outlet temperature reaches to the upper limit it has been turned off by the EMS control signal based on the demand limit. And it is observed that the hot water temperature limits are within the specified limits.

AC Unit

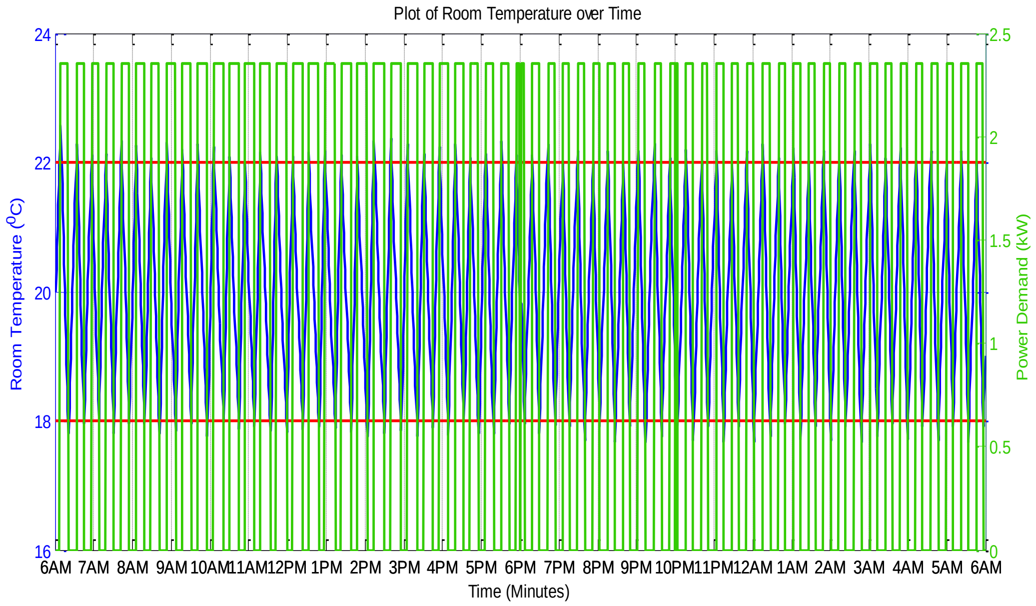


Figure 5.31: Operation of the AC unit with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

The operation of the AC unit for the case of change in user behaviour under the demand limits specified in Table 5.3 is given in Figure 5.31. Around 6 p.m., since the hot water consumption is high, AC unit has been controlled by the EMS permitting water heater to operate.Again at 10 p.m. a switching operation due to demand limits has occurred. But it can be seen that the temperature has been managed within the desired temperature limits and it has not violated the specified limits of the air condition, compared to Figure 5.26.

Clothes Dryer

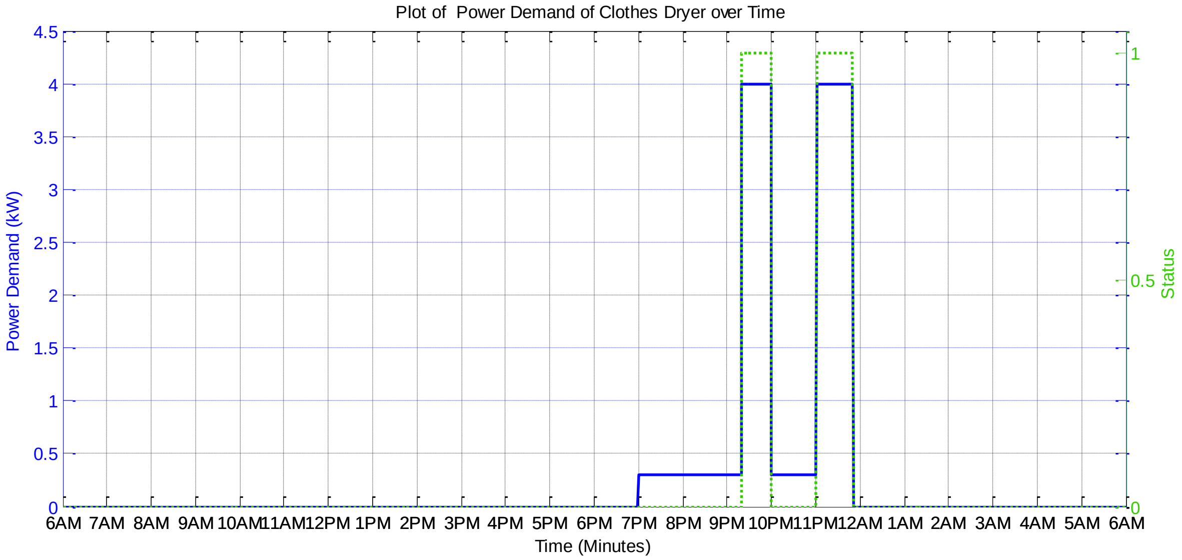


Figure 5.32: Operation of the clothes dryer with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

The clothes dryer operation in case of change in user behavior with EMS algorithm under specified time period demand limits and load priorities are presented in Figure 5.32. As defined, the motor has started at 7 p.m. but due to other load priorities and demand limits, the heating coils of the dryer have not been able to start before 9.15 p.m. Again at 10 p.m. the operation of the clothes dryer heating coils are stopped due to the low demand limits. The heating coils operation of the dryer is managed for the required time duration by considering the demand limits and load priorities. To avoid the continuous switching on and off the motor is not controlled by the EMS.

Electric Vehicle

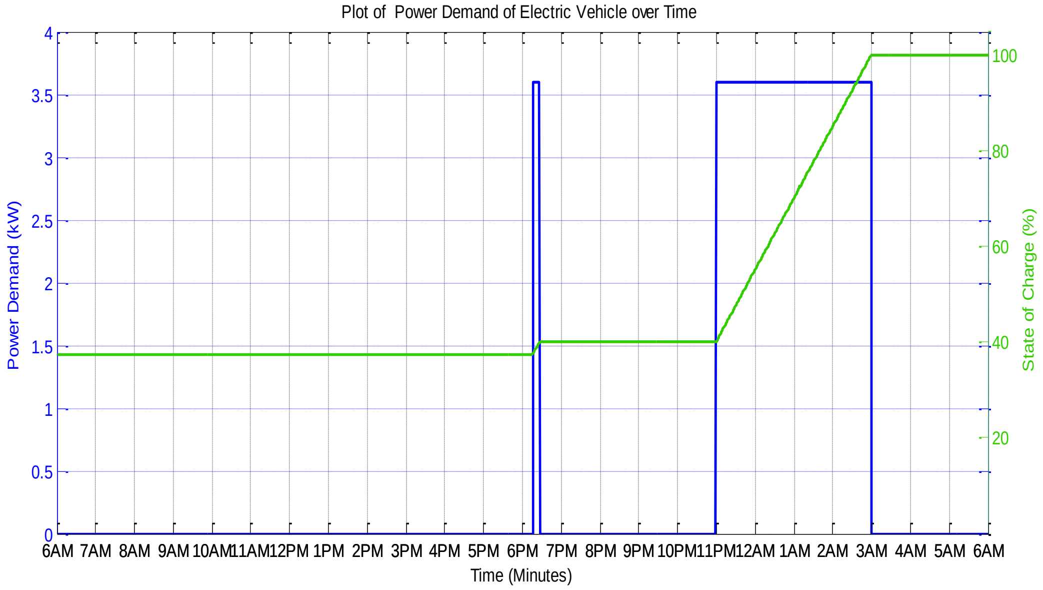


Figure 5.33: Operation of the electric vehicle with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

The charging profile of the electric vehicle for the case of change in user behavior with EMS under the demand limits in Table 5.3 is shown in Figure 5.33. According to this figure, it can be seen that the electric vehicle charging has started around 6.15 p.m. but the operation is interrupted by the EMS few minutes after starting due to the demand limits and load priorities. The charging has resumed at 11.15 p.m. and is fully charged at 3.15 a.m.

Total Household Load

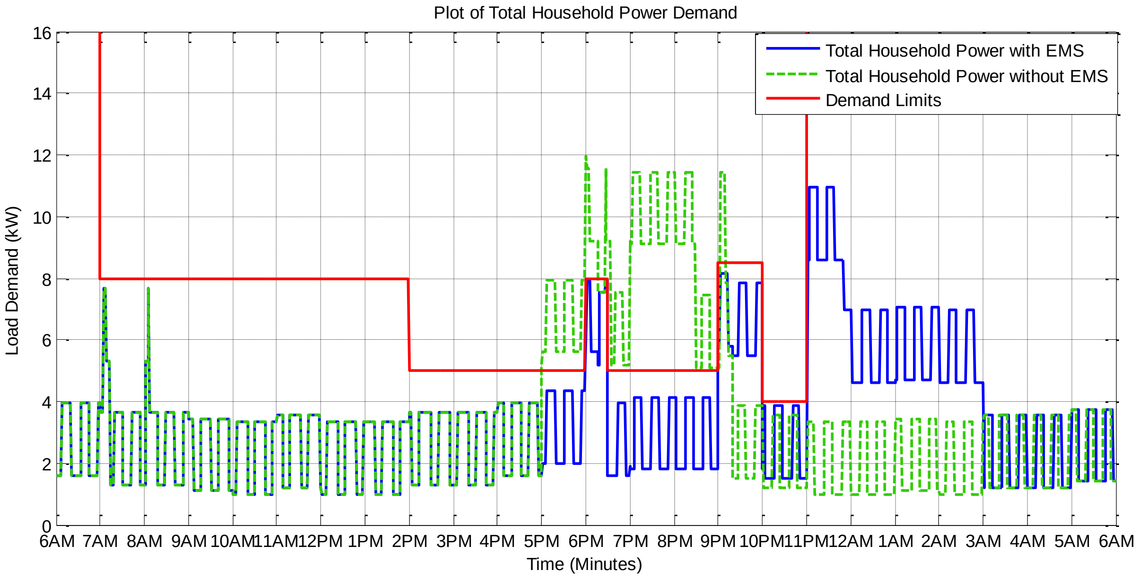


Figure 5.34: Total household load with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

In case of change in user behavior, if the EMS is deployed with revised demand limits (Table 5.3), resulted combined load profile is given in Figure 5.34.It also provides the total household load profile in case of change in user behavior without EMS. The peak demand of the household in the case of without EMS is 11.95 kW whereas the peak demand in the case of with EMS is 10.95 kW. The load factor is 32.56% with EMS and it is 29.84% without EMS. It can be clearly seen that the occurrence time of the peak demand has been shifted to 11.30 p.m. due to the control strategy of the EMS algorithm on non-critical loads. And also it should be noted that the EMS has been able to provide the energy demand that the user requested without any violation. Since the peak demand has been shifted to off peak period almost with the same value, elements in the distribution network may overloaded and fail during that period if the peak demands in all the households in the distribution network are shifted to off peak period due to the EMS algorithm.

Through analyzing the case of change in user behavior with demand limit set 1, it has been found that if the utility has to implement time period based demand limits, then it has to consider the response of the user to the price variations as well as the non-critical load operating limits (not to violate the limits). And also utility has to consider the possibility of overloading of distribution network during off peak periods due to the shifting of low priority loads to off peak periods.

5.5.2 Impact of User Behavior Change on Putting Time Defined Demand Limits in EMS Algorithm with Demand Limit Set 2 (Case E)

It is obvious that the demand limits imposed by the utility will affect the operation of non-critical loads. Therefore different time varying demand limits are considered for analyzing the daily operation of non-critical loads.

A typical set of time specified demand limits is given in Table 5.4. In this case, specially night time demand limit has been reduced. These demand limits are termed as demand limit set 2 in the following sections.

Table 5.4: Demand limit set 2 used in EMS for different time intervals in RTP tariff system in user behavior change case

Time Duration	**Demand limit level (kW)**
7 a.m. -2 p.m.	8
2 p.m. -6 p.m.	5
6 p.m.-6.30 p.m.	8
6.30 p.m.- 9 p.m.	5
9p.m. – 10 p.m.	8.5
10 p.m. -11 p.m.	4
11 p.m. – 7 a.m.	9

The demand limits used in each time period are same as in case 1 except the demand limit for 11 p.m. - 7 a.m. In the earlier case no demand limit is imposed during that period and in this instance a demand limit of 9 kW is used.

The operational behaviors of non-critical loads with EMS for the change in user behavior case with the demand limits in Table 5.4 are discussed in the following section.

Water Heater

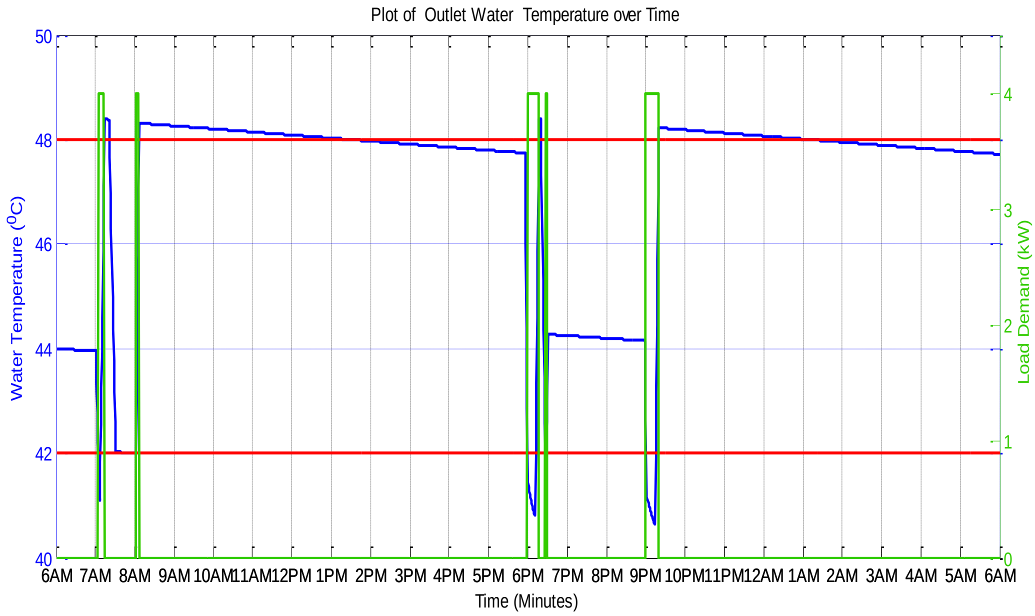


Figure 5.35: Operation of the water heater with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

The operation of the water heater for this specified case is shown in Figure 5.35. In this user behavior change case, the developed EMS has been able to manage the operation of the water heater for keeping the hot water temperature within the desired limits. But if the demand limits are not managed with reference to the user behavior case then there is a violation of hot water temperature limits (Figure 5.25).It is found that if the user changes behavior, the demand limits have to be rearranged to operate the devices within the limits or otherwise the users may have to sacrifice their comfort to some extent.

AC Unit

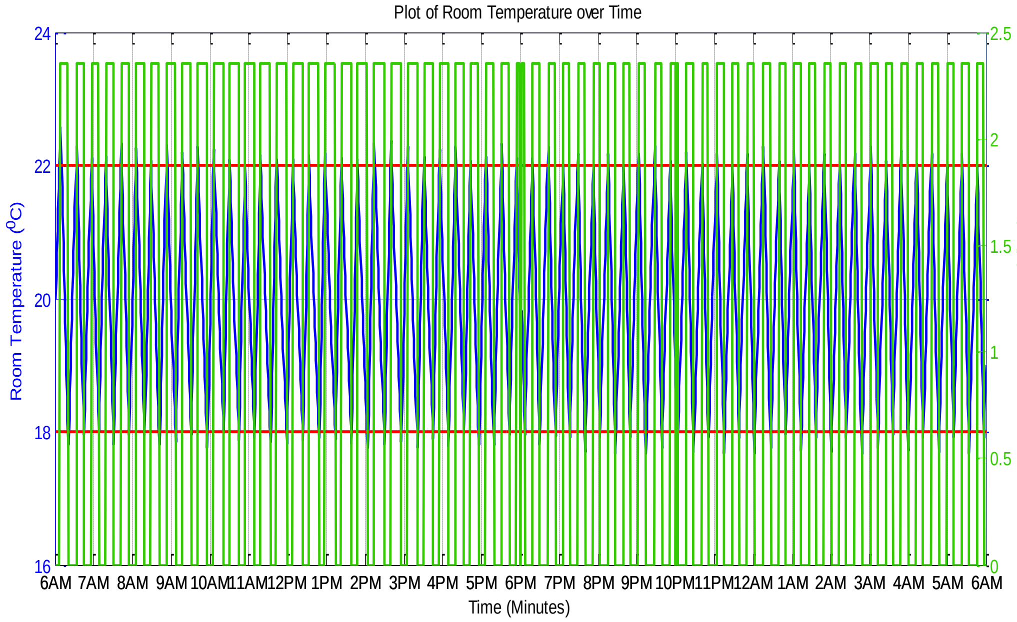


Figure 5.36: Operation of the AC unit with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

The operation of the AC unit with the EMS for the revised set of demand limits is shown in Figure 5.36. It can be seen that around 6 p.m. switch on -off pattern of the AC unit has been changed by the control signal of EMS considering the demand limits and load priorities. But the room temperature has been maintained within the user specified limits.

Clothes Dryer

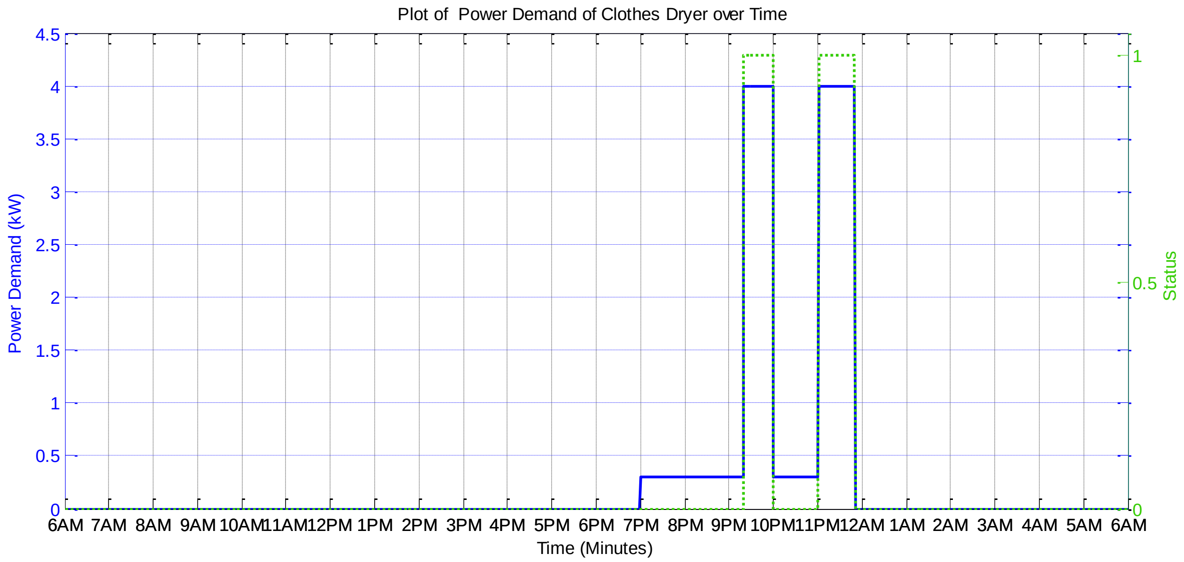


Figure 5.37: Operation of the clothes dryer with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

The operation of the clothes dryer in the change in user behavior case with new specified demand limits in EMS is shown in Figure 5.37. The clothes dryer motor has started its operation at the specified time (7 p.m.) but due to demand limits and load priorities, the dryer heating coils have started around 9.15 p.m. From that time onwards it is operated until 10 p.m. and then again heating coils are turned off due to the demand limits and load priorities. Due to the low value of demand limits during 10 p.m. - 11 p.m. only critical loads and the AC unit are operated during that time period. Then again the dryer heating coils are switched on at 11.00 p.m. and continually operated until the job is completed.

Electric Vehicle

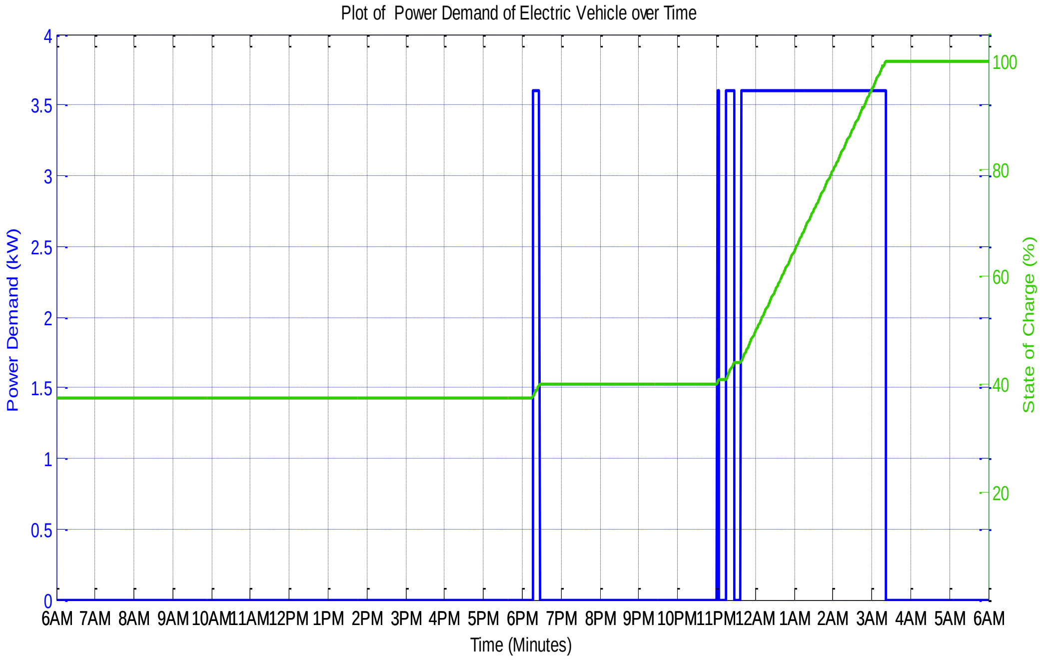


Figure 5.38: Operation of the electric vehicle with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

The electric vehicle has started its operation around 6 p.m. during the time periods where the water heater is not in operation as shown in Figure 5.38 which presents the operation of the electric vehicle with EMS for the revised demand limits. As the electric vehicle is the lowest priority load, it has not started until 11 p.m. due to the demand limits and the operation of higher priority loads. At 11 p.m., the electric vehicle has started charging during the time periods where the AC unit is turned off. It is noted that during that period, the clothes dryer and critical loads are also operated. The electric vehicle has started to charge continuously after the dryer has completed its job around midnight. In this case electric vehicle has finished charging at 3.45 a.m.

Total Household Load

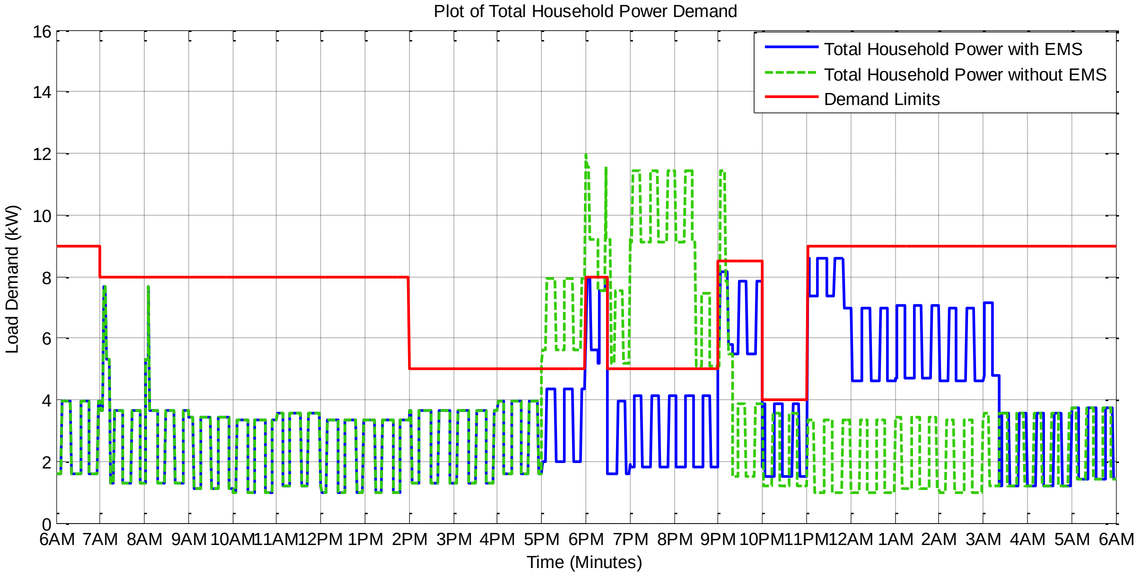


Figure 5.39: Total household load with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

The daily load curve in the household with the EMS system for this case is given in Figure 5.39 in blue and the load curve without EMS is given in green dashed lines. The maximum demand is reduced to 8.6 kW from 11.95 kW due to the installation of developed EMS. And the load factor is improved to 41.47% from 29.84% due to the control mechanism of EMS in change in user behavior case. It can be seen that in this situation, the risk of distribution transformer failures during off peak periods is reduced as the peak demand during the off peak time has been smoothen by the EMS with the demand limits which are shown in red in Figure 5.39.

5.4 Comparison of Electricity Cost

It has been observed that not only the home energy consumption profile load factor has been improved (i.e. reduction in the peak demand) but also a considerable energy cost saving can be obtained by using the presented EMS algorithm under different demand limits as well as different energy pricing mechanisms. The saving in electricity bill due to use of EMS algorithm for managing non-critical loads under TOU and RTP are analyzed for the cases with and without EMS. The following three different scenarios under these pricing mechanisms are considered (described in Section 4.2.3) in the analysis.

1. Energy cost without any demand charges
2. Energy cost with fixed demand charges
3. Energy cost with time varying demand charges

A typical load profile has been considered which consists of critical and non-critical loads. With the help of the developed EMS algorithm the non-critical loads are managed for above mentioned cases.

During these energy management cases, the energy cost/bill has been calculated and compared for different energy pricing mechanisms and presented in the next sections.

5.4.1 Time of Use Pricing

Case A1: Comparison of Energy Cost without Demand Charges for TOU Pricing Mechanism

The operation of non-critical loads for this case is discussed in Section 5.2 (Case A). The demand limit levels for different time intervals used in the EMS under this case are given in Table 5.1. Typical household load profiles used in this case, with and without demand limits are given in Figure 5.14.

For a typical load profile without EMS (Figure 5.14), the daily energy cost for TOU pricing is calculated and found as 791.4727 ¢. After using the EMS algorithm for managing the non-critical loads with considered demand limits, the daily energy cost for TOU pricing is calculated and found to be 598.2428 ¢. The daily energy cost saving under this case is 24.41% (Table 5.5).

Table 5.5: Comparison of the daily energy cost for TOU pricing with EMS and without EMS (Case A1)

Energy price without EMS (¢)	Energy price with EMS (¢)	Saving (%)
791.4727	598.2428	**24.41**

From Table 5.5, it can be seen that the energy cost for the same household load profile is less when the developed EMS is deployed in the household for managing the non-critical loads. The saving which a consumer can obtain by using this EMS with the considered demand limits is 24.4% per day and it should be noted that consumer comfort has not been violated in reaching this electricity cost saving.

Case A2: Comparison of Energy Cost with Fixed Demand Charges for TOU Pricing Mechanism

In this case, for calculating the energy cost, fixed demand charges are considered. The demand limits are the same as the previous case (case A1) and typical household load profiles with and without demand limits are given in Figure 5.14. The fixed demand charges are discussed in Section 4.2.3 and the demand charge used in this case is 18.09 $ per kW. Most of the utility detect the maximum demand or peak demand occurring during the monthly billing period and impose the demand charge on it. Therefore in this case, the monthly energy bill is considered and it is assumed that the considered daily load profile is representing the monthly average daily load profile. The electricity cost with fixed demand charges under TOU energy pricing is calculated for without and with EMS. The EMS limits the peak demand of the household and reduces the demand charge that a consumer has to pay. Therefore other than the savings in energy cost, the consumer can gain a large saving in peak demand charge by using the EMS. From Table 5.6, it can be seen that when the EMS is used, the maximum demand of the household is reduced to 8.15 kW where it is 15.452 kW when EMS is not in used and the load factor has improved to 43.45% from 22.8%. From Table 5.6, it can be seen that the demand charge has reduced almost 50% due to the reduction in peak demand. The electricity cost without EMS for a month with peak demand charges is found as 516.9685 $. If the EMS is implemented, then the electricity cost with peak demand charges is found to be 326.9425 $

for a month. The monthly energy cost saving which can be obtained by using the EMS with fixed demand charges is 36.75% (Table 5.6).

Table 5.6: Comparison of the energy cost per month under TOU pricing for fixed demand charge with EMS and without EMS (Case A2)

	Without EMS	With EMS
Maximum Demand (kW)	15.452	8.152
Energy Cost ($)	237.441	179.473
Demand Charge ($)	279.5275	147.469
Electricity Bill ($)	516.9685	326.9425
Saving (%)		**36.76**

Case A3: Comparison of Energy Cost with Time Varying Demand Charges for TOU Pricing Mechanism

In this case, the energy cost is calculated for TOU energy pricing mechanism with time varying demand charges. The time varying demand charges are presented in Section 4.2.3 and the corresponding values used in this case are shown in Figure 4.3. The demand limits are the same as previous cases (case A1, case A2) and typical household load profiles considered in this case with and without demand limit have been given in Figure 5.14.

Most of the electric utilities impose demand charges which vary with the time as described in Chapter 4 and in such type of schemes the demand charges during on peak hours are high and are lower during off peak hours (Figure 4.3). With the help of the presented EMS by managing the non-critical loads, the peak demand of the household can be reduced and it can be shifted to off peak hours. So when the consumer is charged with a pricing mechanism where the demand charges vary with time, as the EMS limits the peak demand as well as shifts the peak demand to off peak hours, the consumer can get more electricity cost savings by using the EMS. The comparison of electricity cost with EMS and without EMS for TOU pricing mechanism where the demand charges are varying with time is shown in Table 5.7. The household load variation without EMS and with EMS under this case is given in Figure 5.14. And it is observed that the peak demand is 15.452 kW for the case without EMS and 8.152 kW for the case with EMS. The daily load factor has been improved to 43.45% with the EMS which is 22.8 % without EMS. The peak demand occurrence times without EMS and with EMS can be observed in Figure 5.14 and also given in Table 5.7. The monthly electricity bill under this pricing mechanism without EMS is 447.0868 $ and with EMS it can be reduced to 290.0751 $. In this case, the monthly electricity bill can be reduced by 35.12% with the help of the EMS. The variation in energy cost for TOU energy pricing with and without EMS for different demand charging schemes can be observed from Tables 5.5- 5.7

Table 5.7: Comparison of the monthly energy cost under TOU pricing for time varying demand charge with EMS and without EMS (Case A3)

	Without EMS	**With EMS**
Maximum Demand (kW)	15.452	8.152
Maximum Demand occurrence time	7.05 p.m.-7.14 p.m.	7.04 p.m.-7.14 p.m. & 8.15 p.m.-8.21 p.m.
Energy Cost ($)	237.441	179.473
Demand Charge ($)	209.6458	110.6021
Electricity Bill ($)	447.0868	290.0751
Saving (%)		**35.12**

5.4.2 Real Time Pricing

Many utilities are charging the electricity by using RTP mechanism. In real time pricing, the unit price of electricity is changing hourly and the price is informed to the consumer ahead of time. When RTP is used, the consumer has to monitor the real time prices and should actively participate in shifting their loads to harness the maximum benefits. The real time pricing is discussed in Section 4.2.2 and in this study, a typical real time pricing is used which is shown in Figure 4.2. In this case, the same load profile is used as in the case of TOU pricing (case A). It is considered that the EMS manages the non-critical load operation as per priorities specified by the user. In RTP mechanism, the demand charges are considered in the same way as considered in the TOU pricing mechanism.

Case B1: Comparison of Electricity Cost without Demand Charges for RTP

In this case, the operational managements of non-critical loads are discussed in Section 5.3. The demand limit levels for different time intervals used in the EMS under this case are given in Table 5.2. The demand limits and load profiles with and without EMS for this case are given in Figure 5.19.

For a typical daily load profile, without EMS (Figure 5.19), the daily energy cost under RTP is calculated and found as 431.0238 ¢. The daily energy cost with EMS for this case is calculated and found as 397.3316 ¢. The daily energy cost saving under this case is 7.82% (Table 5.8).

Table 5.8: Comparison of the energy cost under RTP with EMS and without EMS with the same load profile in TOU pricing mechanism (Case B1)

Energy Price without EMS (¢)	**Energy Price with EMS (¢)**	**Saving (%)**
431.0238	397.3316	**7.82**

To increase the energy cost saving the demand limit levels can be managed properly and it can be arranged based on other load profiles.

Case B2: Comparison of Electricity Cost with Fixed Demand Charges for RTP

In this case, fixed demand charges are considered in calculating the energy cost. The load profile curves with and without EMS used in this case are shown in Figure 5.19. It is observed that the peak demand has been reduced from 15.452 kW to 8.152 kW as a result of the developed EMS. Due to the reduction of peak demand, the load factor has improved to 43.5% from 22.8%. The energy cost for a typical month with demand charges is calculated and for the case without EMS it is found to be 408.8338 $. When EMS is used in the household, the energy bill has reduced to 266.6692 $. Therefore, the saving of the electricity bill due to the operation of developed EMS is 34.77%. The energy saving is mostly due to the saving in the demand charge as illustrated in Table 5.9.

Table 5.9: Comparison of the energy cost with fixed demand charges under RTP with EMS and without EMS (Case B2)

	Without EMS	With EMS
Maximum Demand (kW)	15.452	8.152
Energy Cost ($)	129.307	119.1995
Demand Charge ($)	279.5266	147.4697
Electricity Bill ($)	408.8338	266.6692
Saving (%)		**34.77**

Case B3: Comparison of Electricity Cost with Time Varying Demand Charges for RTP

Time varying demand charges which are explained in Section 4.2.3., with RTP are considered to calculate the electricity bill for this case. As shown in Figure 5.19, the peak demand has been reduced from 15.45 kW to 8.15 kW due the operation of EMS. As a result, the load factor has been increased to 43.5% which was 22.8% when EMS is not in use. The peak demand occurrence time in the household with EMS and without EMS can be seen from Figure 5.19 and are summarized in Table 5.10. The energy cost for a typical month with time varying demand charges for RTP, without EMS is calculated and found as 338.9521 $ which includes an energy cost of 129.307 $ and a demand charge of 209.6449 $. With EMS the electricity bill for this case is 229.8018 $ in which the energy cost is 119.1995 $ and demand charge is 110.6023 $. It can be clearly seen that, the reduction in the bill is mainly due to the reduction in demand charge. The total saving that a consumer can obtain by installing the developed EMS to manage the operational time of non-critical loads with RTP and time varying demand charges is found to be 32.20%. Summary of the analysis carried out to compare the electricity bill saving for RTP with time varying demand charges for the proposed EMS is given in Table 5.10.

Table 5.10: Comparison of the energy cost with fixed demand charges under RTP with EMS and without EMS (Case B3)

	Without EMS	**With EMS**
Maximum Demand (kW)	15.4520	8.1520
Maximum Demand Occurrence Time	7.05-7.14 p.m. & 8.15p.m.-8.21 p.m.	7.06 p.m.-7.14 p.m. & 8.15 p.m.-8.21 p.m.
Energy Cost ($)	129.307	119.1995
Demand Charge ($)	209.6449	110.6023
Electricity Bill ($)	338.9521	229.8018
Saving (%)		**32.20**

It is possible that the user may change operational time of non-critical loads due to RTP (e.g. hot water consumption, starting times of the clothes dryer and electric vehicle). If this situation happens, then the operation of the non-critical loads will also depend on the user behavior other than the demand limits. These issues are discussed in detail in Section 5.4 (case C). It is observed that there have been violations in operating limits of the non-critical loads in case C where the user has changed the hot water consumption and the starting time of clothes dryer based on the RTP. Therefore case C has not been considered in energy cost analysis.

In RTP when the energy prices are low, the demand limits are higher and when the energy prices are high demand limits are lower. In Section 5.4, effect on daily load pattern due to the changes in user behavior and demand limits are discussed in detail under case D and Case E. Since the demand limit is higher during the low energy price periods, the non-critical loads are shifted to the low price periods based on their priorities as explained in case D in Section 5.4.1. It has been found that the total peak load is moving towards the low energy price periods. So there are chances that these low price periods may get higher peak demand when EMS is used and as a result, the cumulative peak demand on the utility during low price periods (i.e. during off peak periods) will increase. This will have a negative impact to the power system stability as well as demand response and therefore is not discussed in the cost analysis.

Case E is carried out to manage the non- critical load operating times when the user changes electricity consumption according to the available RTP. In case E, the negative impacts in case D has been avoided by using a reasonable demand limit during low price periods (i.e. off peak periods) as explained in Section 5.4.2. By this, the peak demand of the household is maintained below a threshold value and the negative impacts to the power grid stability have been minimized. The cost analysis for case E is carried out for the three demand charge scenarios as in the previous cases and is discussed in the next section.

Case E1: Comparison of Electricity Cost without Demand Charges for RTP with Changes in Non-Critical Load Timing

The operation of non-critical loads for this case is discussed in Section 5.5.2 (Case E).The total household load profile with and without EMS for this case is shown in Figure 5.39 and the demand limits considered for different time intervals in this case are presented in Table 5.4.

The daily energy cost for the typical load profile considered in this case for RTP, without EMS is found as 428.0704 ¢. By using the EMS it has been possible to reduce the daily energy cost to 382.397 ¢ and obtain a cost saving of 10.67% (Table 5.11).

Table 5.11: Comparison of the energy cost without demand charges under RTP with EMS and without EMS for the load profile in change in user behavior case (Case E1)

Energy price without EMS (¢)	**Energy price with EMS (¢)**	**Saving (%)**
428.0704	382.397	**10.67**

Case E2: Comparison of Electricity Cost with Fixed Demand Charges for RTP with Changes in Non-Critical Load Timing

The EMS algorithm is used to manage the non-critical loads in the user behavior change case for RTP, to reduce the peak demand in the household. The daily load curve obtained with EMS in this case is shown in Figure 5.39 and the load curve for the case of without EMS is also indicated in the same figure. From this figure it can be observed that the peak demand of the household has been reduced to 8.6 kW from 11.95 kW due to the management of EMS on the operational timing of the non-critical loads. The reduction in the peak demand with EMS has improved the load factor to 41.47% from 29.47%. The electricity bill for a one month billing period which comprised with energy charge for the entire billing period and the respective demand charge for the particular month is calculated under fixed demand charges and the bill is found to be 344.6328 $ when the EMS is not in use. The electricity bill has reduced to 270.4801 $ resulting an electricity bill saving of 21.51% when the EMS is used in the household. It can be observed that the saving in the demand charge has been very high compared to the energy cost saving as shown in Table 5.11.

Table 5.12: Comparison of the electrical bill under RTP pricing with fixed demand charges with EMS and without EMS with the load profile in change in user behavior case (Case E2)

	Without EMS	**With EMS**
Maximum Demand (kW)	11.952	8.6
Energy Cost ($)	128.421	114.719
Demand Charge ($)	216.211	155.761
Electricity Bill ($)	344.6328	270.4801
Saving (%)		**21.51**

Case E3: Comparison of Electricity Bill with Time Varying Demand Charges for RTP with Changes in Non-Critical Load Timing

The developed EMS is used to reduce the peak demand of house by managing the operational times of the power intensive non-critical loads considering the user behavior changes based on RTP fluctuations. The daily load profile for this case which is managed below the demand limits specified in Table 5.4, along with the unmanaged load profile is shown in Figure 5.39. The load factor has improved to 41.47% from 29.47% as the EMS has reduced the peak demand to 8.6 kW from 11.95 kW. It can be seen that the operation of the non-critical loads with low priorities are shifted to off peak hours as the demand limits during those periods are high. The electricity cost with varying demand charges for RTP is calculated for this case. If there is no EMS system, then the bill is found to be 344.6328 $ and with EMS the bill is found as 192.6888 $. From Table 5.13, it can be observed that the peak demand occurrence time has shifted to off peak hours where the demand charges are low. The bill reduction is mainly due to the reduction in the peak demand and the shifting of peak demand to off peak hours. The saving in the electricity bill due to the implementation of developed EMS is 44.09% for this case. It is clear that in this situation the saving in the electricity bill is very high compared to the cases considered earlier. And also peak demand of the house is maintained below the demand limit levels over the course of the day. So the stability of the grid can be improved and the risk of failures in the distribution network can be reduced without compromising the customer comfort.

Table 5.13: Comparison of the energy bill under RTP with varying demand charges with EMS and without EMS with the load profile in change for the user behavior case (Case E3)

	Without EMS	**With EMS**
Maximum Demand (kW)	11.9520	8.6
Maximum Demand Occurrence Time	6 p.m.	11.17 p.m. - 11.26 p.m. & 12.02 p.m. -12.06 p.m.
Energy Cost ($)	128.421	114.719
Demand Charge ($)	216.212	77.969
Electricity Bill ($)	344.6328	192.6888
Saving (%)		**44.09**

Chapter 6

Conclusion

6.1 Conclusion

Demand side management in the domestic sector can play an important role in reducing the peak demand on power system network. Eventually it can help in reducing overloading and the stress on transmission and distribution lines. In many countries there are various demand response programs implemented for the industrial and commercial sector. In these programs load control is mainly achieved through RTP and TOU pricing. Very few demand response programs are in use for energy management in the domestic sector. Direct curtailment of the loads is the most popular method used to reduce the peak demand. But by direct load control, customer comfort may be compromised. In contrast, by the load shifting method in which the loads which have less impact to the customer life style are shifted to off -peak hours, customers will be impacted less whereas the stability of the grid will be improved.

In order to analyze demand response it is important to understand physical based power intensive non-critical load models especially for water heaters, air conditioners, clothes dryers and electric vehicles. In developing these models thermodynamic principles of buildings and technical parameters of these appliances have to be considered. These load models have been mostly used for direct load control applications. With development of smart grid system specially in the distribution network there is a necessity for load models that can assist in the study of change in electricity consumption with respect to customer behavior and demand limits given by utility.

It is important to manage the demand of power intensive domestic loads in order to reduce the peak demand of the household. Domestic loads can be categorized as critical loads and non-critical loads. In this work, power intensive non-critical loads are managed through developed EMS algorithm and these loads are water heater, AC unit, clothes dryer and electric vehicle. With introduction of the electric vehicles, demand responses can be performed within home for avoiding any overloading problems in the distribution network as well as on power generation. The highlight of the presented EMS algorithm for home energy management is its capability to control the operation of non-critical loads to maintain the total household demand below specified peak demand limits by considering consumer behavior or priorities and giving customers more flexibility in their operational time.

In this project, the objective has been to develop an intelligent energy management algorithm for optimum scheduling of the household non-critical power intensive loads based on time varying demand limits given by the utility and consumer behavior with priorities of the loads. Also it is expected to identify the customer benefits which can be obtained through the developed EMS under different electrical energy pricing mechanisms. To achieve these objectives, a complete

program is developed to model the above mentioned power intensive non-critical domestic loads and the EMS algorithm has been developed to manage the operational time of these non-critical loads considering the demand limits, the priorities of the loads and consumer behavior. To find the energy cost saving that can be gained through the EMS, different pricing mechanisms are embedded in to the developed program.

The obtained results show that it is possible to shift the operational time of considered power intensive non-critical loads to off-peak hours based on the load priorities within the specified peak demand limits without violating their operating limits by using the developed EMS. By shifting the non-critical loads, the proposed EMS has effectively reduced the peak demand of the household below the specified limits. Also with the demand response enabled load models, it has been possible to monitor the operation of the non-critical power intensive loads at appliance level.

TOU and RTP mechanisms are used to identify the electricity cost savings that can be gained through the proposed EMS. In each pricing mechanism three cases (Section 4.2.3) are considered where the demand charges are also taken into account.

In case A, operation of the proposed EMS with TOU tariff is considered and it is observed that the peak demand has reduced from 15.45 kW to 8.15 kW by using the EMS. The total energy consumption has not changed due to the installation of EMS with the considered demand limits and the load factor has improved from 22.8 % to 43.45 %. Also it can be seen that the household demand has distributed throughout the day when EMS is installed. It is observed that if the demand limits are reduced below a threshold value, then the non-critical loads will not be operated within their limits and therefore the customer comfort will be violated. In case A, three pricing scenarios are used to evaluate the effect of EMS on energy price of the consumers. In case A1, operation of non-critical loads for the TOU tariff system with no demand charges are considered and the energy saving when EMS is used is 24.4 %. In case A2 where a fixed demand charge is included in the TOU tariff system, the saving due to the proposed EMS is 36.7 %. If time varying demand limits are used along with TOU pricing mechanism as in case A3, the consumer can make a saving of 35.12 % with the help of the EMS. Therefore, the findings show that the developed EMS works efficiently in managing the non-critical operating times for TOU pricing mechanism to reduce the peak demand in the grid while delivering a considerable electricity cost saving to the consumers.

The same three cases are also discussed for the RTP in case B with the same typical load profile as used in case A. Due to the EMS, the peak demand is reduced to 8.15 kW from 15.45 kW and the load factor has improved to 43.5 %. The energy saving that can result by using the developed EMS in case B1, where demand charges are not taken in to account, is 7.82 %. The findings show that 34.77 % of electricity cost saving can be obtained for case B2 where fixed demand charges are included. In case B3, time varying demand charges are considered and the saving which can be obtained by EMS is 32.2 %. It is clear that the relative cost benefits which can be obtained through the EMS are higher when demand charges are imposed on the electricity bill along with RTP mechanism.

In case C, it is assumed that the consumer may change operational time of non-critical loads based upon the available real time prices. By taking demand limits into consideration, the analysis for scheduling the operational time of non-critical loads is carried out. It is observed that due the change in the load profile and the considered demand limits, some of the non-critical load operations are deviated from their specified limits. Although the total household demand is maintained below the specified demand limits through the EMS, the consumer is not able to use the same energy that can be used when the EMS is not in use. In simple words, customers have to sacrifice their comfort to some extent. If such a situation occurs, the consumers might not agree to engage in demand response although they can gain savings in electricity bill as well as improvement in load factor to 29.8 %.

In case D, the case of change in user behavior discussed under case C is analyzed with a different set of demand limits. In this case, the demand limits are selected in such a way that it will not violate desired limits of any non-critical load. And it is considered that there will be no demand limits for the time period from 11 p.m. – 7 a.m. as the real time prices are very low for that period. It is observed that the peak demand of the household has shifted to the time period around 11 p.m. This is due to the scheduling of non-critical load operations based on the priorities and demand limits considered in the EMS. It is observed that the peak demand has reduced to 10.95 kW from 11.95 kW and the load factor has improved to 32.56% from 29.84%. A high off-peak demand has been created in this instance due to the shifting of low priority loads based on the demand limits. Consequently it will create overloading in the distributed network and also on power generation. Therefore this situation needs be avoided by proper selection of demand limits provided by the utility by considering the consumer load patterns and the real time prices.

In case E, the same set of demand limits and the load profile with user behavior changes as in case D is used under RTP, but a demand limit of 9 kW is used for the low energy pricing time interval between 11p.m. – 7 a.m. It is observed that the off-peak demand also has been reduced by the EMS. The peak demand is reduced to 8.6 kW with the EMS and without EMS it is 11.95 kW. The load factor has increased to 41.47% from 29.84%. It is noted that the saving in cost of electricity with use of EMS is 10.67% in case E1 where demand charges are not considered. In E2 where fixed demand charges are used the saving in electricity cost using EMS is 21.5%. Time varying demand charges are considered in E3 and it is noticed that the saving is 44% as the peak demand has reduced and shifted to off-peak period. It is observed that the properly selected demand limits based on real time pricing while considering customer behavior can lead to considerable savings and effective peak load reduction without affecting customer comfort.

It is observed from the analysis that the selection of demand limits by utility should be made considering the real time energy pricing and operating limits of the non-critical loads. It is noticed that in RTP, the consumer also should align their electricity consumption accordingly in such a way that the desired operating limits of these loads are not violated as some of the loads such as hot water usage cannot be controlled by the EMS without violating their preferred limits. It is possible for utility to change the demand limits according to RTP for effective peak demand reduction through the developed EMS. Importantly, the peak load reduction in the domestic sectors can help in reducing the overloading of the distribution network as well as power generation. The analysis shows that there is a limit on how much demand response can be performed in the domestic sector. It is expected that the results of this work can benefit to utilities in providing a better understanding of the limits and possibilities of demand response in domestic sector. Additionally, this will provide financial motivation for the domestic consumers in participating demand response programs.

6.2 Scope for Future Works

This work can be used for doing further detailed demand response studies on analyzing the impact of different demand response policies and customer behaviors on non-critical power intensive load operations. It can be extended to analyze the impact of domestic demand response on distributed power system network. This EMS can also be studied for building integrated renewable energy system with/without energy storage.

In addition the load models can be developed by considering time changing technical advancements and user behavior as future work.

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Appendix A

To evaluate the developed home energy algorithm discussed in Chapter 3, a Matlab program is developed. In this program, the load models for the power intensive non-critical loads are implemented as described in Chapter 2. To evaluate the financial benefits of the developed EMS, the TOU and RTP mechanism are considered which are presented in Chapter 4 and the energy cost calculations are also carried out in the developed program.

Areas highlighted in blue are only carried out for the case of TOU energy pricing and the areas highlighted in pink are carried out only for the case of RTP.

```
% Programme Name         :      Home Energy Management
% Author                 :      M.A.S.T.Ireshika
% Version                :      Final
% Last Update            :      25/05/2014
% Software               :      Matlab

clear all;
close all;

% General Data

%-----Load Preference------------------------------------------------------

Pr_WH=4;
Pr_AC=3;
Pr_CD=2;
Pr_EV=1;

%-----Load Model for AC-------------------------

delta_T=1/60;                      %in hours (1 minute)
C_HVAC=-33000;                     %cooling capacity in Btu
Awall=1564;                        %area of the walls in square feet
Rwall=12;                          %heat resistance of the walls
Aceiling=2664;                     %area of the ceiling in square feet
Rceiling=32;                       %heat resistance of the ceiling
Awindow=228;                       %area of the windows in square feet
Rwindow=2;                         %heat resistance of the windows
ACH=0.5/60;                        %no of air changes in slot i
Vhouse=21312;                      %volume of the house
Tout1=34;                          %in Celsius
Tout=(Tout1*9/5)+32;               %convert to Fahrenheit
C_air=0.0195;                      %specific heat capacity of air
SGHC=0.67;                         %solar heat gain coefficient for windows
A_Swin=32;                         %area of the south facing windows
H_solar=xlsread('Solar_radiation.xlsx','B:B');%import solar radiation data
H_p=3*392.38;                      %heat gain from 3 people
```

```
Ts1_AC=20;                         %in Celsius
Ts_AC=(Ts1_AC*9/5)+32;             %convert to Fahrenheit
delta_temp=2;                        %in Celsius
Ts_max_AC=(Ts1_AC+delta_temp)*9/5+32;%upper limit of AC in Fahrenheit
Ts_min_AC=(Ts1_AC-delta_temp)*9/5+32;%lower limit of AC in Fahrenheit
P_AC=2.352;                          %AC power consumption

%------------Load Model for Water Heater-----------------------------------

V_tank=80;                             %volume of the tank in gallons
fr=xlsread('Water_usage_RT.xlsx','B:B')%water usage in gallons per minute
T_inlet1=20;                           %inlet water temperature in Celsius
T_inlet=(T_inlet1*9/5)+32;             %conversion to Fahrenheit
P_WH=4;                                %power consumption of water heater
A_tank=14;                             %surface area of the tank
R_tank=16;                             %heat resistance of the tank
Ts1_WH=48;                             %water temperature set point_Celsius
Ts_WH=(Ts1_WH*9/5)+32;                 %conversion to Fahrenheit
T_outlet_i1=44;                        %initial temperature water_ Celsius
T_outlet_i=(T_outlet_i1*9/5)+32;       %conversion to Fahrenheit
eff_WH=0.8;                            %efficiency of the water heater
Delta_Temp_WH=6;                       %allowable temperature band_ Celsius
Temp_low1=Ts1_WH-Delta_Temp_WH;        %lower limit of water temperature
Temp_low=(Temp_low1*9/5)+32;           %conversion to Fahrenheit

%-------------Load Model for Cloth Dryer-----------------------------------

P_m=0.3;                               %motor power consumption in kW
P_HC=3.7;                              %heating coil power demand in kW
M=5;                                   %no of drying levels
k=5/M;                                 %selected drying level
Required_time_CD=90;                   %duration of drying job
Start_Time_CD=(13)*60;                 %starting time at 6 p.m.
Acc_ON_Time=0;                         %accumulated time of job in slot_i

%-------------Load Model for Electric Vehicle------------------------------

P_EV=3.6;                              %EV power with charge rate of 3.6 kW
C_batt=24;                             %capacity of the battery in kWh
E_dr=15;                               %energy used in driving in kWh
SOC_0=(1-E_dr/C_batt)*100;             %initial state of charge
SOC_max=100;                           %maximum state of charge
charge_rate=3.6;                       %charging rate
Req_charge_time_EV=(SOC_max-SOC_0)/(100*(P_EV*delta_T/C_batt))
Finish_Time_EV=12*60;                  %required finish time for user
Start_Time_EV=11*60;                   %starting time of EV
Charge_time_EV=0;                      %accumulated on time of EV


%-------------Critical Loads-----------------------------------------------

P_cri=xlsread('Critical_loads2.xlsx','B:B');%import critical load data

%-------------Pricing Data-------------------------------------------------

%---------TOU Energy Price-------------------------------------------------

On_Peak_price=20.3217;
Off_Peak_price=6.1132;
Super_Off_Peak_price=1.3063;
```

```
%---------RT Energy Price-----------------------------------------------------

HUP=xlsread('Real_Time_Pricing.xlsx','B:B');%import Hourly Unit Price
```

```
%--------------TOU Time Intervals------------------------------------------

Off_Peak1_Start_Time=1*60;             %at 7 a.m.
On_Peak_Start_Time=8*60;               %at 2 p.m.
Off_Peak2_Start_Time=13*60;            %at 7 p.m.
Off_Peak2_Finish_Time=17*60;           %at 11 p.m.
```

```
%--------------------Demand charge ----------------------------------------

On_peak_Demand_Charge_perkW=18.09*1;
Off_peak_Demand_Charge_perkW=18.09*0.75;
Super_off_peak_Demand_charge_perkW=18.09*0.5;

%--------------------Energy -----------------------------------------------

En_tot=0;                           %accumulated total energy consumed
Energy_cost=0;                      %accumulated total cost
Max_demand=0;                       %Maximum demand
Max_demand_Time=0;                  %Maximum demand occurrence time
Power_noDL=xlsread('power_no_DL_RT_LP2.xlsx');

%------------------Initial Data--------------------------------------------
Time=1;
WWHi=0;
DWHi=0;
WACi=0;
DACi=0;
WCDi=0;
DCDi=0;
WEVi=0;
DEVi=0;
Ti=Ts_AC;                           %initial room temperature
End_time=60*24;                     %total simulation time (24 hours)

while Time<= End_time

 %-----------------Demand Limit--------------------------------------------
```

```
%--------------- TOU Demand Limits-----------------------------------------

if Time<Off_Peak1_Start_Time
    DL=20;
    else if Time<On_Peak_Start_Time
      DL=8;
       else if Time<Off_Peak2_Start_Time
         DL=5;
           else if Time<Off_Peak2_Finish_Time
             DL=8.5;
              else
                DL=20;
           end;
```

```
        end;
     end;
  end;
```

```
%----------RTP Demand Limits-----------------------------------------------
if Time<60
    DL=9;
    else if Time<8*60
     DL=8;
      else if Time<12*60
        DL=5;
         else if Time<12.5*60
          DL=8;
           else if Time<15*60
            DL=5;
             else if Time<16*60
              DL=8.5;
               else if Time<17*60
                DL=4;
                 else
                  DL=9;
                 end;
               end;
            end;
         end;
      end;
   end;
end;
```

```
%-----------------------------------Pricing--------------------------------
```

```
%-----------------------------------TOU Pricing----------------------------

if Time<=Off_Peak1_Start_Time
   Pri_i=Super_Off_Peak_price;
    else if Time<=On_Peak_Start_Time
       Pri_i=Off_Peak_price;
       else if Time<=Off_Peak2_Start_Time
          Pri_i=On_Peak_price;
          else if Time<=Off_Peak2_Finish_Time
             Pri_i=Off_Peak_price;
             else
               Pri_i=Super_Off_Peak_price;
          end;
       end;
    end;
end;
```

```
%-----------------------------------RT Pricing----------------------------

Pri_i=HUP(Time);              %energy price in time slot_i
```

```
%---------------------------Demand charge-------------------------------

if Time<=Off_Peak1_Start_Time
   Demand_Pri_i=Super_off_peak_Demand_charge_perkW;
  else if Time<=On_Peak_Start_Time
    Demand_Pri_i=Off_peak_Demand_Charge_perkW;
     else if Time<=Off_Peak2_Start_Time
       Demand_Pri_i=On_peak_Demand_Charge_perkW;
         else if Time<=Off_Peak2_Finish_Time
           Demand_Pri_i=Off_peak_Demand_Charge_perkW;
            else
             Demand_Pri_i=Super_off_peak_Demand_charge_perkW;
         end;
     end;
  end;
end;

%----------------Load Modelling--------------------------------------------

%----------------Critical Loads--------------------------------------------

P_cri_i=P_cri(Time);

%--------------------AC Unit-----------------------------------------------

%----------Deciding Status of AC Unit--------------------------------------

if Ti>=Ts_max_AC        %if temperature exceed max-limit switch on AC
    WACi=1;
end;
if Ti<=Ts_min_AC        %if temperature drops below min-limit switch off AC
    WACi=0;
end;

%-----Calculating Room temperature and power in time slot_i---------------

Gi=((Awall/Rwall)+(Aceiling/Rceiling)+(Awindow/Rwindow)+(1.177*ACH*Vhouse))
*(Tout-Ti)+(SGHC*A_Swin*H_solar(Time)*3.412/10.76)+H_p;

delta_c=C_air*Vhouse;
Ti_new=Ti+delta_T*(Gi/delta_c) +delta_T*(C_HVAC*WACi*DACi/delta_c);
P_AC_i=P_AC*WACi*DACi;

%-------------------------Water Heater-------------------------------------

%----------Deciding Status of the Water heater-----------------------------

if T_outlet_i<Temp_low  %if temperature exceed min-limit switch on WH
    WWHi=1;
end;
if T_outlet_i>=Ts_WH    %if temperature exceed max-limit switch-off WH
    WWHi=0;
end;
```

```
%-----Calculating outlet temperature and power in time slot----------------

fr_i=fr(Time);           %water usage in time slot_i in gpm
Ta=Ti;                   %ambient temperature=room temperature
P_WHi=WWHi*P_WH*DWHi;    %water heater power consumption

%outlet water temperature

T_outlet_new=(T_outlet_i*(V_tank-fr_i*delta_T*60)/V_tank)
+(T_inlet*fr_i*delta_T*60/V_tank)
+(P_WHi*eff_WH*3412-A_tank*(T_outlet_i-Ta)/R_tank)*delta_T/V_tank;


%----------Cloth Dryer Model-----------------------------------------------

%----------Deciding Status of the Cloth dryer------------------------------

if Time<Start_Time_CD
   WCDi=0;
  else if Acc_ON_Time<Required_time_CD
      WCDi=1;
    else
       WCDi=0;
  end;
end;

%-----Calculating CD Power in time slot_i----------------------------------

    P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;

%----------Electric Vehicle Model------------------------------------------

%----------Deciding Status of the Electric vehicle-------------------------

if Time<Start_Time_EV
    SOC_i=SOC_0;
    WEVi=0;
  else if single(SOC_i)<SOC_max
      WEVi=1;
     else
         WEVi=0;
  end;
end;

%-----Calculating EV Power in time slot_i---------------------------------

P_EV_i=P_EV*WEVi*DEVi;

%-----Calculating total Total power in time slot---------------------------

Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;


%------DR control signal for water heater----------------------------------

if WWHi==1 && DWHi==0          %check request to turn on from WH
    if DL>Tot_P_i              %check if household power is below DL
     DWHi=1;                   %EMS decides to turn on WH
     P_WHi=WWHi*P_WH*DWHi;
```

```
     Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
    end;

%if household load is above DL turn off low priority loads and turn on WH
if DL<Tot_P_i
    while DL<Tot_P_i
       switch x
          case 1
             if WEVi==1 && DEVi==1
                if Pr_EV<Pr_WH
                   DEVi=0;
                   DWHi=1;
                   P_EV_i=P_EV*WEVi*DEVi;
                   P_WHi=WWHi*P_WH*DWHi;
                   Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
                else
                   Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
               end;
             else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=x+1;
             end;
          case 2
             if WCDi==1 && DCDi==1
               if Pr_CD<Pr_WH
                  DCDi=0;
                  DWHi=1;
                  P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                  P_WHi=WWHi*P_WH*DWHi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               end;
             else
             Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
             x=x+1;
            end;
         case 3
             if WACi==1 && DACi==1
               if Pr_AC<Pr_WH
                 DACi=0;
                 DWHi=1;
                 P_AC_i=P_AC*WACi*DACi;
                 P_WHi=WWHi*P_WH*DWHi;
                 Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                 x=x+1;
               else
                 Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                 x=x+1;
               end;

             else
             Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
             x=x+1;
            end
         case 4
            if WWHi==1 && DWHi==1
```

```
               if Pr_WH<Pr_WH
                  DWHi=0;
                  P_WHi=WWHi*P_WH*DWHi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               end;
            else
             Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
             x=1;
             break;
            end;
         end;
      end;
    x=1;
   end;
end;


%after switching on of WH check total power of house and switch off loads

if DL<Tot_P_i
   while DL<Tot_P_i
      switch y
         case 1
            if WEVi==1 && DEVi==1
               DEVi=0;
               P_EV_i=P_EV*WEVi*DEVi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 2
            if WCDi==1 && DCDi==1
               DCDi=0;
               P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 3
            if WACi==1 && DACi==1
               DACi=0;
               P_AC_i=P_AC*WACi*DACi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               DWHi=0;
```

```
               P_WHi=WWHi*P_WH*DWHi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               break;
            end;
         end;
      end;
    y=1;
 end;

%------DR control signal for AC unit--------------------------------------

if WACi==1 && DACi==0
   if DL>Tot_P_i
      DACi=1;
      P_AC_i=P_AC*WACi*DACi;
      Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
   end;

if DL<Tot_P_i
    while DL<Tot_P_i
       switch x
          case 1
             if WEVi==1 && DEVi==1
                if Pr_EV<Pr_AC
                   DEVi=0;
                   DACi=1;
                   P_EV_i=P_EV*WEVi*DEVi;
                   P_AC_i=P_AC*WACi*DACi;
                   Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
                else
                   Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
                end;
             else
                Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                x=x+1;
             end;
          case 2
             if WCDi==1 && DCDi==1
                if Pr_CD<Pr_AC
                   DCDi=0;
                   DACi=1;
                   P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                   P_AC_i=P_AC*WACi*DACi;
                   Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
                else
                   Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
                end;
              else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               x=x+1;
              end;

         case 3
            if WACi==1 && DACi==1
               if Pr_AC<Pr_AC
                  DACi=0;
                  P_AC_i=P_AC*WACi*DACi;
```

```
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=x+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               if Pr_WH<Pr_AC
                  DWHi=0;
                  DACi=1;
                  P_WHi=WWHi*P_WH*DWHi;
                  P_AC_i=P_AC*WACi*DACi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=1;
              break;
            end;
         end;
      end;
    x=1;
  end;
end;

%after swiching on of AC check total power of house and switch off loads
if DL<Tot_P_i
   while DL<Tot_P_i
      switch y
         case 1
            if WEVi==1 && DEVi==1
               DEVi=0;
               P_EV_i=P_EV*WEVi*DEVi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 2
            if WCDi==1 && DCDi==1
            DCDi=0;
            P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
            Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
            y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 3
```

```
            if WACi==1 && DACi==1
               DACi=0;
               P_AC_i=P_AC*WACi*DACi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               DWHi=0;
               P_WHi=WWHi*P_WH*DWHi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               break;
            end;
         end;
      end;
    y=1;
end;



%------DR control signal for Cloth Dryer--------------------------------

if WCDi==1 && DCDi==0
   if DL>Tot_P_i
      DCDi=1;
      P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
      Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
   end;

if DL<Tot_P_i
   while DL<Tot_P_i
      switch x
         case 1
            if WEVi==1 && DEVi==1
               if Pr_EV<Pr_CD
                  DEVi=0;
                  DCDi=1;
                  P_EV_i=P_EV*WEVi*DEVi;
                  P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=x+1;
            end;
         case 2
            if WCDi==1 && DCDi==1
               if Pr_CD<Pr_CD
                  DCDi=0;
                  P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                   x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
```

```
                  x=x+1;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=x+1;
            end;
         case 3
            if WACi==1 && DACi==1
               if Pr_AC<Pr_CD
                  DACi=0;
                  DCDi=1;
                  P_AC_i=P_AC*WACi*DACi;
                  P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=x+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               if Pr_WH<Pr_CD
                  DWHi=0;
                  DCDi=1;
                  P_WHi=WWHi*P_WH*DWHi;
                  P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
              x=1;
              break;
            end;
         end;
     end;
   x=1;
  end;
end;

%after switching on of cloth dryer check total power of house and switch off loads

if DL<Tot_P_i
   while DL<Tot_P_i
      switch y
         case 1
            if WEVi==1 && DEVi==1
               DEVi=0;
               P_EV_i=P_EV*WEVi*DEVi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
```

```
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 2
            if WCDi==1 && DCDi==1
            DCDi=0;
            P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
            Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
            y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 3
            if WACi==1 && DACi==1
               DACi=0;
               P_AC_i=P_AC*WACi*DACi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               DWHi=0;
               P_WHi=WWHi*P_WH*DWHi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               break;
            end;
         end;
      end;
    y=1;
end;

%------DR control signal for Electric Vehicle------------------------------

if WEVi==1 && DEVi==0
    if DL>Tot_P_i
       DEVi=1;
       P_EV_i=P_EV*WEVi*DEVi;
       Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
    end;

if DL<Tot_P_i
   while DL<Tot_P_i
      switch x
         case 1
            if WEVi==1 && DEVi==1
               if Pr_EV<Pr_EV
                  DEVi=0;
                  P_EV_i=P_EV*WEVi*DEVi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
                end;
             else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
```

```
               x=x+1;
             end;
         case 2
            if WCDi==1 && DCDi==1
               if Pr_CD<Pr_EV
                  DCDi=0;
                  DEVi=1;
                  P_EV_i=P_EV*WEVi*DEVi;
                  P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               end;
            else
              Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               x=x+1;
            end;
         case 3
            if WACi==1 && DACi==1
               if Pr_AC<Pr_EV
                  DACi=0;
                  DEVi=1;
                  P_EV_i=P_EV*WEVi*DEVi;
                  P_AC_i=P_AC*WACi*DACi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=x+1;
               else
                 Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                 x=x+1;
               end;
            else
             Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
             x=x+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               if Pr_WH<Pr_CD
                  DWHi=0;
                  DEVi=1;
                  P_EV_i=P_EV*WEVi*DEVi;
                  P_WHi=WWHi*P_WH*DWHi;
                  Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                  x=1;
                  break;
               else
                 Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
                 x=1;
                 break;
               end;
            else
             Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
             x=1;
             break;
            end;
         end;
      end;
    end;
end;
```

```
%after switching on of EV check total power of house and switch off loads

if DL<Tot_P_i
   while DL<Tot_P_i
      switch y
         case 1
            if WEVi==1 && DEVi==1
               DEVi=0;
               P_EV_i=P_EV*WEVi*DEVi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 2
            if WCDi==1 && DCDi==1
            DCDi=0;
            P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
            Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
            y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 3
            if WACi==1 && DACi==1
               DACi=0;
               P_AC_i=P_AC*WACi*DACi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 4
            if WWHi==1 && DWHi==1
               DWHi=0;
               P_WHi=WWHi*P_WH*DWHi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               break;
            end;
         end;
      end;
    y=1;
end;

%if EV needs early give a high priority to EV


if Time<(Finish_Time_EV+Start_Time_EV)
    if P_EV_i==0
       if (Req_charge_time_EV-
Charge_time_EV)>(Finish_Time_EV+Start_Time_EV-Time)
            DEVi=1;
            P_EV_i=P_EV*WEVi*DEVi;
            Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
       end;
    end;
end;
```

```
%after switching on of EV check total power of house and switch off loads

if DL<Tot_P_i
   while DL<Tot_P_i
      switch y
         case 1
            if WCDi==1 && DCDi==1
            DCDi=0;
            P_CD_i=k*P_HC*WCDi*DCDi+P_m*WCDi;
            Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
            y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 2
            if WACi==1 && DACi==1
               DACi=0;
               P_AC_i=P_AC*WACi*DACi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            else
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               y=y+1;
            end;
         case 3
            if WWHi==1 && DWHi==1
               DWHi=0;
               P_WHi=WWHi*P_WH*DWHi;
               Tot_P_i=P_EV_i+P_CD_i+P_WHi+P_AC_i+P_cri_i;
               break;
            end;
         end;
      end;
    y=1;
end;

%-----------------Update EV SOC--------------------------------------------

if WEVi==1 && DEVi==1
   SOC_i_new=SOC_i+(P_EV*delta_T/C_batt)*100;
   SOC_i=SOC_i_new;
   Charge_time_EV=Charge_time_EV+1;
else
   SOC_i=SOC_i;
end;

%-----------------Update Cloth Dryer on Time-------------------------------

if WCDi==1 && DCDi==1
   Acc_ON_Time=Acc_ON_Time+1;
end;

%-----------------Find Maximum Demand--------------------------------------

if Tot_P_i>=Max_demand
    Max_demand_Time=Time;
    Max_demand=Tot_P_i;
    Demand_charge=Demand_Pri_i*Max_demand;
end;
```

```
%---------Calculating Total Energy Consumed--------------------------------
          En_i=Tot_P_i*delta_T;
          En_tot=En_tot+En_i;
          cost_i=En_i*Pri_i;
          Energy_cost=Energy_cost+cost_i;

%--------------Saving Data to plot wave forms------------------------------
            Plot_T_outlet(Time)=(T_outlet_i-32)*5/9;
            PlotWWH(Time)=WWHi*DWHi;
            PlotMax_WH(Time)=Ts1_WH;
            PlotMin_WH(Time)=Temp_low1;
            PlotP_WH(Time)= P_WHi;
            PlotTime(Time)=Time;
            PlotTemp(Time)=(Ti-32)*5/9;
            PlotWAC(Time)=WACi*DACi;
            PlotPAC(Time)=P_AC_i;
            PlotMax_AC(Time)=Ts1_AC+delta_temp;
            PlotMin_AC(Time)=Ts1_AC-delta_temp;
            PlotWCD(Time)=WCDi*DCDi;
            PlotP_CD(Time)=P_CD_i;
            PlotPEV(Time)=P_EV_i;
            PlotSOC(Time)=SOC_i;
            PlotTotPower(Time)=Tot_P_i;
            PlotCtri_power(Time)=P_cri_i;
            PlotEn(Time)=En_i;
            Plotprice(Time)=Pri_i;
            PlotDemandCharge(Time)=Demand_Pri_i;
            Plotcost(Time)=cost_i;
            PlotDL(Time)=DL;
            PlotPowernoDL(Time)=Power_noDL(Time);

%-----------------Update Room Temperature and Time-------------------------

T_outlet_i=T_outlet_new;
Ti=Ti_new;Time=Time+1;

end;

%xlswrite('power_no_DL_RT_LP2.xlsx',PlotTotPower);

%----------Plotting Ac unit wave forms-------------------------------------

figure;
[haxes,hline1,hline2] = plotyy(PlotTime,PlotTemp,PlotTime,PlotPAC);
set(hline1,'Color','b','linewidth',1.5)% to change the first line
set(hline2,'Color',[0.2 0.8 0],'linewidth',1.5) % to change the second line
set(haxes, 'XTick',(0:60:1440));
set(haxes,
'XTickLabel',{'6AM','7AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM
','4PM','5PM','6PM','7PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM
','4AM','5AM','6AM'});
set(haxes, 'Xlim',[0,1440]);
set(haxes(1),'ylim',[16,24]);
set(haxes(1), 'YTick',(16:2:24));
set(haxes(2), 'YTick',(0:0.5:2.5));
set(haxes(2),'ylim',[0,2.5]);
set(haxes(2),'YColor',[0.2 0.8 0])
hold on;
plot(PlotTime,PlotMax_AC,'r','LineWidth',1.5);
hold on;
plot(PlotTime,PlotMin_AC,'r', 'LineWidth',1.5);
```

```
grid;
title('Plot of Room Temperature over Time '); % title
ylabel(haxes(1),'Room Temperature (^0C)') % label left y-axis
ylabel(haxes(2),'Power Demand (kW) ') % label right y-axis
xlabel(haxes(2),'Time (Minutes)') % label x-axis


%-----------Plotting Critical Loads Power Demand----------------------------
figure;
plot(PlotTime,PlotCtri_power,'linewidth',1.5);
grid;
xlim([0,1440]);
ylim([0,2.2]);
set(gca, 'XTick',(0:60:1440));
set(gca,
'XTickLabel',{'6AM','7AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM
','4PM','5PM','6PM','7PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM
','4AM','5AM','6AM'}');
title('Plot of Power Demand of Critical Loads over Time '); % title
ylabel('Load Demand (kW)');% label for y axis
xlabel('Time (Minutes)');% label for x axis

%----------Plotting WH unit wave forms-------------------------------------
figure;
[haxes,hline3,hline4] = plotyy(PlotTime,Plot_T_outlet,PlotTime,PlotP_WH);
set(hline3,'Color','b','linewidth',1.5)% to change the first line
set(hline4,'Color',[0.2 0.8 0],'linewidth',1.5) % to change the second line
set(haxes(1),'ylim',[40,50]);
set(haxes(1), 'YTick',(40:2:50));
set(haxes(2),'ylim',[0,4.5]);
set(haxes(2), 'YTick',(0:1:4.5));
set(haxes, 'Xlim',[0,1440]);
set(haxes, 'XTick',(0:60:1440));
set(haxes(2),'YColor',[0.2 0.8 0])
set(haxes,
'XTickLabel',{'6AM','7AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM
','4PM','5PM','6PM','7PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM
','4AM','5AM','6AM'}');
grid;
hold on;
plot(PlotTime,PlotMax_WH,'r','linewidth',1.5);
hold on;
plot(PlotTime,PlotMin_WH,'r','linewidth',1.5);
title('Plot of  Outlet Water  Temperature over Time '); % title
ylabel(haxes(1),'Water Temperature (^0C)') % label left y-axis
ylabel(haxes(2),'Load Demand (kW) ') % label right y-axis
xlabel(haxes(2),'Time (Minutes)') % label x-axis


%----------Plotting CD wave forms------------------------------------------
figure;
[haxes,hline5,hline6] = plotyy(PlotTime,PlotP_CD,PlotTime,PlotWCD);
set(hline5,'Color','b','linewidth',1.5)% to change the first line
set(hline6,'linestyle', ':','Color',[0.2 0.8 0],'linewidth',1.5) % to
change the second line
grid;
set(haxes, 'Xlim',[0,1440]);
set(haxes, 'XTick',(0:60:1440));
set(haxes(1),'ylim',[0,4.5]);
set(haxes(1), 'YTick',(0:0.5:4.5));
```

```
set(haxes(2),'ylim',[0,1.05]);
set(haxes(2),'YColor',[0.2 0.8 0])
set(haxes,
'XTickLabel',{'6AM','7AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM
','4PM','5PM','6PM','7PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM
','4AM','5AM','6AM'}');
title('Plot of  Power Demand of Cloths Dryer over Time '); % title
ylabel(haxes(1),'Power Demand (kW)') % label left y-axis
ylabel(haxes(2),'Status ') % label right y-axis
xlabel(haxes(2),'Time (Minutes)') % label x-axis

%----------Plotting EV  wave forms-----------------------------------------

figure;
[haxes,hline7,hline8] = plotyy(PlotTime,PlotPEV,PlotTime,PlotSOC);
set(hline7,'Color','b','linewidth',1.5)% to change the first line
set(hline8,'Color',[0.2 0.8 0],'linewidth',1.5) % to change the second line
grid;
set(haxes(1),'ylim',[0,4]);
set(haxes(1), 'YTick',(0:0.5:4));
set(haxes(2),'ylim',[0,105]);
set(haxes, 'Xlim',[0,1440]);
set(haxes, 'XTick',(0:60:1440));
set(haxes(2),'YColor',[0.2 0.8 0])
set(haxes,
'XTickLabel',{'6AM','7AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM
','4PM','5PM','6PM','7PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM
','4AM','5AM','6AM'}');
title('Plot of  Power Demand of Electric Vehicle over Time '); % title
ylabel(haxes(1),'Power Demand (kW)') % label left y-axis
ylabel(haxes(2),'State of Charge (%)  ') % label right y-axis
xlabel(haxes(2),'Time (Minutes)') % label x-axis

%----------Plotting Total Power--------------------------------------------

figure;
plot(PlotTime,PlotTotPower,'linewidth',1.5);
hold on;
plot(PlotTime,PlotPowernoDL,'--', 'Color',[0.2 0.8 0],'linewidth',1.5);
hold on;
plot(PlotTime,PlotDL, 'r','linewidth',1.5);
grid;
xlim([0,1440]);
ylim([0,16]);
set(gca, 'XTick',(0:60:1440));
set(gca,
'XTickLabel',{'6AM','7AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM
','4PM','5PM','6PM','7PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM
','4AM','5AM','6AM'}');
title('Plot of Total Household Power Demand'); % title
ylabel('Load Demand (kW)');% label for y axis
xlabel('Time (Minutes)');% label for x axis
legend('Total Household Power with Demand Limit', 'Total Household Power
without Demand Limit','Demand Limit');
```

```
%----------Plotting Price---------------------------------------------------

figure;
plot(PlotTime,Plotprice, 'r','linewidth',1.5);
grid;
xlim([0,1440]);
set(gca, 'XTick',(0:60:1440));
set(gca, 'XTickLabel',{'6AM','7
AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM','4PM','5PM','6PM','7
PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM','4AM','5AM','6AM'}')
;
title('Plot of Electricity Price over Time '); % title
ylabel('Price (cents)');% label for y axis
xlabel('Time (Minutes)');% label for x axis
%Demand Charge

figure;
plot(PlotTime,PlotDemandCharge, 'r','linewidth',1.5);
grid;
xlim([0,1440]);
set(gca, 'XTick',(0:60:1440));
set(gca, 'XTickLabel',{'6AM','7
AM','8AM','9AM','10AM','11AM','12PM','1PM','2PM','3PM','4PM','5PM','6PM','7
PM','8PM','9PM','10PM','11PM','12AM','1AM','2AM','3AM','4AM','5AM','6AM'}')
;
title('Plot of Variation of Demand Charge over Time '); % title
ylabel('Price ($)');% label for y axis
xlabel('Time (Minutes)');% label for x axis

Max_demand
Max_demand_Time
Energy_cost
En_tot
Average_energy=En_tot/24
Load_factor= Average_energy/Max_demand

%Bill for the month(Assuming the selected day has the peak demand

Bill=(Demand_charge+Energy_cost*0.3)
```

Appendix B

Critical Load Profile

A typical load profile for the critical loads in the household is selected for this work and the hourly variation of the critical load demand is shown in Table B.1.

Time	Power demand (kW)
6 a.m. – 7 a.m.	1.6
7 a.m. – 8 a.m.	1.3
8 a.m. – 9 a.m.	1.3
9 a.m. – 10 a.m.	1.1
10 a.m. – 11 a.m.	1
11 a.m. – 12 noon	1.2
12 noon. – 1 p.m.	1
1 p.m. – 2 p.m.	1
2 p.m. – 3 p.m.	1.3
3 p.m. – 4 p.m.	1.3
4 p.m. – 5 p.m.	1.6
5 p.m. – 6 p.m.	2
6 p.m. – 7 p.m.	1.6
7 p.m. – 8 p.m.	1.5
8 p.m. – 9 p.m.	1.5
9 p.m. – 10 p.m.	1.5
10 p.m. – 11 p.m.	1.2
11 p.m. – 12 midnight	1
12 midnight. – 1 a.m.	1
1 a.m. – 2 a.m.	1.1
2 a.m. – 3 a.m.	1
3 a.m. – 4 a.m.	1.2
4 a.m. – 5 a.m.	1.2
5 a.m. – 6 a.m.	1.4

Appendix C

Solar Radiation Data

Hourly variation of solar irradiation data in Atlanta, US for hot summer day is considered. Corresponding solar irradiation data are extracted from ASHRAE handbook [18].

Table C.1: Hourly variation of solar irradiation data in Atlanta, US

Time	Solar Radiation (W/m^2)
6 a.m. – 7 a.m.	115
7 a.m. – 8 a.m.	320
8 a.m. – 9 a.m.	528
9 a.m. – 10 a.m.	702
10 a.m. – 11 a.m.	838
11 a.m. – 12 noon	922
12 noon. – 1 p.m.	949
1 p.m. – 2 p.m.	922
2 p.m. – 3 p.m.	838
3 p.m. – 4 p.m.	702
4 p.m. – 5 p.m.	528
5 p.m. – 6 p.m.	320
6 p.m. – 7 p.m.	115
7 p.m. – 8 p.m.	1
8 p.m. – 9 p.m.	0
9 p.m. – 10 p.m.	0
10 p.m. – 11 p.m.	0
11 p.m. – 12 midnight	0
12 midnight – 1 a.m.	0
1 a.m. – 2 a.m.	0
2 a.m. – 3 a.m.	0
3 a.m. – 4 a.m.	0
4 a.m. – 5 a.m.	0
5 a.m. – 6 a.m.	1

Appendix D

D1.Water Usage Profile for case A and case B

A typical hot water usage profile is considered assuming that there are three people in the house. The hot water usage for shower, bath and cooking are considered as shown in Table D.1. The water usage profile presented in Table D.1 is used in case A and B discussed in Chapter 5.

Table D.1: A typical hot water usage profile in a house

Time	**Flow rate of water(*gpm*)**
6 a.m. – 7 a.m.	0
7 a.m. – 7.10 a.m.	2
7.20 a.m. – 7.30 a.m.	2
8 a.m. – 9 a.m.	0
9 a.m. – 10 a.m.	0
10 a.m. – 11 a.m.	0
11 a.m. – 12 noon	0
12 noon. – 1 p.m.	0
1 p.m. – 2 p.m.	0
2 p.m. – 3 p.m.	0
3 p.m. – 4 p.m.	0
4 p.m. – 5 p.m.	0
5 p.m. – 6 p.m.	0
6 p.m. – 7 p.m.	0
7 p.m. – 7.15 p.m.	5
7.15 p.m. – 8 p.m.	0
8 p.m. – 8.15 p.m.	5
8.15 p.m. – 9 p.m.	0
9 p.m. – 9.15 p.m.	3
9.15 p.m. – 10 p.m.	0
10 p.m. – 12 midnight	0
12 midnight. – 6 a.m.	0

D2.Water Usage Profile for case C, case D and case E

It is assumed that the consumer has changed the water usage timing based on the available real prices as shown in Table D.2. This water usage profile is used in case C, D and E which are discussed in Chapter 5.

Table D.2: Hot water usage profile of the house with change in user behavior for the real time prices

Time	**Flow rate of water (*gpm*)**
6 a.m. – 7 a.m.	0
7 a.m. – 7.10 a.m.	2
7.20 a.m. – 7.30 a.m.	2
8 a.m. – 9 a.m.	0
9 a.m. – 10 a.m.	0
10 a.m. – 11 a.m.	0
11 a.m. – 12 noon	0
12 noon. – 1 p.m.	0
1 p.m. – 2 p.m.	0
2 p.m. – 3 p.m.	0
3 p.m. – 4 p.m.	0
4 p.m. – 5 p.m.	0
5 p.m. – 6 p.m.	0
6 p.m. – 6.15 p.m.	5
6.20 p.m. – 7.30 p.m.	3
7.30 p.m. – 8 p.m.	0
8 p.m. – 8.15 p.m.	0
8.15 p.m. – 9 p.m.	0
9 p.m. – 9.15 p.m.	5
9.15 p.m. – 10 p.m.	0
10 p.m. – 12 midnight	0
12 midnight. – 6 a.m.	0

Appendix E

Real Time Prices

Real time prices for 7th May 2014 in US [38] are selected for the case study as in Table D.1. These data are used to calculate the energy prices for the different cases discussed in Chapter 5.

Table D.1: Real time prices for 7th May 2014 in US

Time	Price (cents/kWh)
6 a.m. – 7 a.m.	4.2
7 a.m. – 8 a.m.	4.5
8 a.m. – 9 a.m.	4.7
9 a.m. – 10 a.m.	4.9
10 a.m. – 11 a.m.	4.9
11 a.m. – 12 noon	5.1
12 noon. – 1 p.m.	5.2
1 p.m. – 2 p.m.	5.6
2 p.m. – 3 p.m.	5.9
3 p.m. – 4 p.m.	6.1
4 p.m. – 5 p.m.	6.1
5 p.m. – 6 p.m.	5.9
6 p.m. – 7 p.m.	5.1
7 p.m. – 8 p.m.	6
8 p.m. – 9 p.m.	6.5
9 p.m. – 10 p.m.	4.5
10 p.m. – 11 p.m.	4.1
11 p.m. – 12 midnight	3.4
12 midnight. – 1 a.m.	3.3
1 a.m. – 2 a.m.	3.4
2 a.m. – 3 a.m.	3.3
3 a.m. – 4 a.m.	3
4 a.m. – 5 a.m.	3.2
5 a.m. – 6 a.m.	3.7

Appendix F

All the waveforms obtained for the five cases discussed in Chapter 5 are presented in this section.

Operation of the Non-Critical Loads with TOU Pricing (Case A)

Operation of the Non-Critical Loads without EMS for TOU Energy Pricing

Water Heater

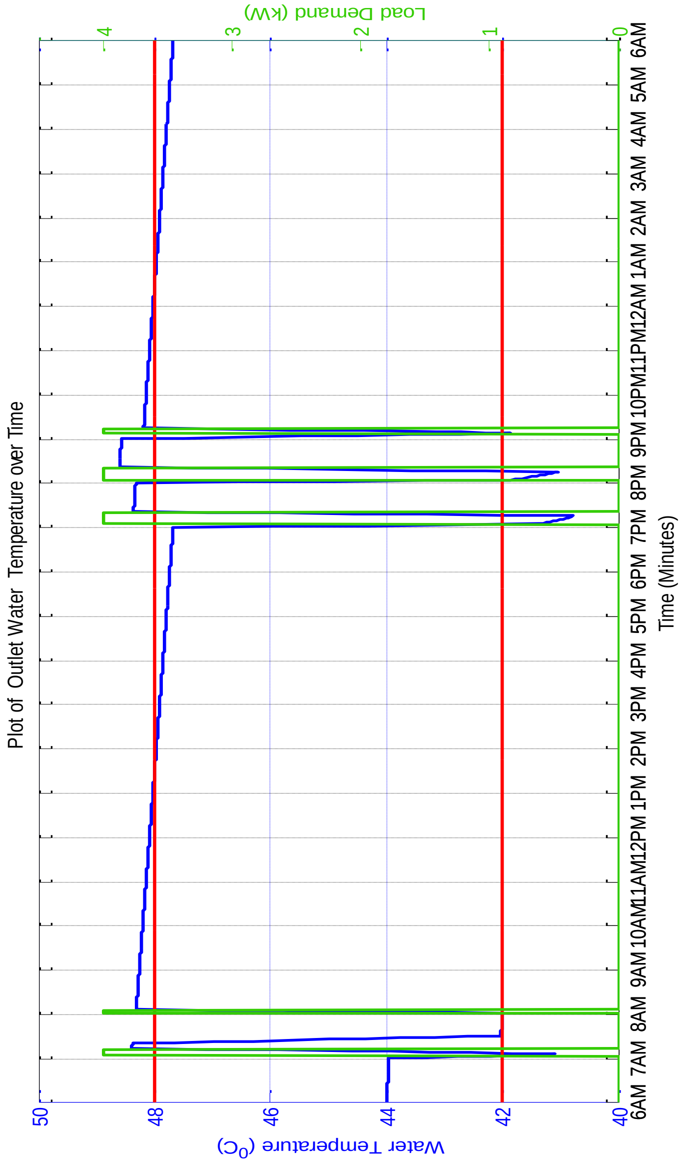

Figure 5.5: Outlet water temperature of the water heater without EMS control for TOU Pricing

AC Unit

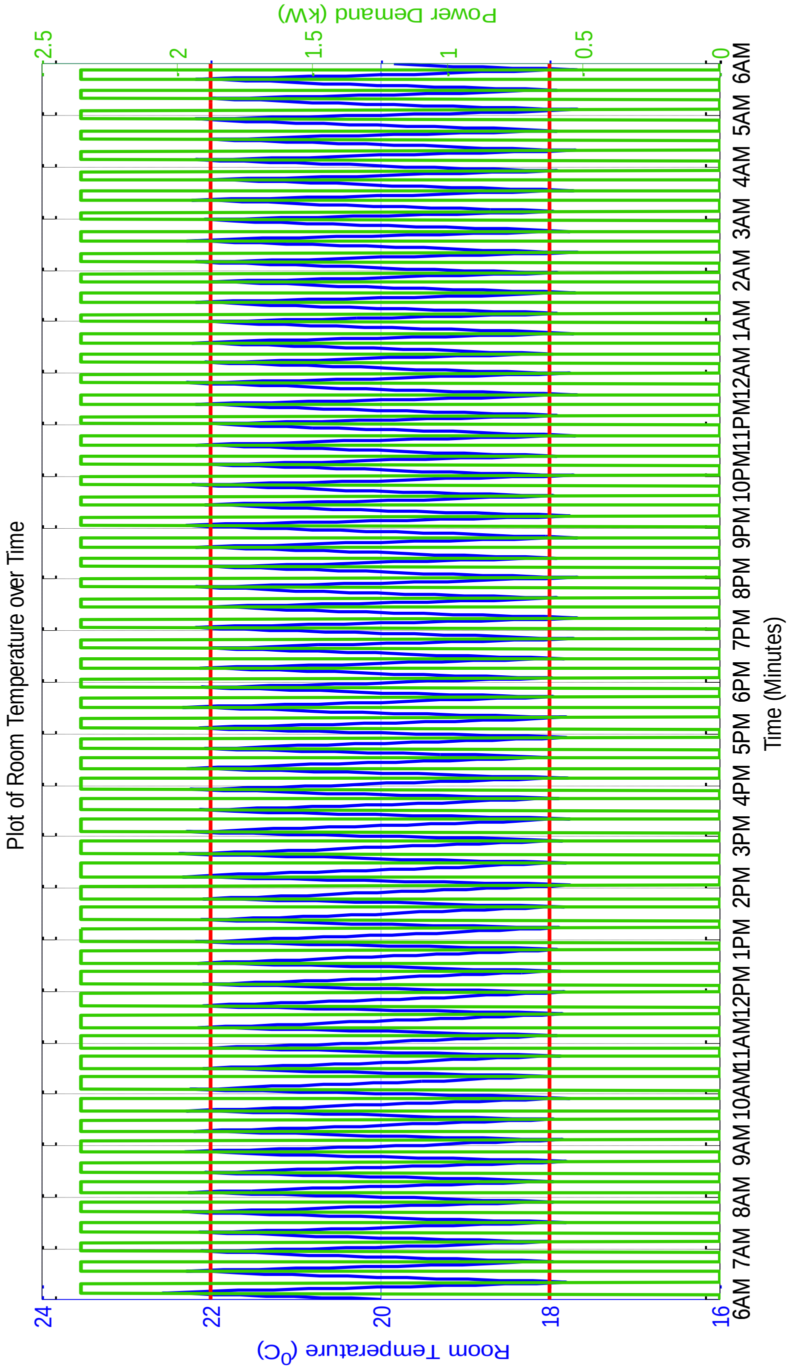

Figure 5.6: Operation of the AC unit without EMS for TOU pricing

Clothes Dryer

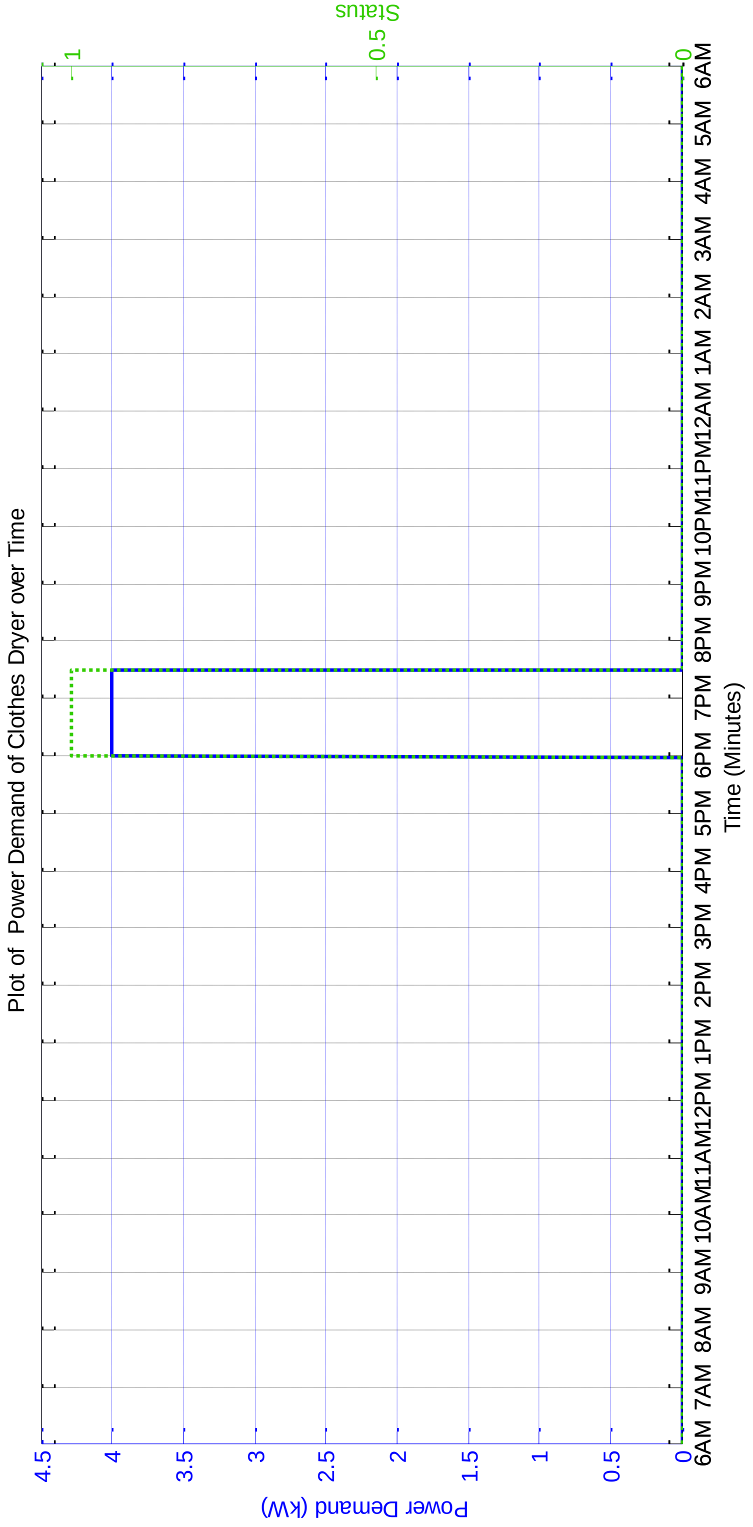

Figure 5.7: Operation of the cloth dryer without EMS control for TOU pricing

Electric Vehicle

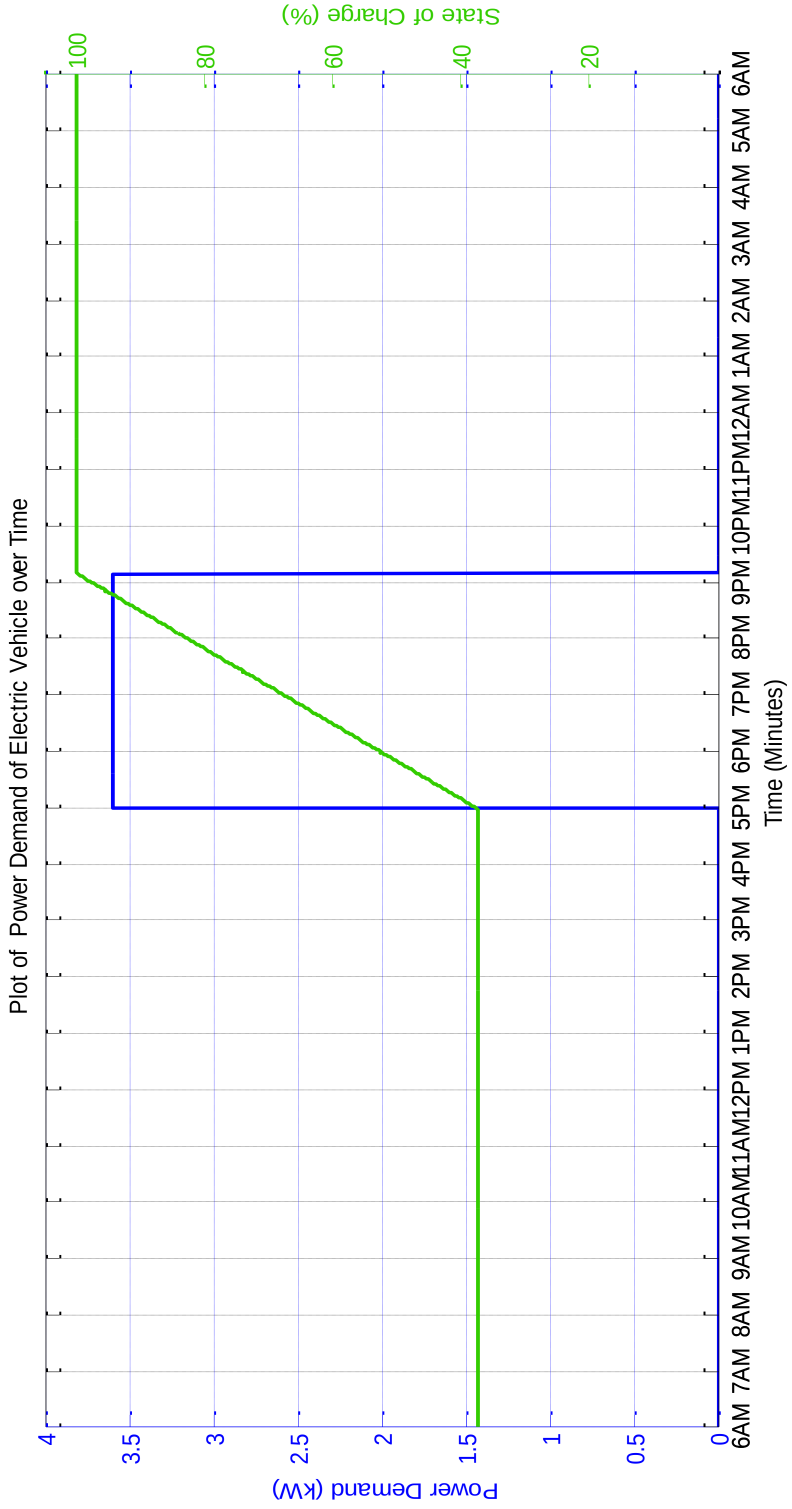

Figure 5.8: Operation of the electric vehicle without EMS for TOU pricing

Total Household Load

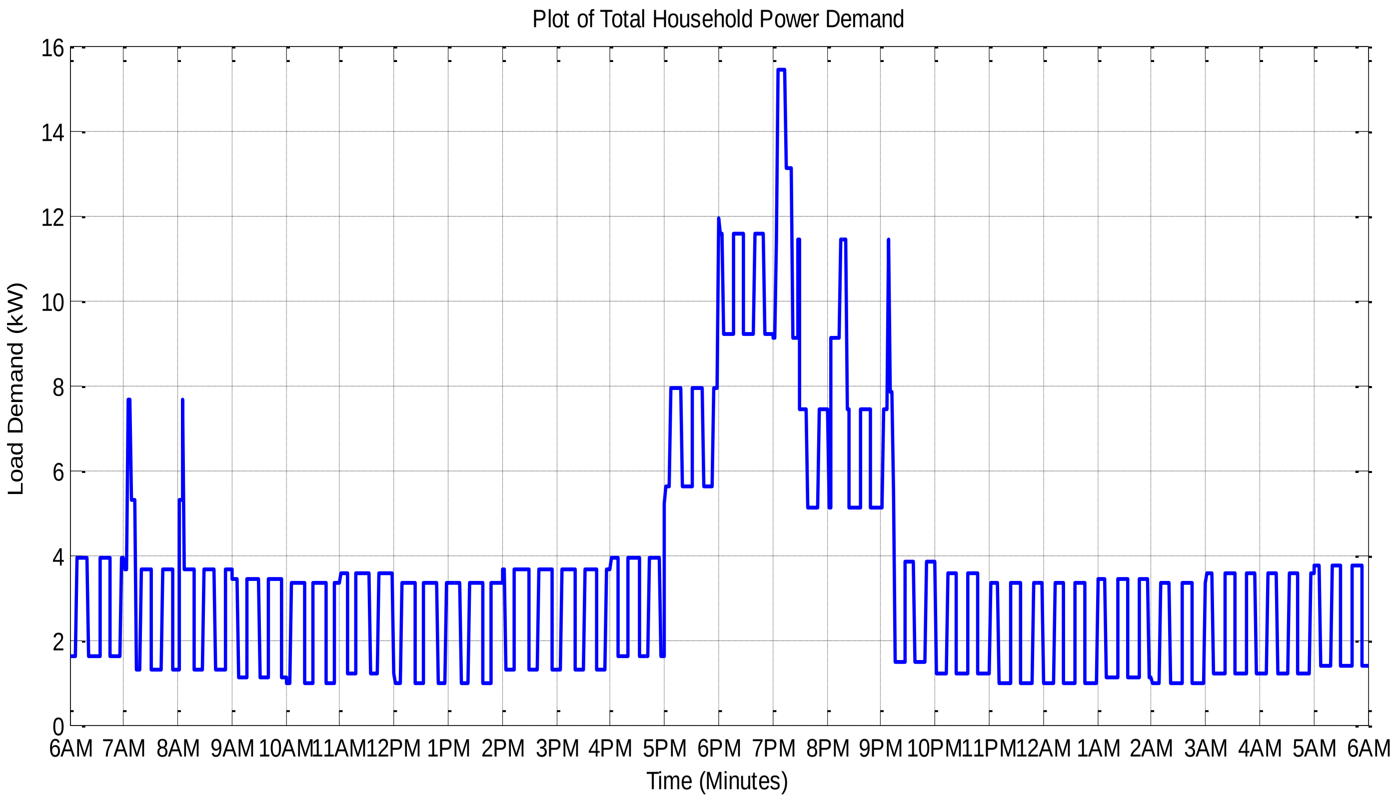

Figure 5.9: Total household load for 24 hours without EMS for TOU pricing

Operation of the Non-Critical Loads for TOU Energy Pricing with EMS

Water Heater

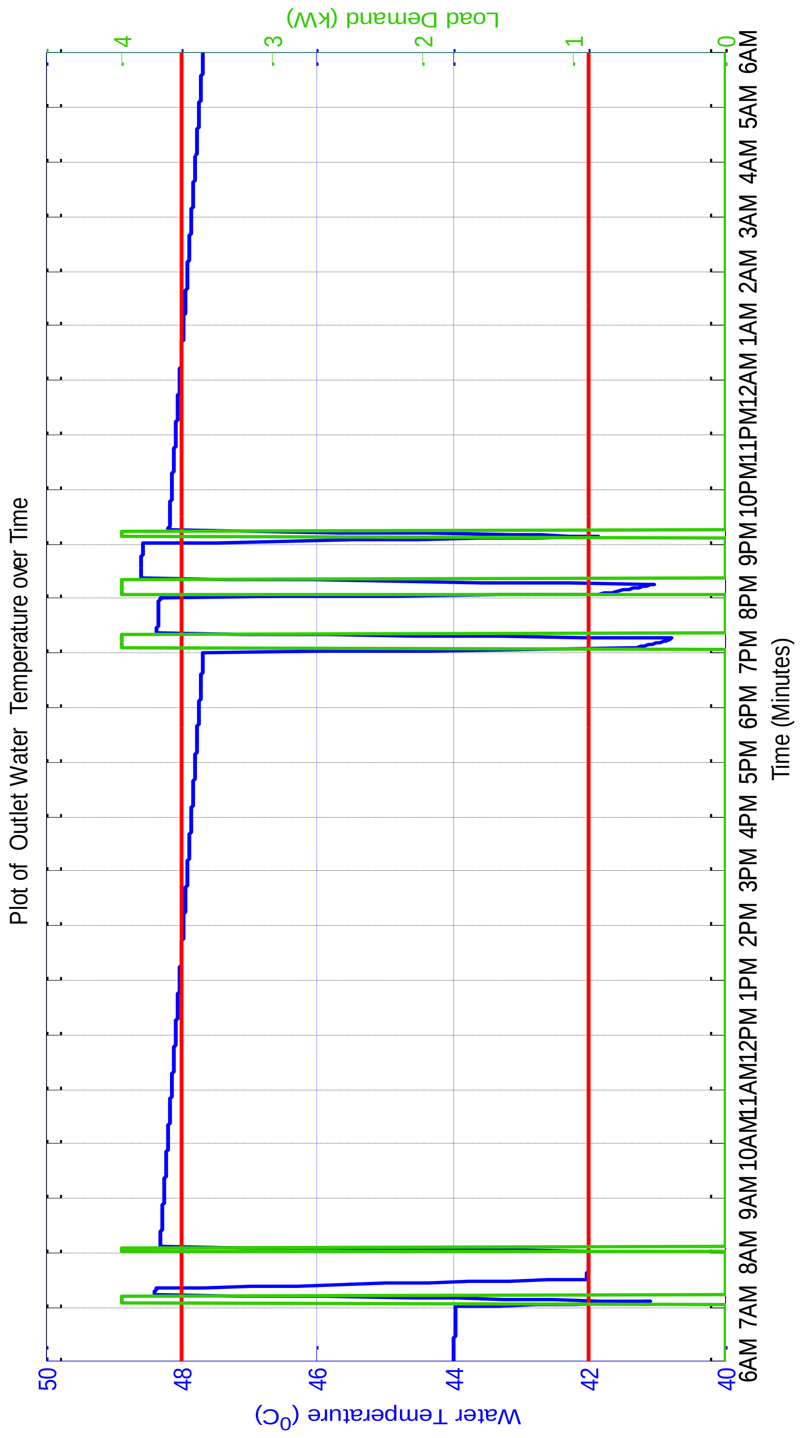

Figure 5.10: Operation of the water heater with EMS for TOU energy pricing mechanism

AC Unit

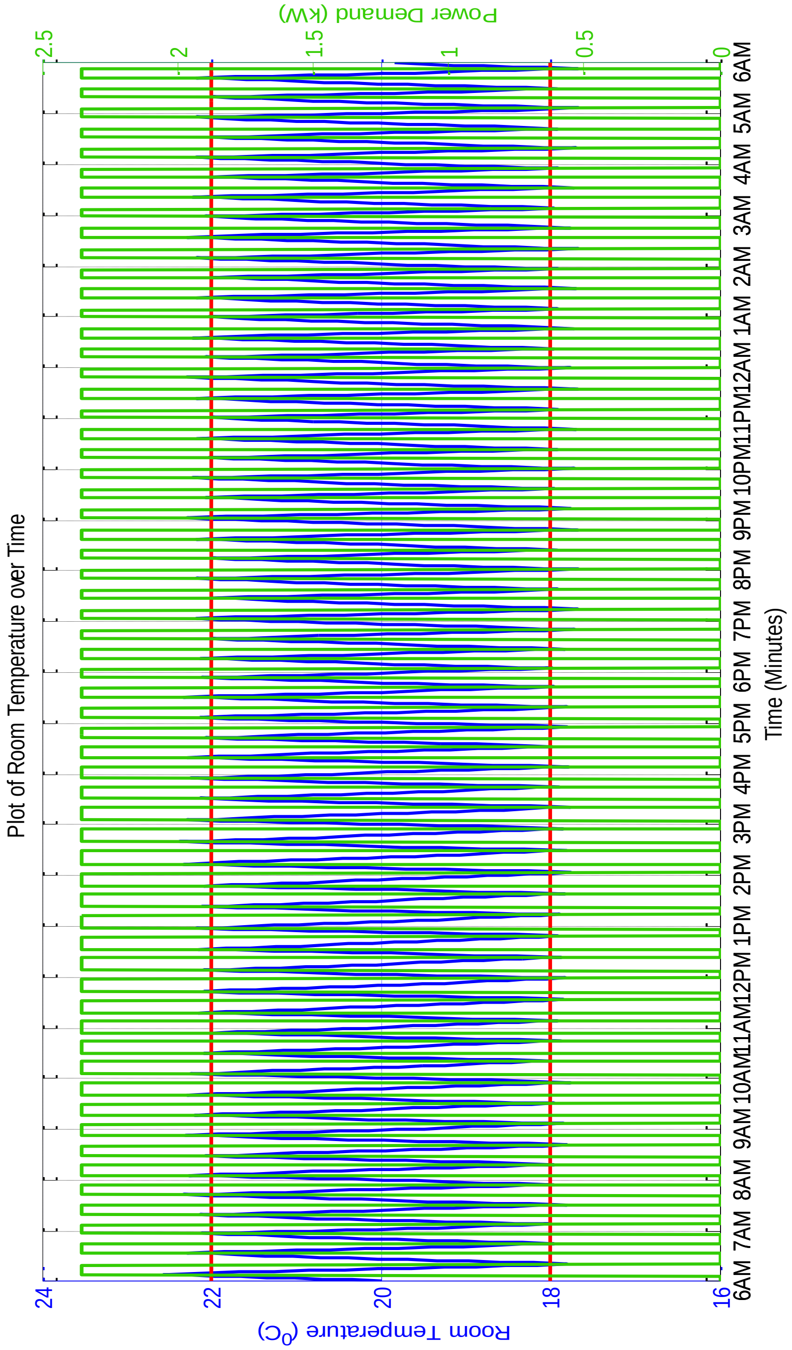

Figure 5.11: Operation of the AC unit with EMS for TOU pricing

Clothes Dryer

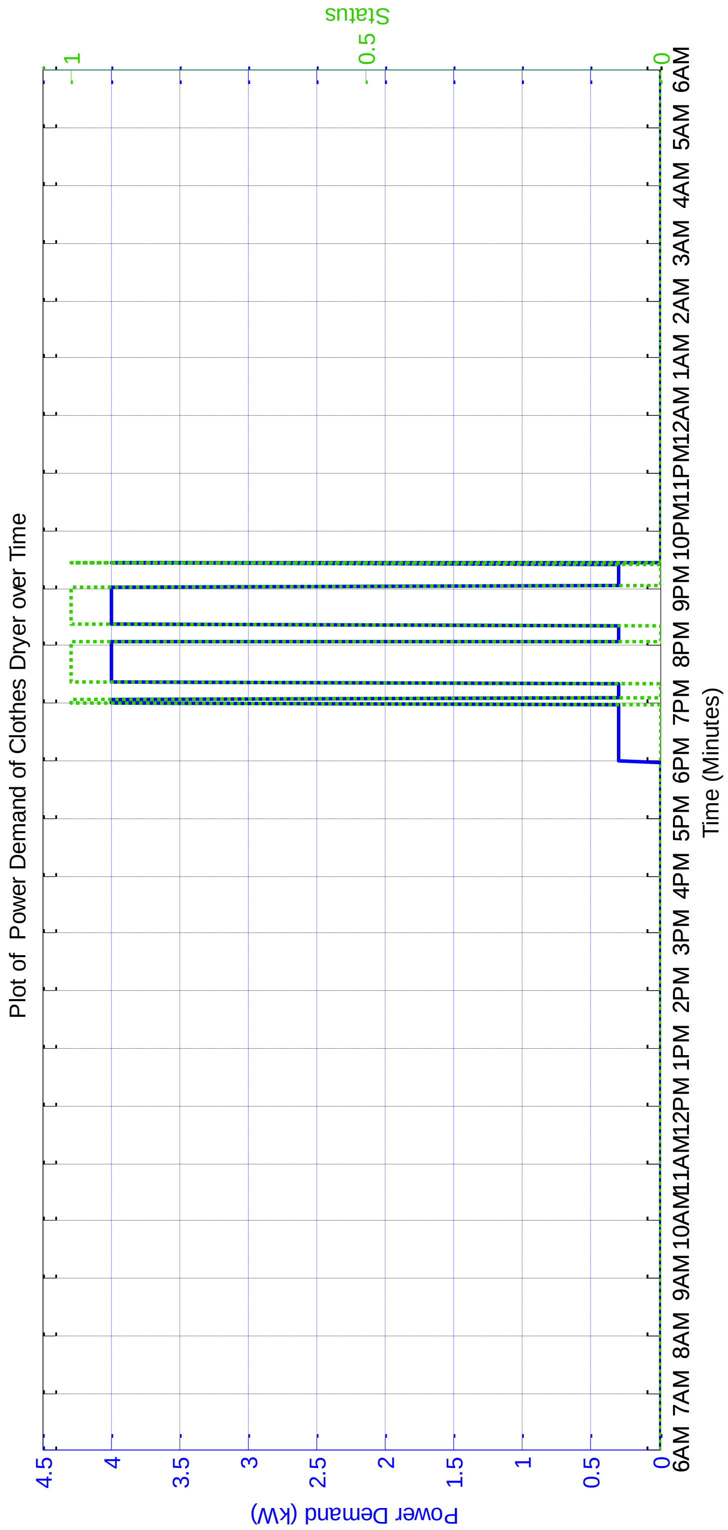

Figure 5.12: Operation of the cloth dryer with EMS for TOU pricing

Electrical vehicle

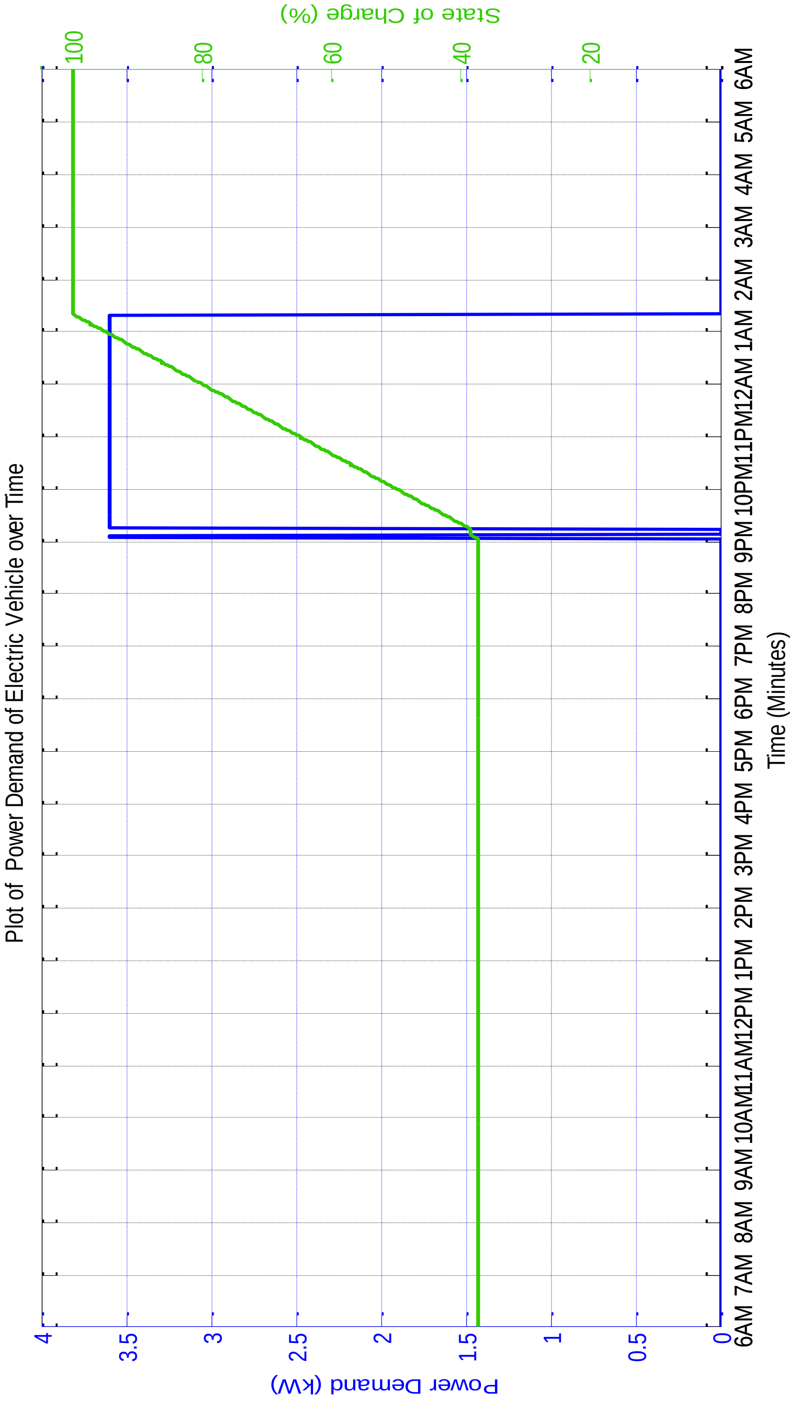

Figure 5.13: Operation of the electric vehicle with EMS for TOU pricing

Total Household Load

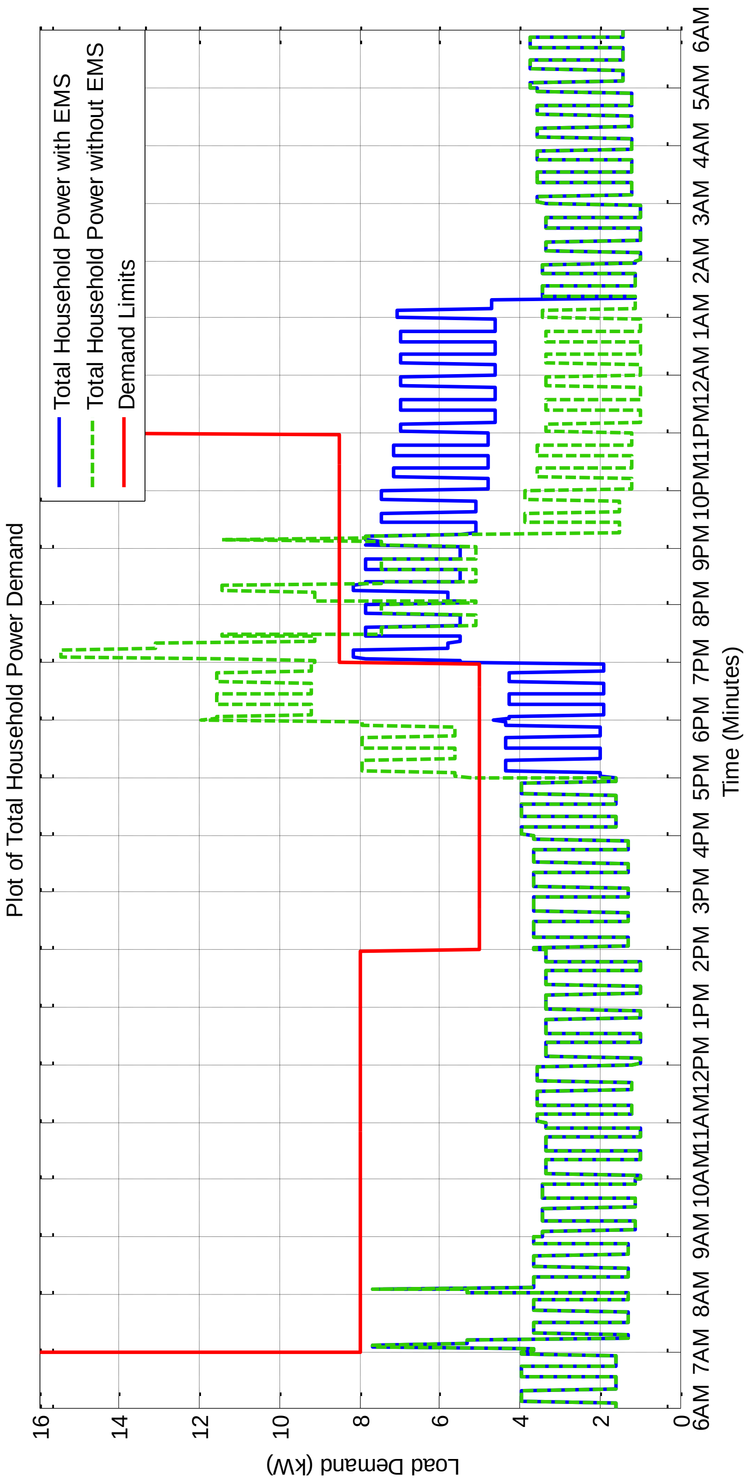

Figure 5.14: Total household load with EMS for TOU pricing

Operation of the non-critical loads with RTP (Case B)

Operation of the Non Critical Loads for RTP Energy Pricing with EMS

Water Heater

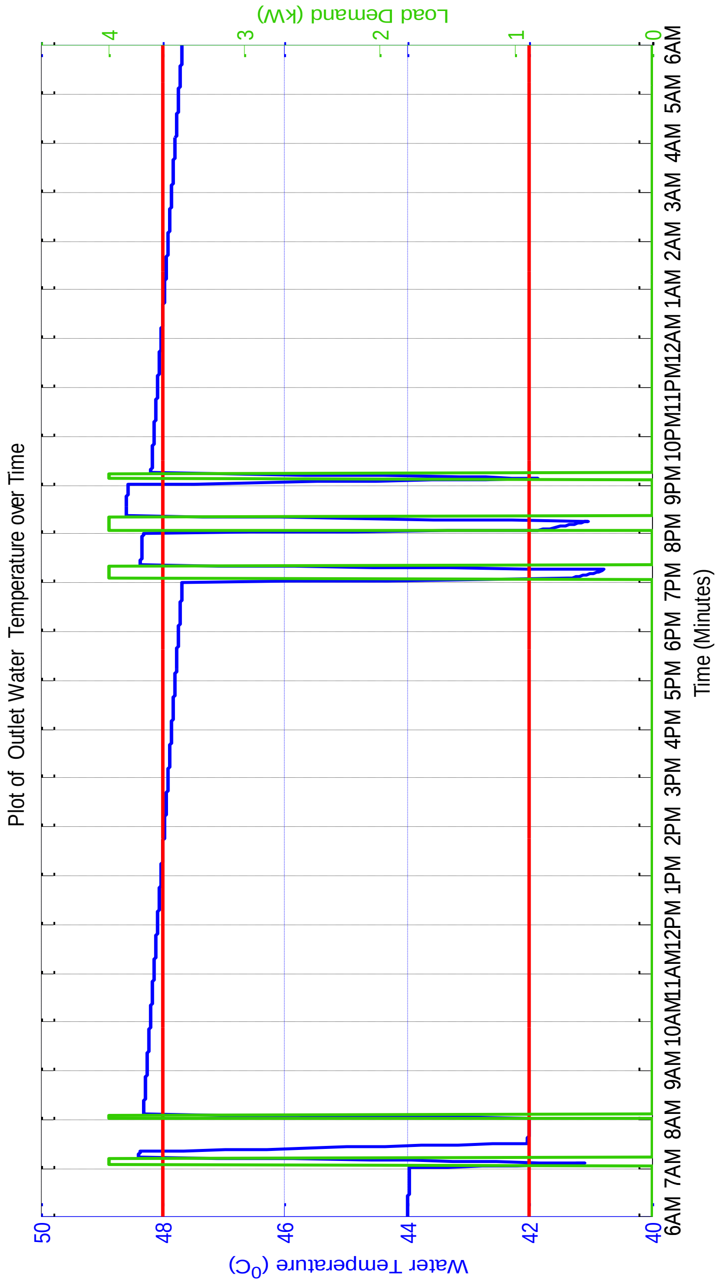

Figure 5.15: Operation of the water heater with EMS for RTP mechanism

AC Unit

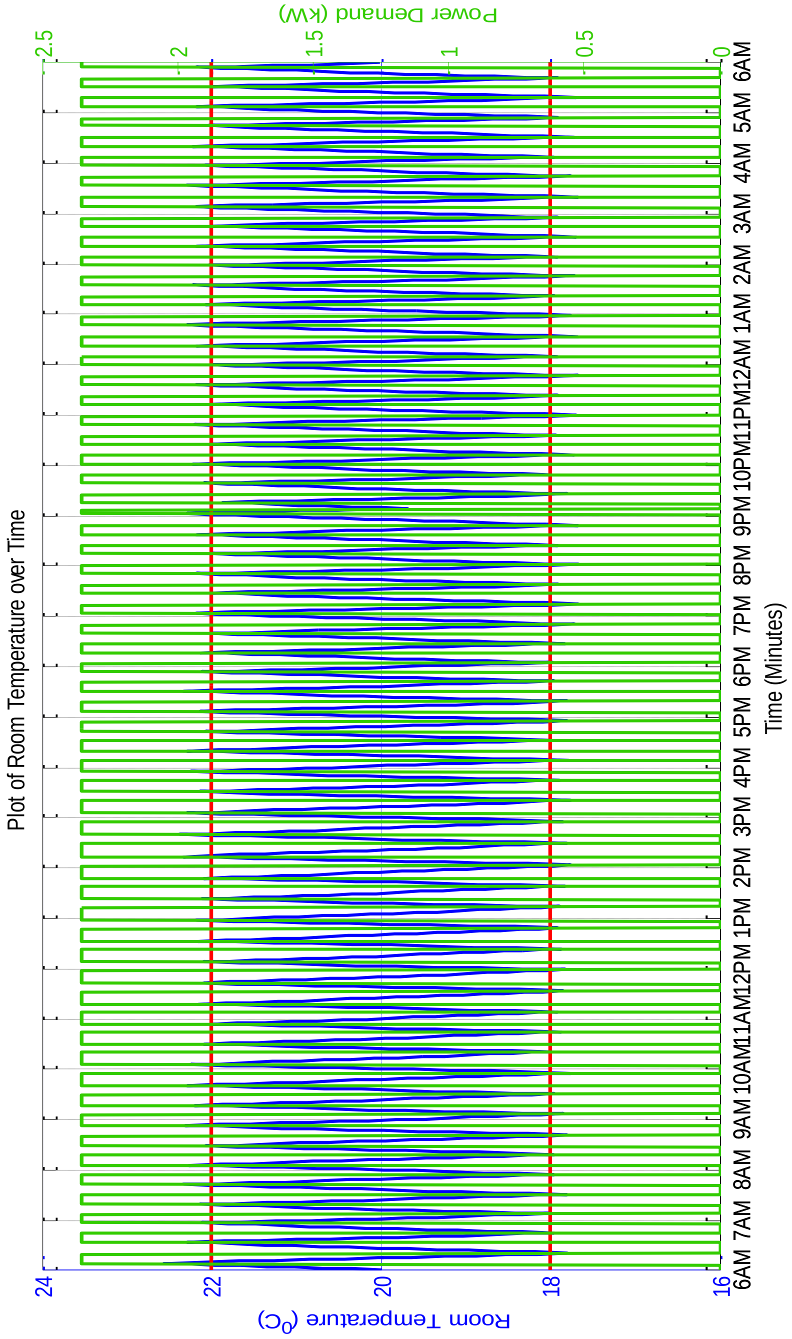

Figure 5.16: Operation of the AC unit with EMS for RTP mechanism

Clothes Dryer

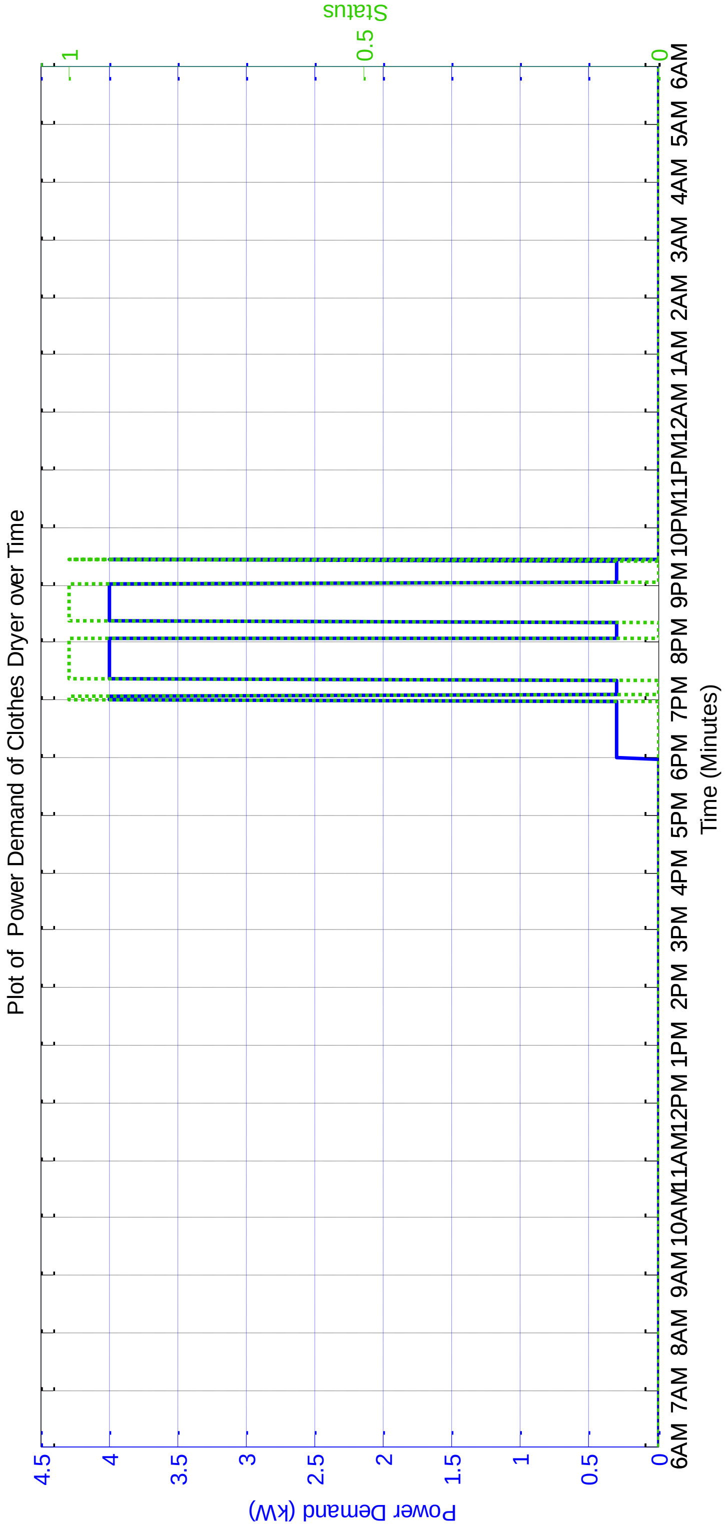

Figure 5.17: Operation of the water heater with EMS for RTP mechanism

Electric Vehicle

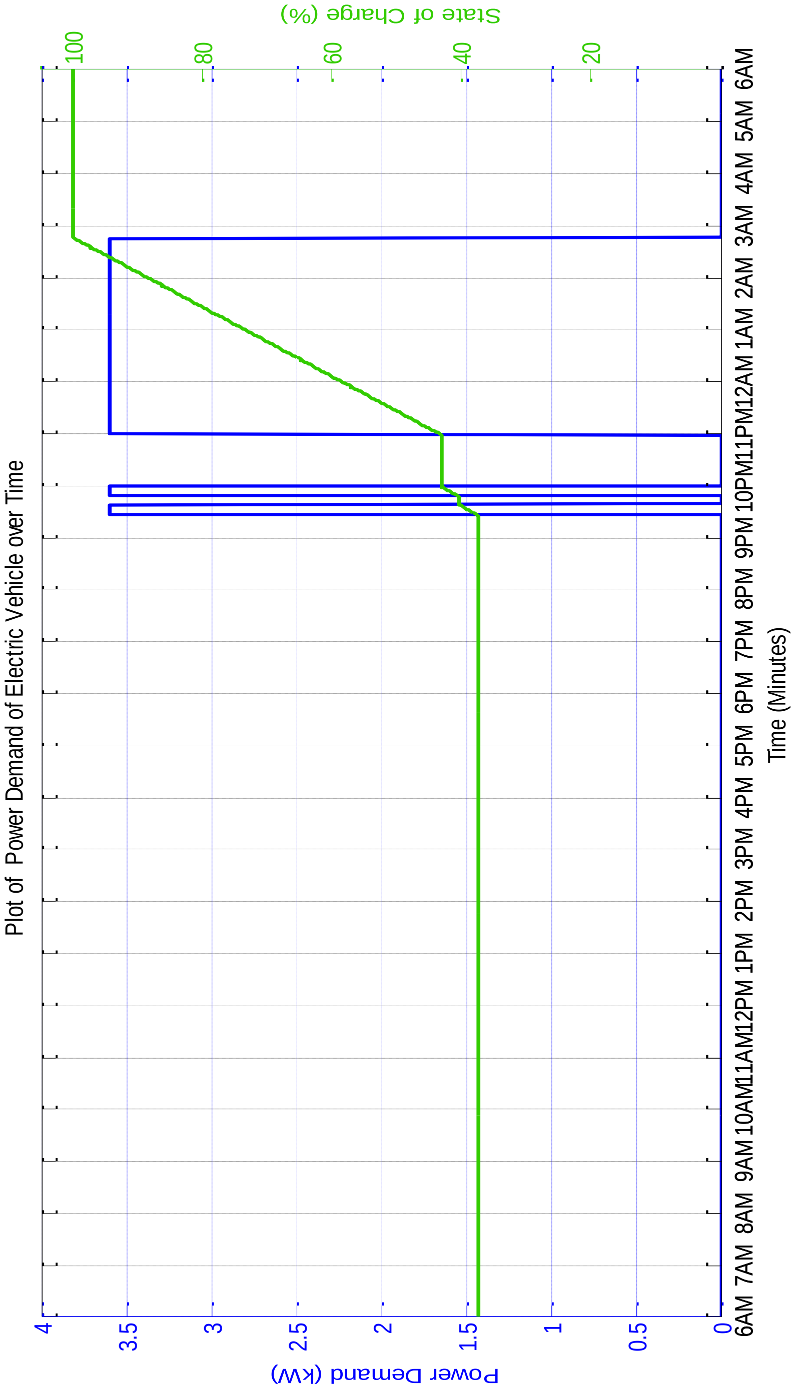

Figure 5.18: Operation of the electric vehicle with EMS for RTP mechanism

Total Household Load

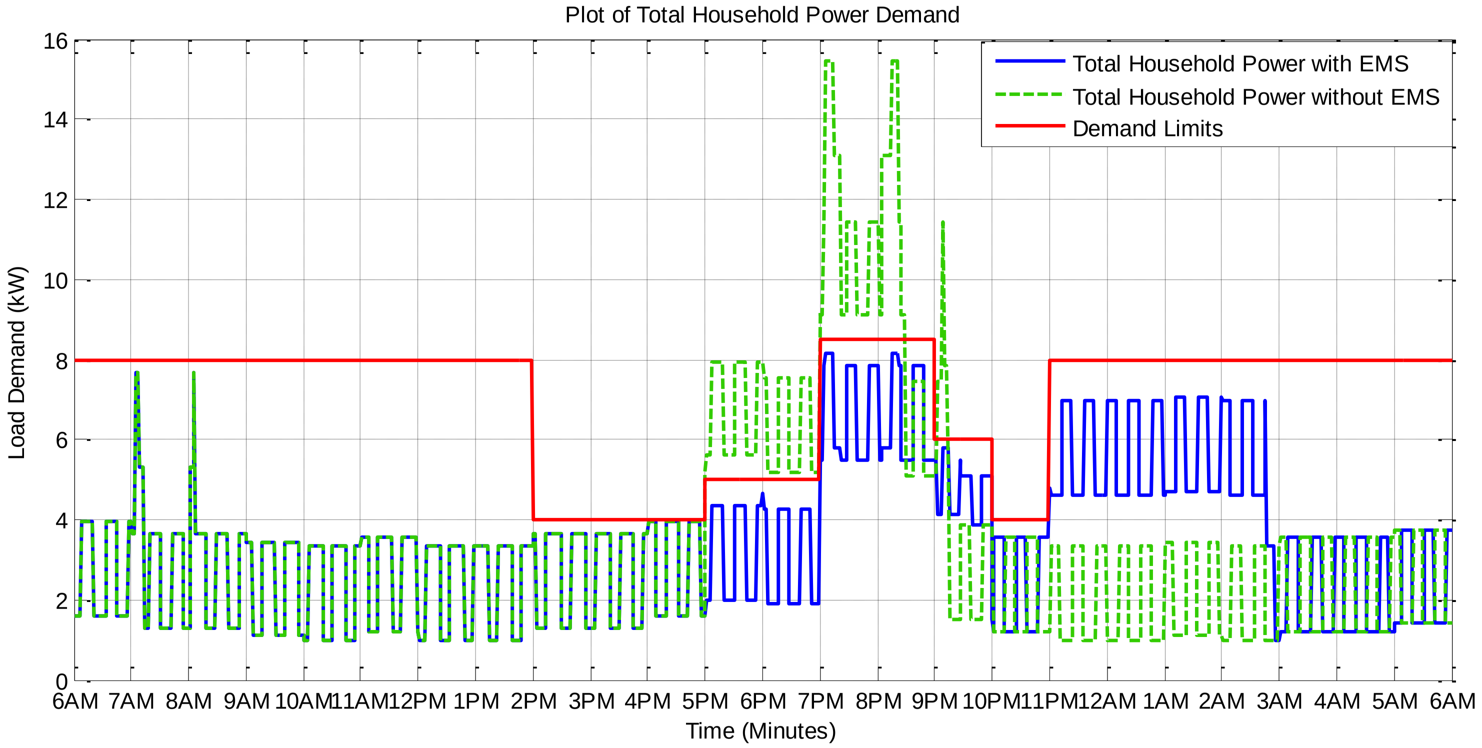

Figure 5.19: Total household energy consumption with EMS for RTP mechanism

Possible Change of User Energy Consumption Behavior Due to RTP (Case C)

Operation of the Non-Critical Loads for RTP with EMS

Water Heater

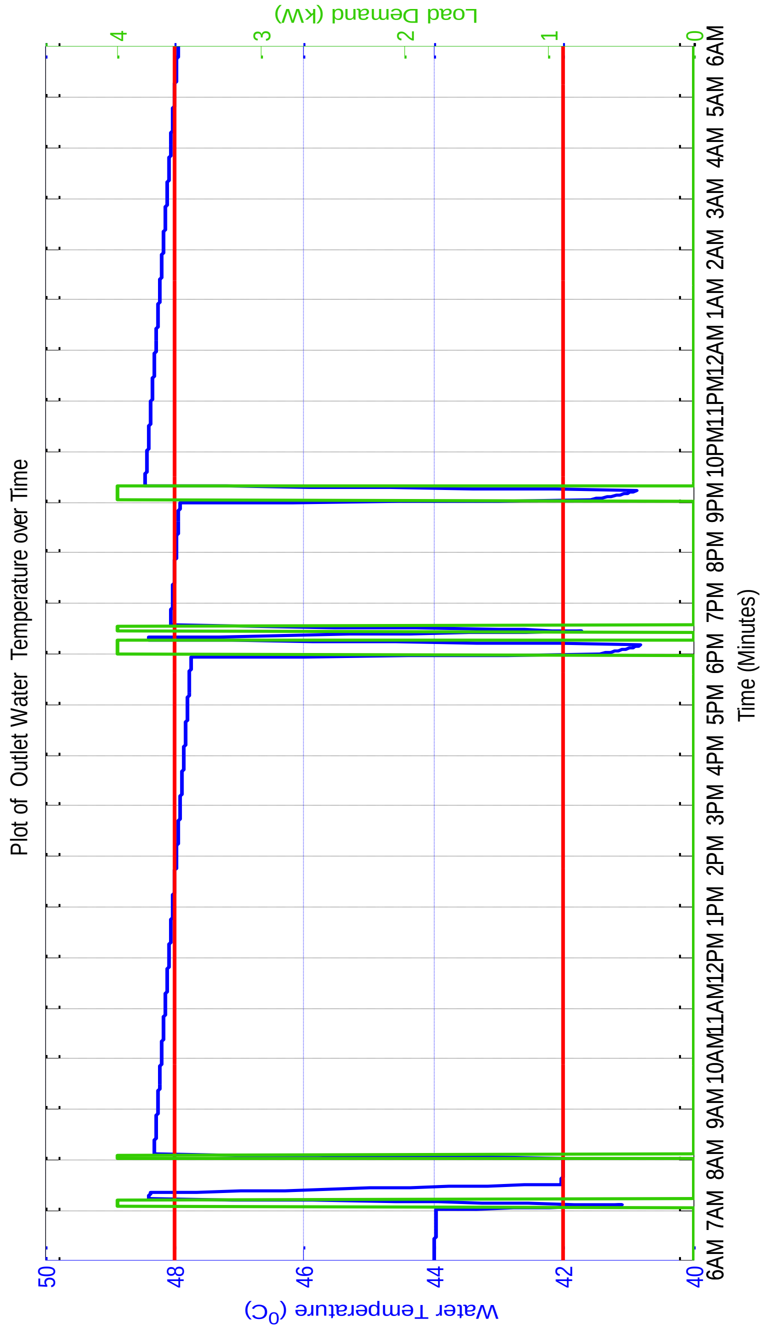

Figure 5.20: Operation of the water heater without EMS for RTP mechanism

AC Unit

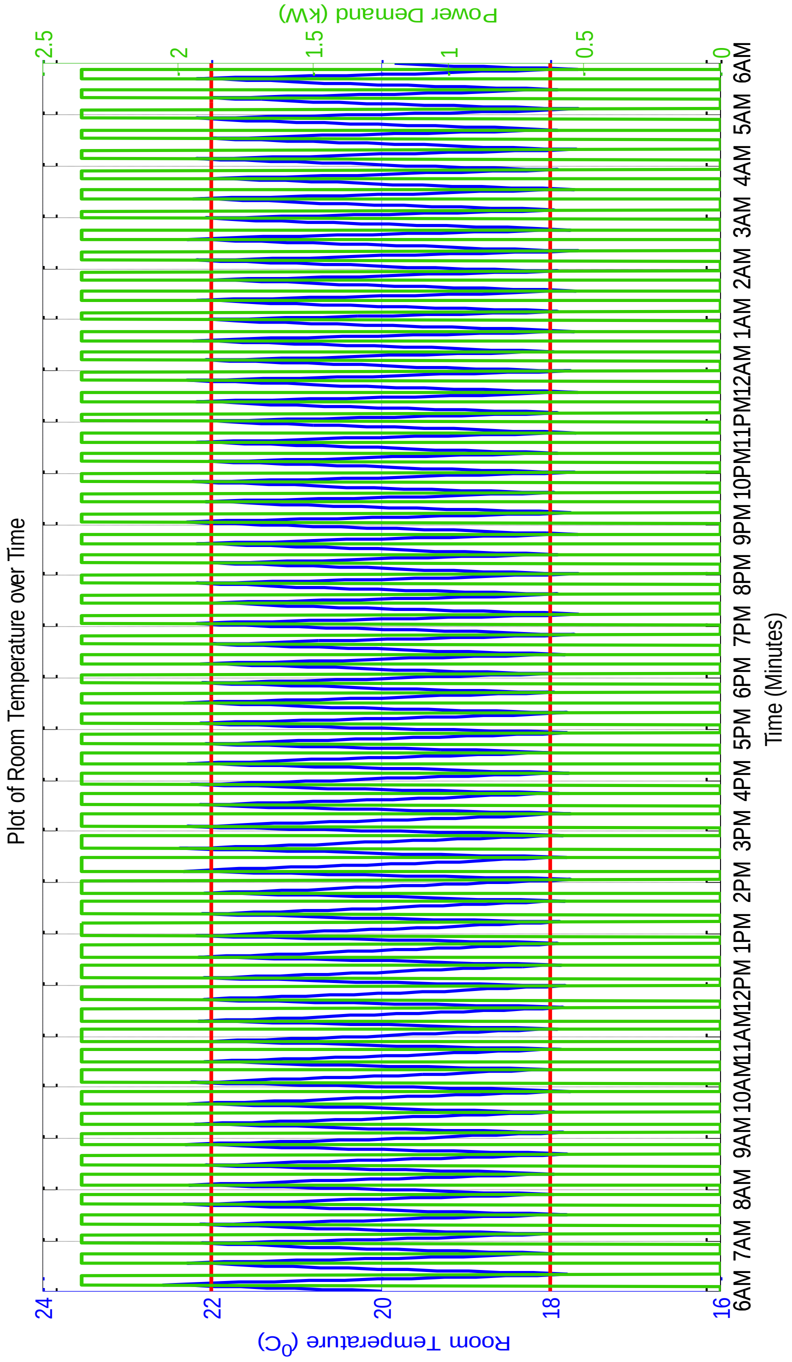

Figure 5.21: Operation of the AC unit without EMS for RTP mechanism

Clothes Dryer

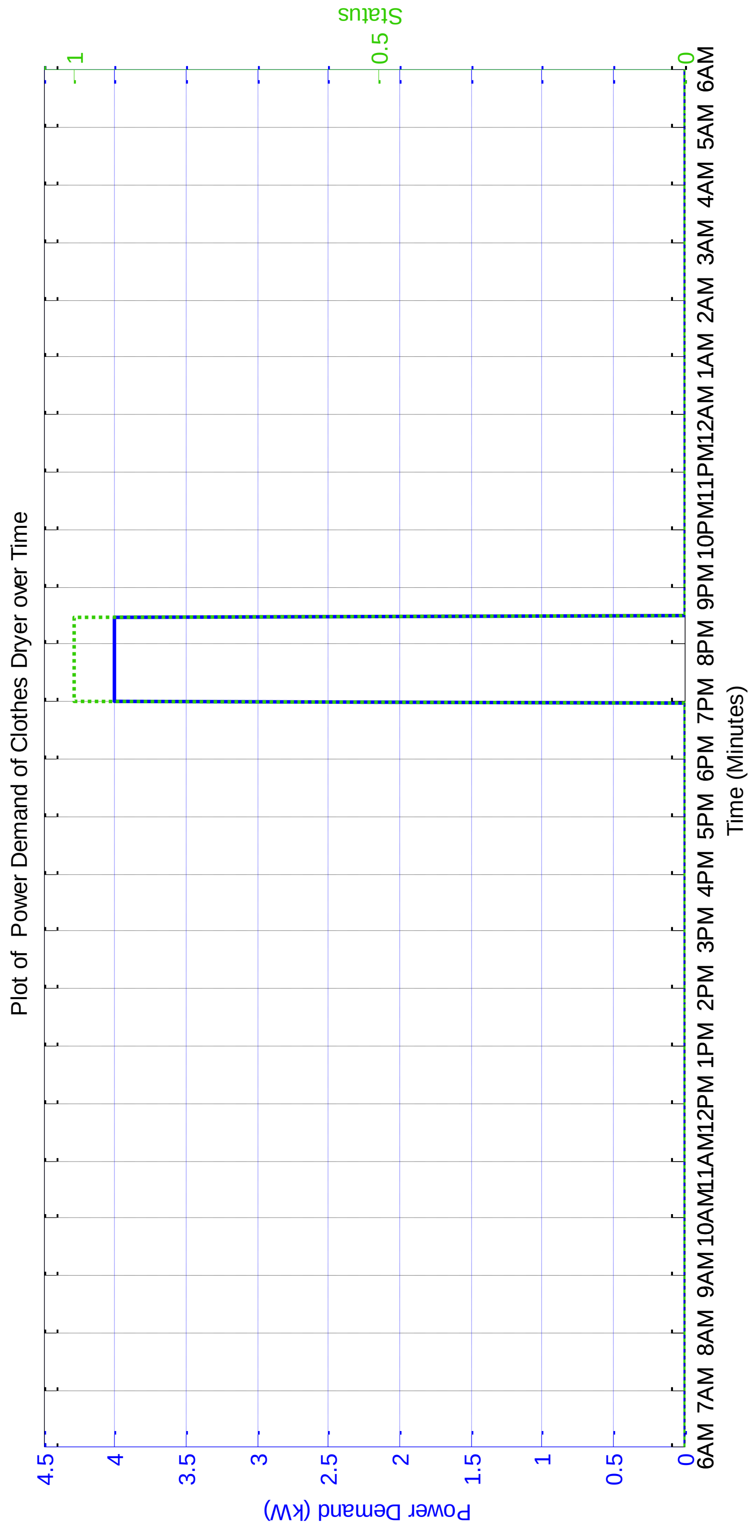

Figure 5.22: Operation of the clothes dryer without EMS for RTP mechanism

Electric Vehicle

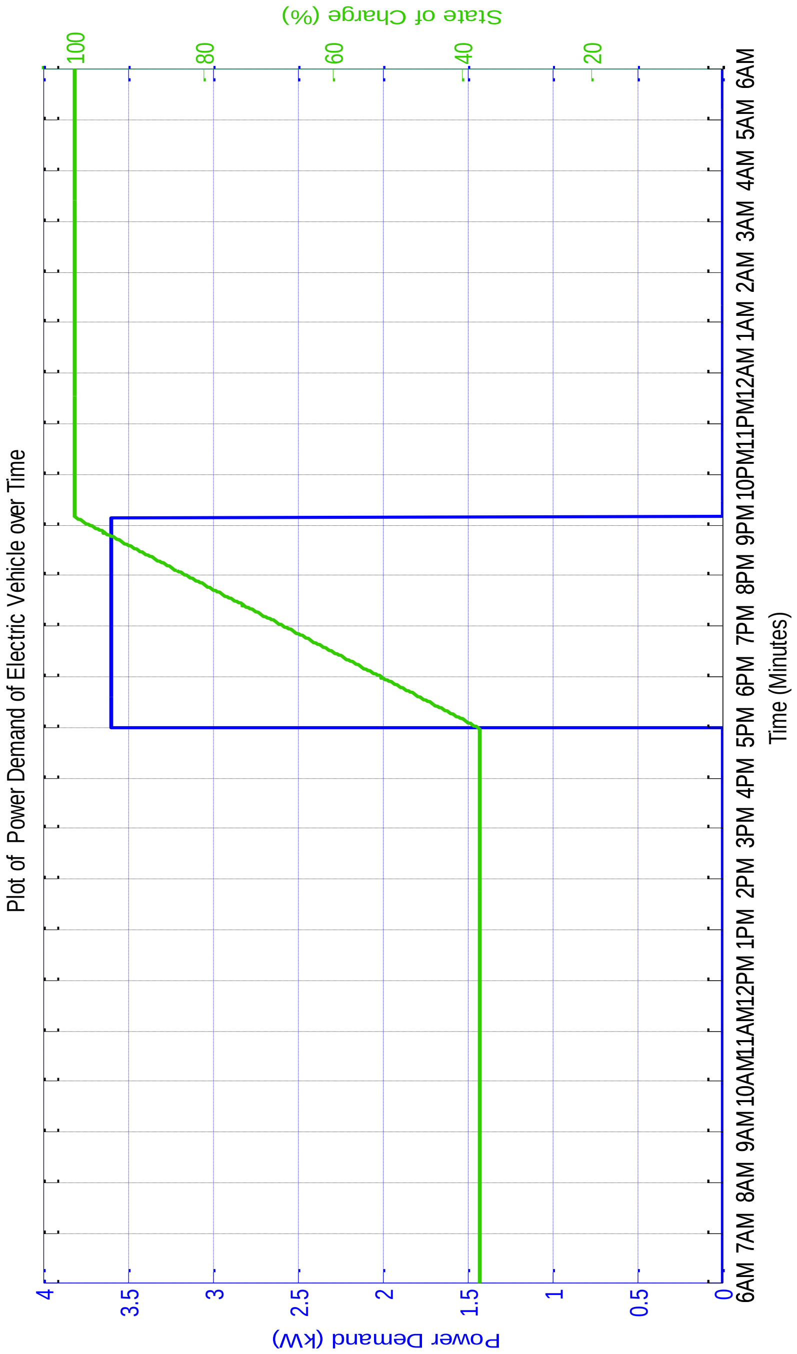

Figure 5.23: Operation of the electric vehicle without EMS for RTP mechanism

Total Household Load

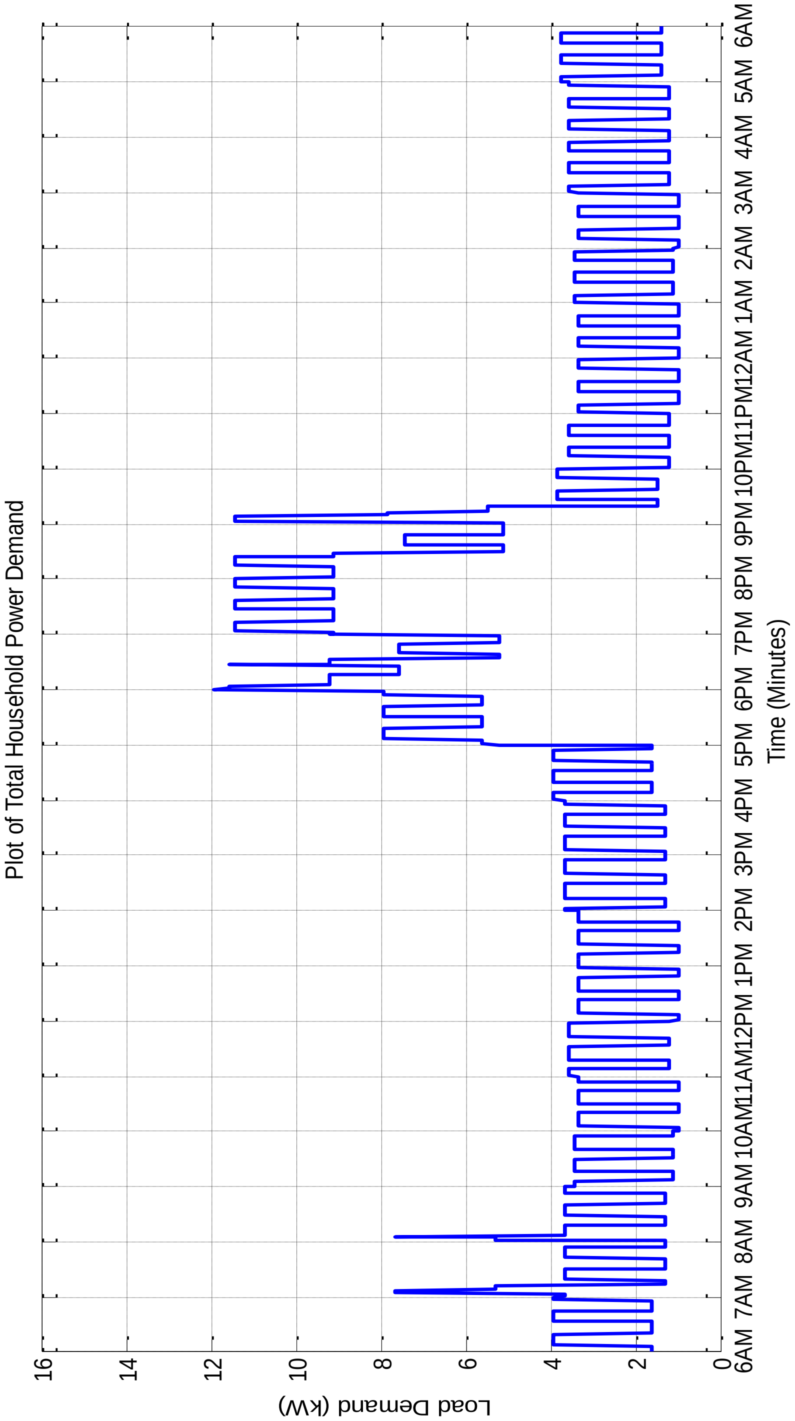

Figure 5.24: Total household energy consumption without EMS for RTP mechanism

Operation of the Non-Critical Loads for RTP with EMS

Water Heater

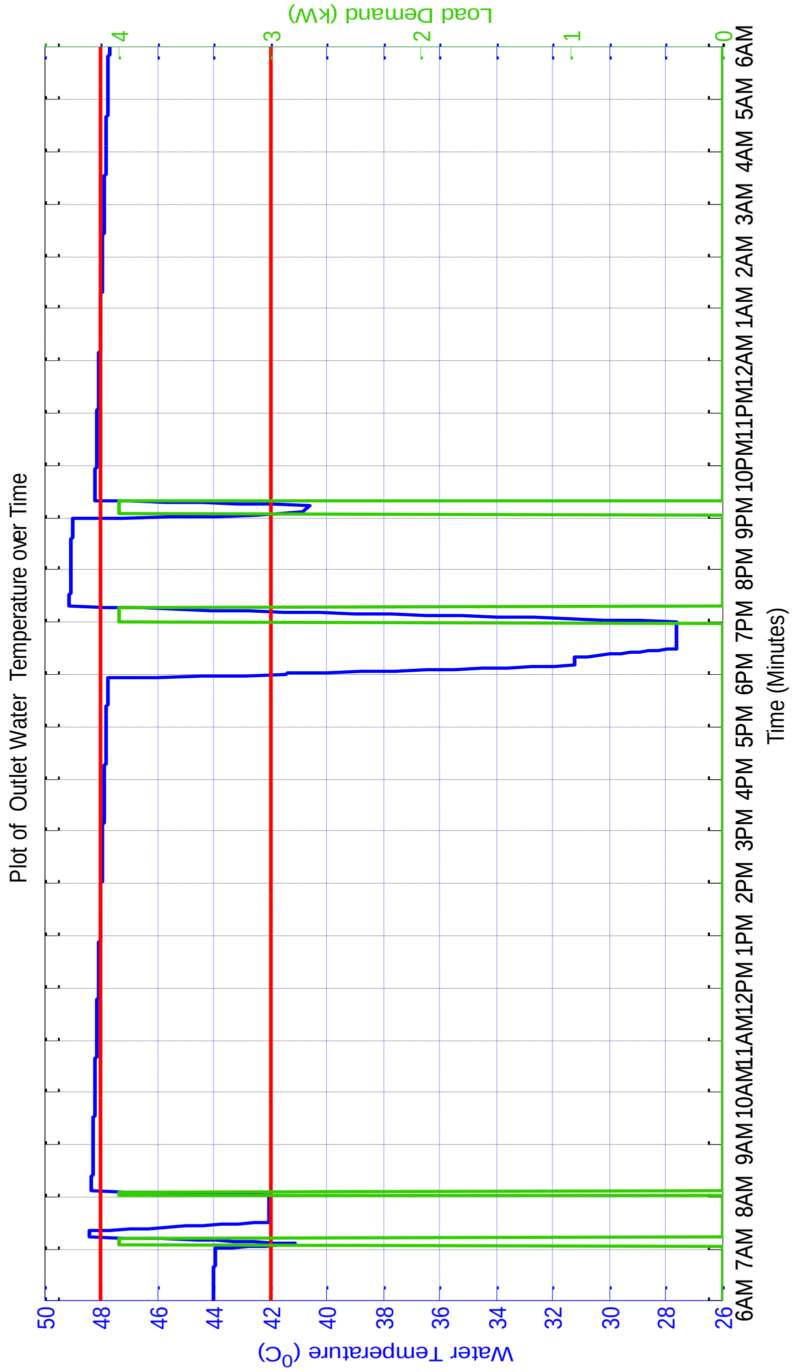

Figure 5.25: Operation of the water heater with EMS for RTP mechanism with load pattern changes due to change in user behavior

AC Unit

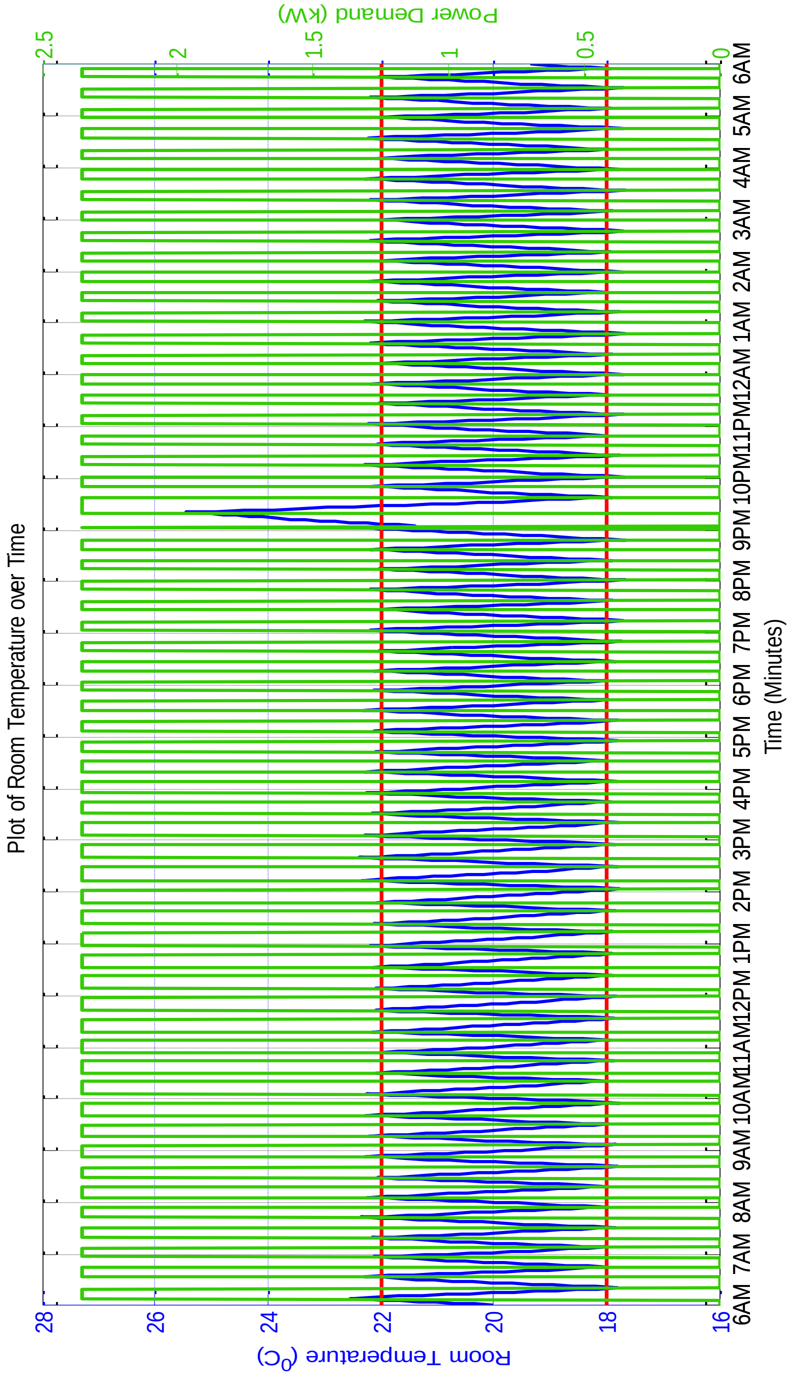

Figure 5.26: Operation of the AC unit with EMS for RTP mechanism with load pattern changes due to change in user behavior

Clothes Dryer

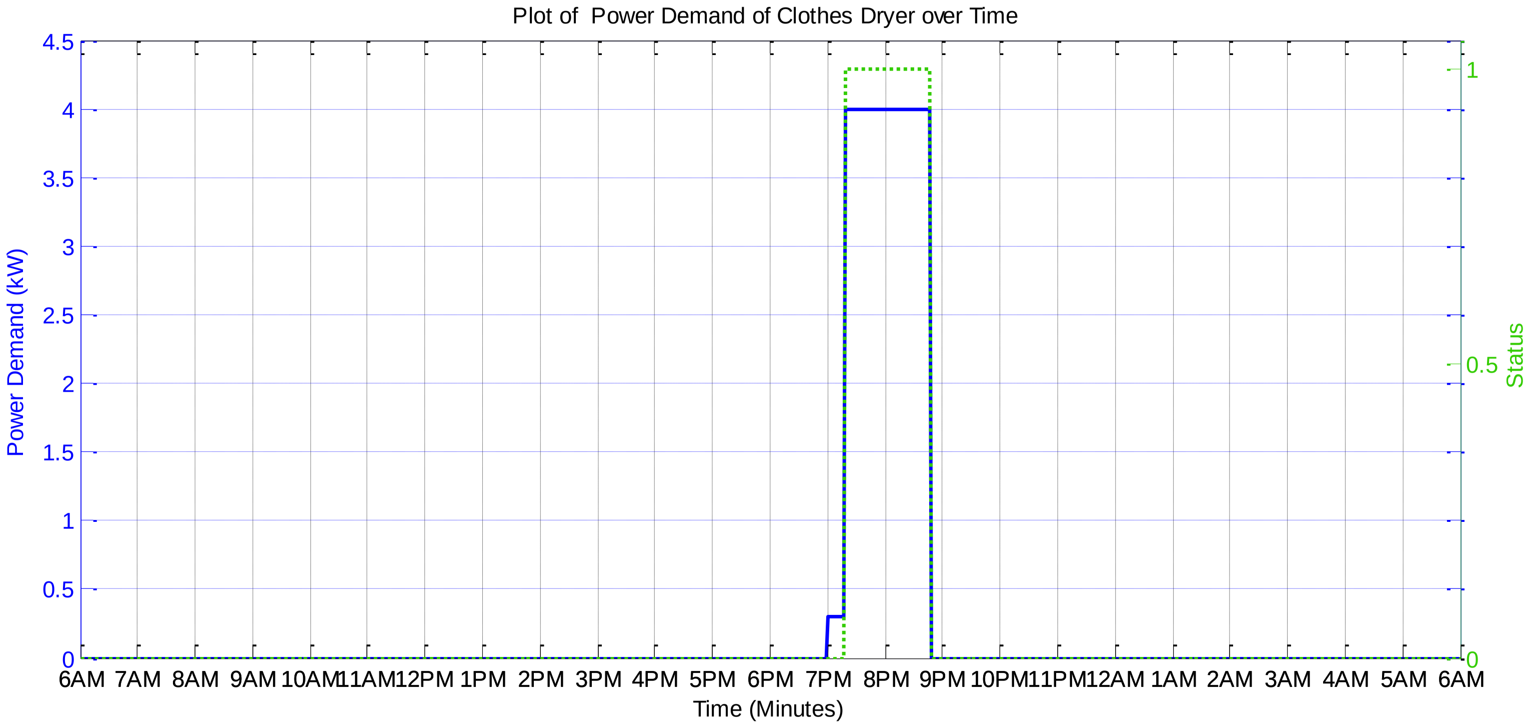

Figure 5.27: Operation of the clothes dryer with EMS for RTP mechanism with load pattern changes due to change in user behavior

Electric Vehicle

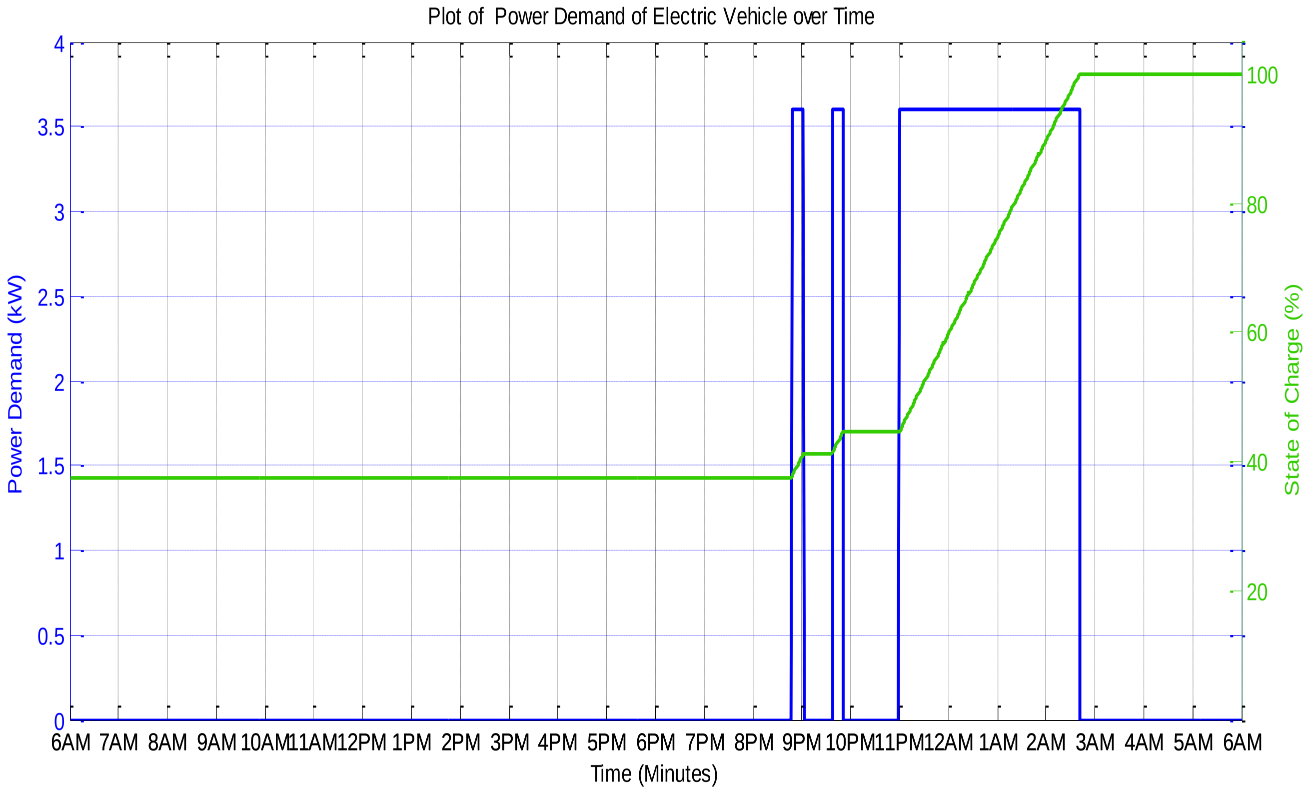

Figure 5.28: Operation of the Electric vehicle with EMS for RT pricing mechanism with load pattern changes due to change in user behavior

Total Household Load

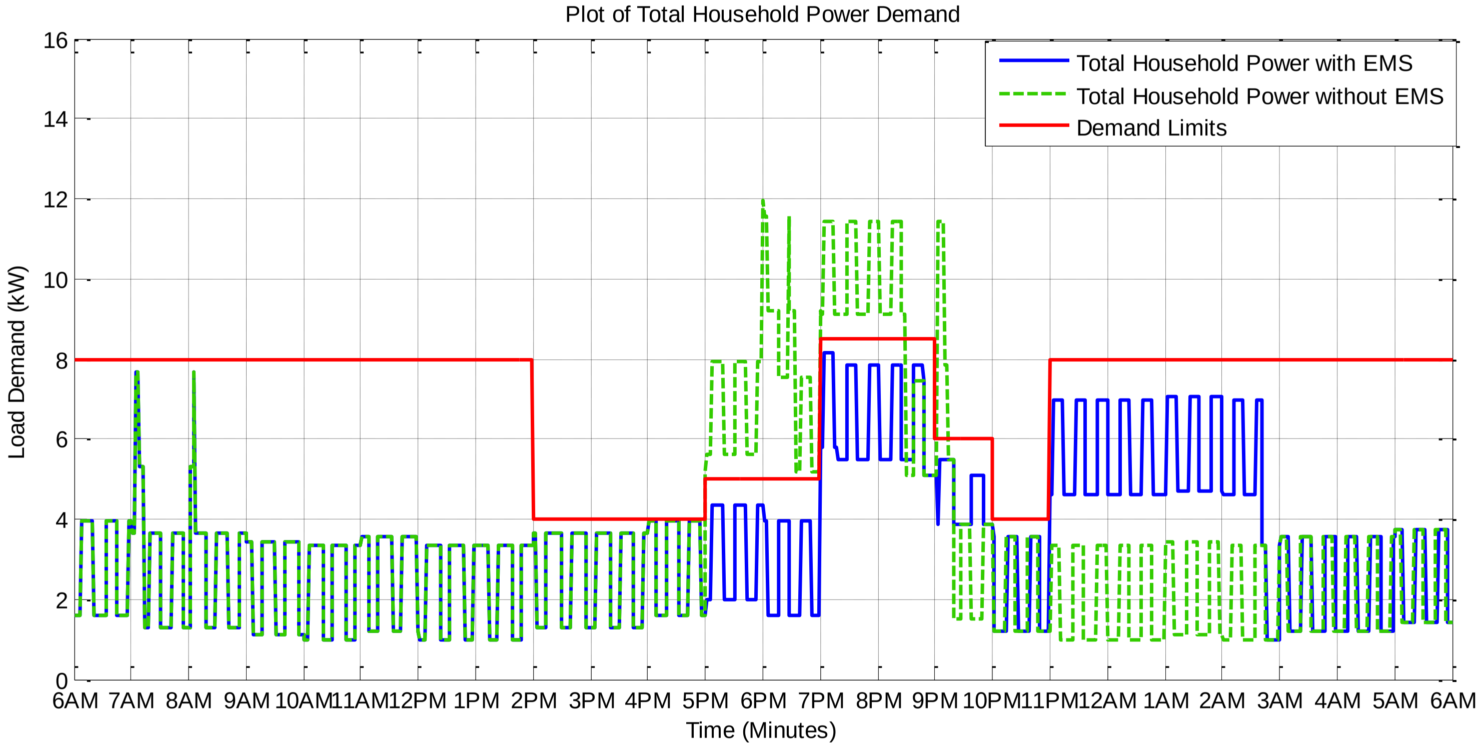

Figure 5.29: Total household load with EMS for RTP mechanism with load pattern changes due to change in user behavior

Impact of User Behavior Change on Putting Time Defined Demand Limits in EMS Algorithm with Demand Limit Set 1 (Case D)

Water Heater

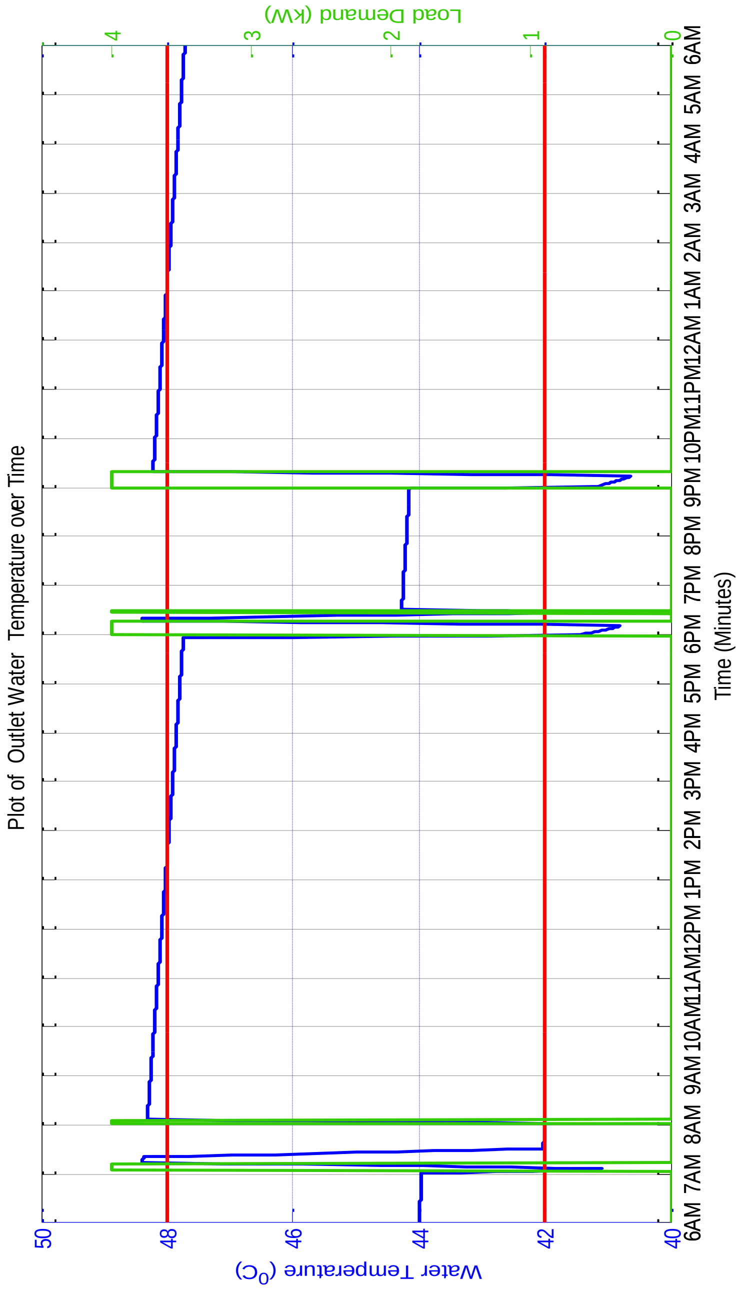

Figure 5.30: Operation of the water heater with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

AC Unit

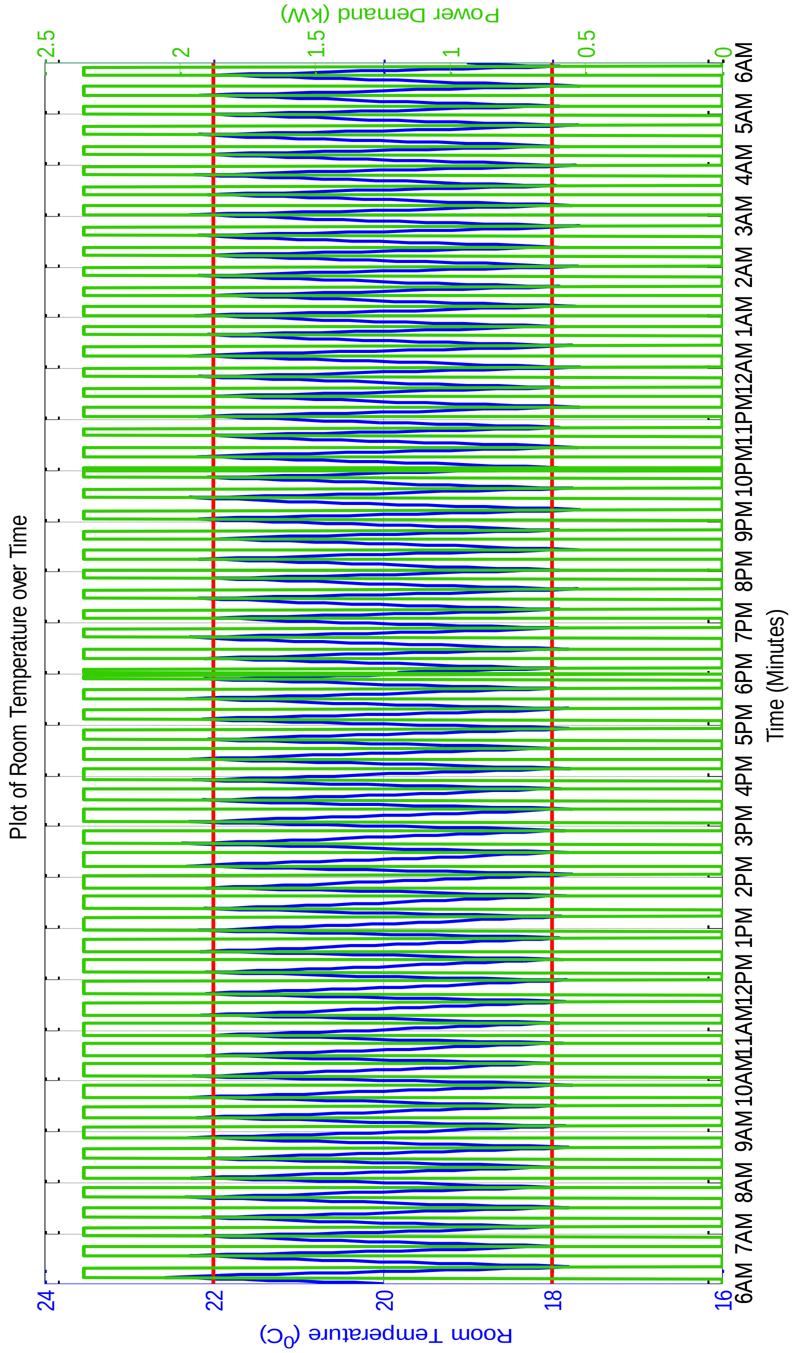

Figure 5.31: Operation of the AC unit with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

Clothes Dryer

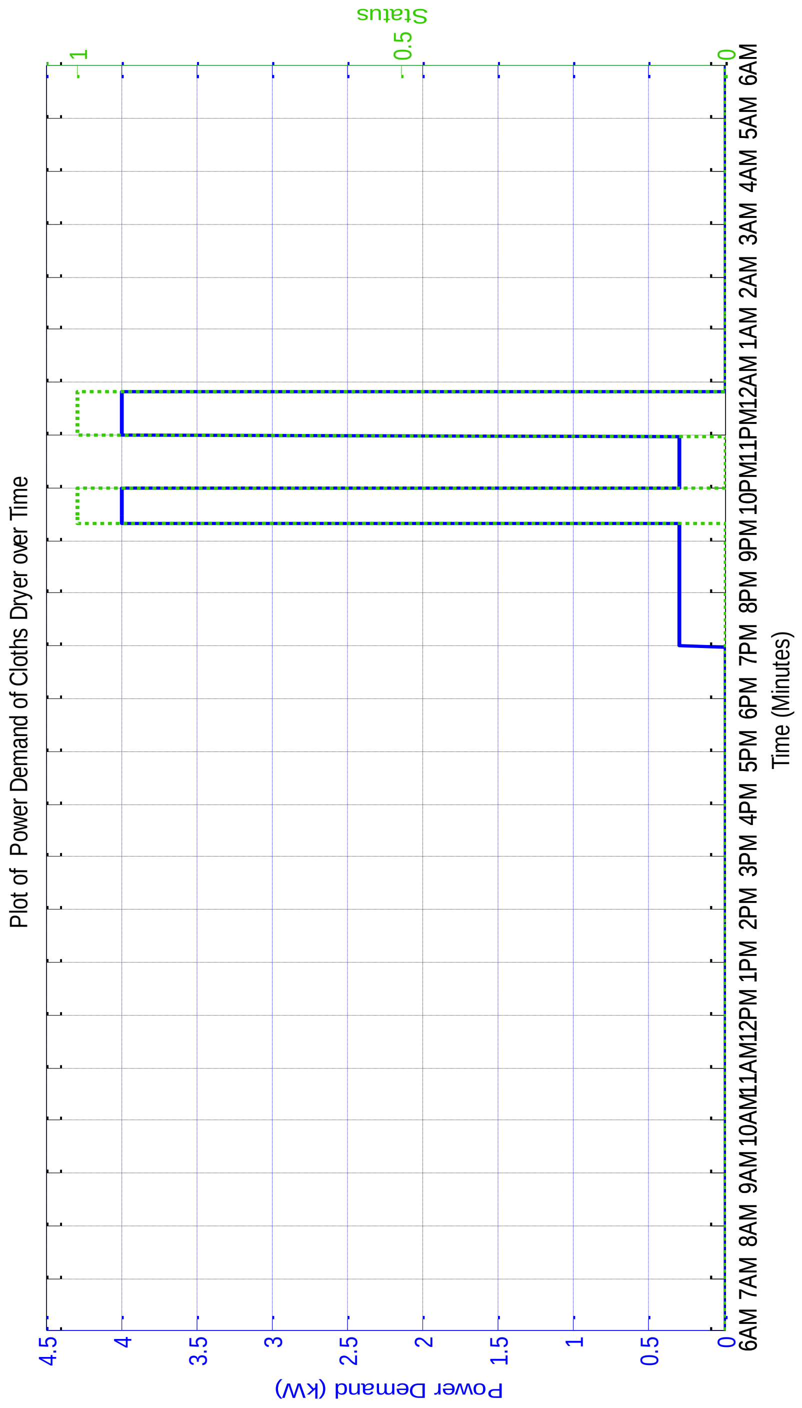

Figure 5.32: Operation of the clothes dryer with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

Electric Vehicle

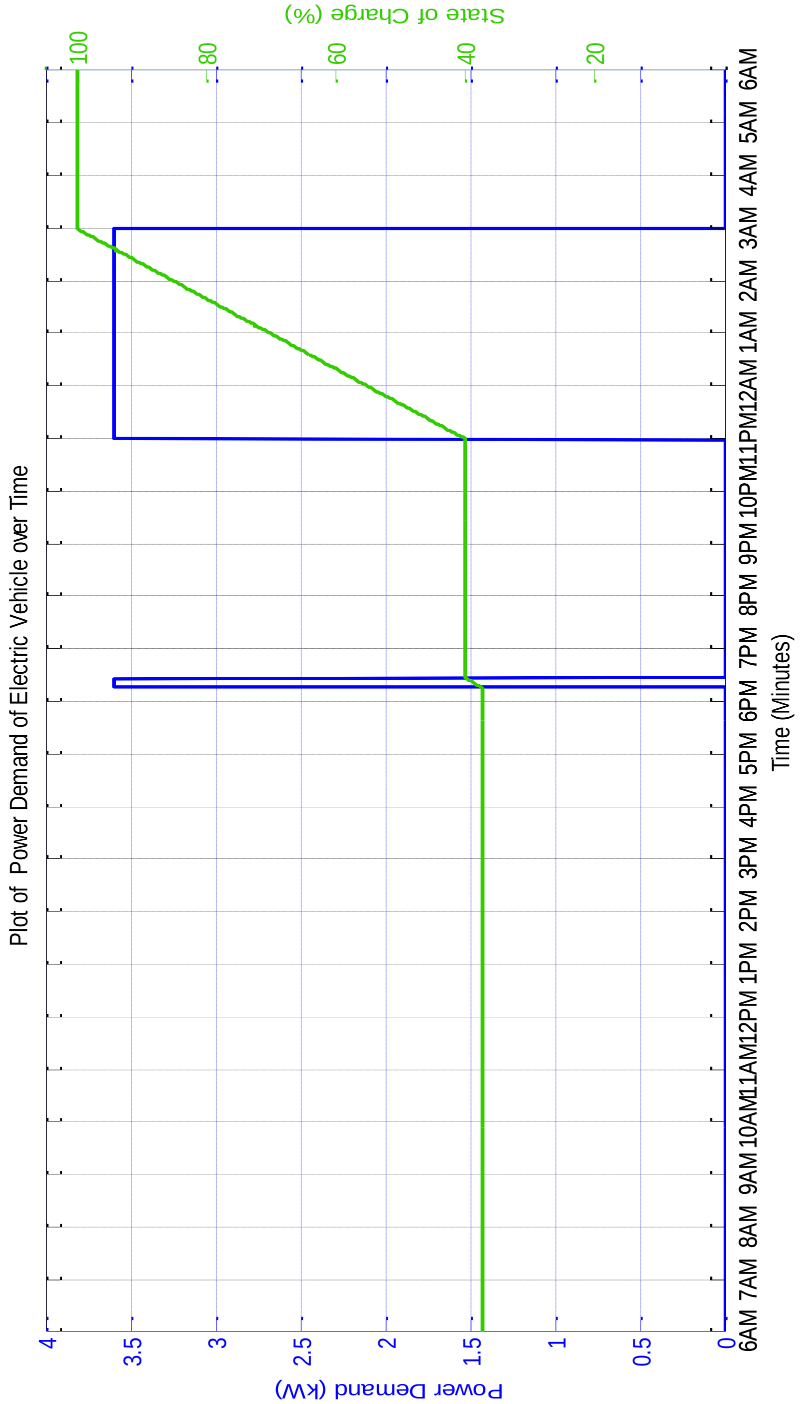

Figure 5.33: Operation of the electric vehicle with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

Total Household Load

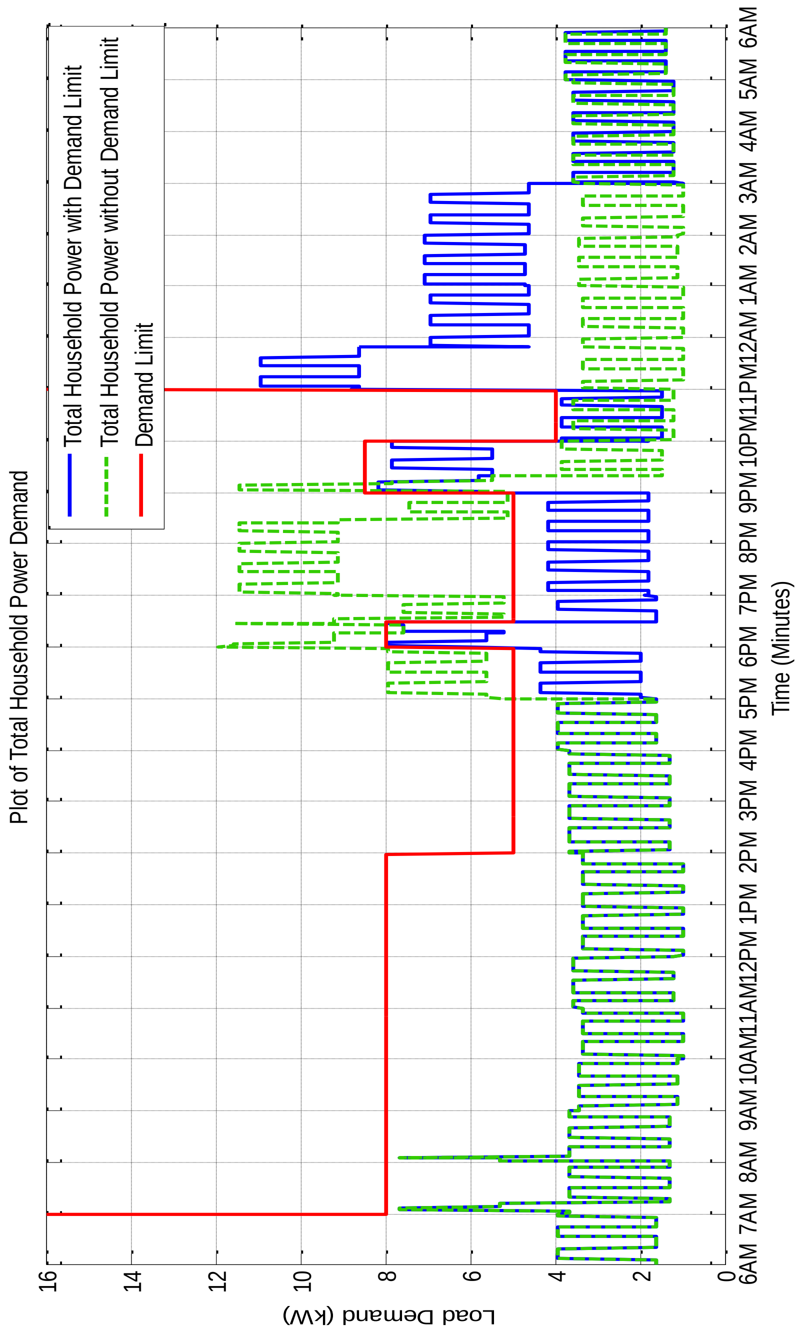

Figure 5.34: Total household load with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 1

Impact of User Behavior Change on Putting Time Defined Demand Limits in EMS Algorithm with Demand Limit Set 2 (Case E)

Water Heater

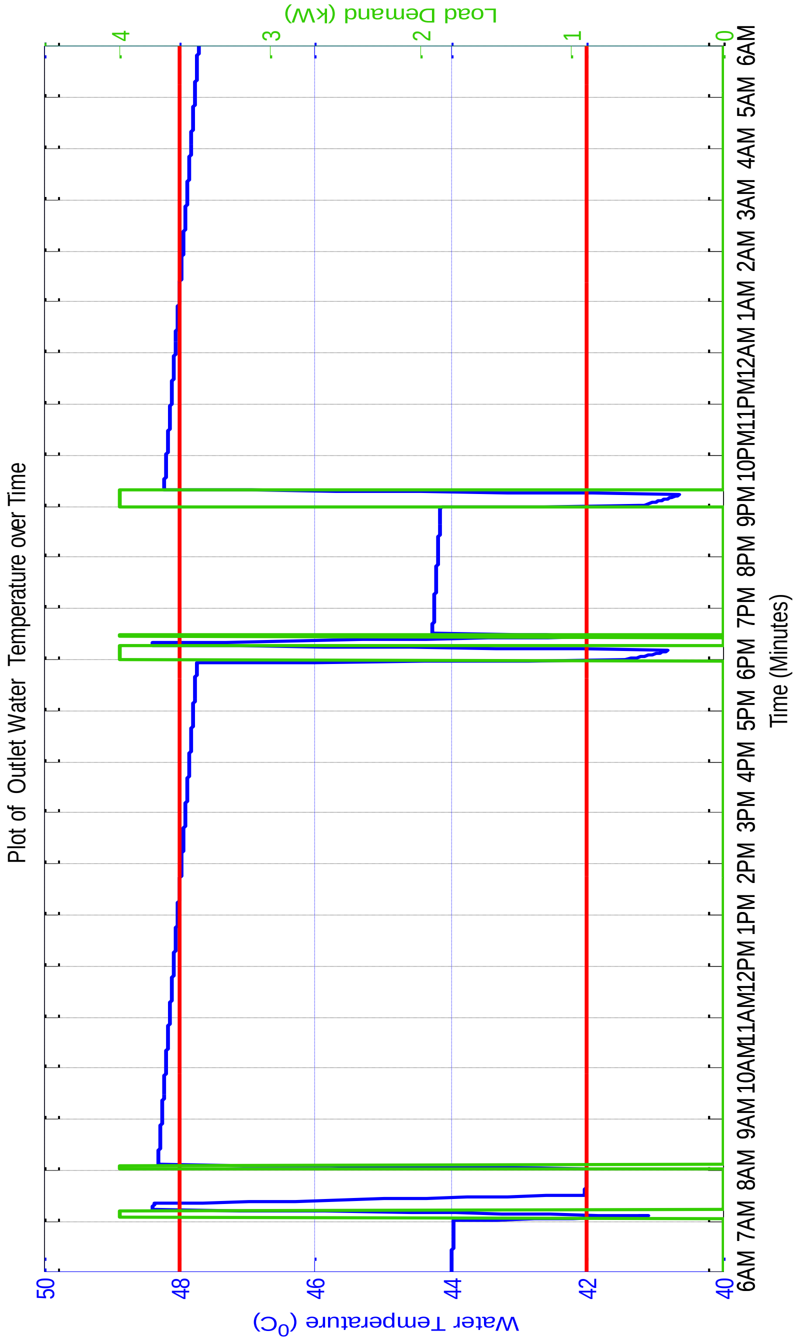

Figure 5.35: Operation of the water heater with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

AC Unit

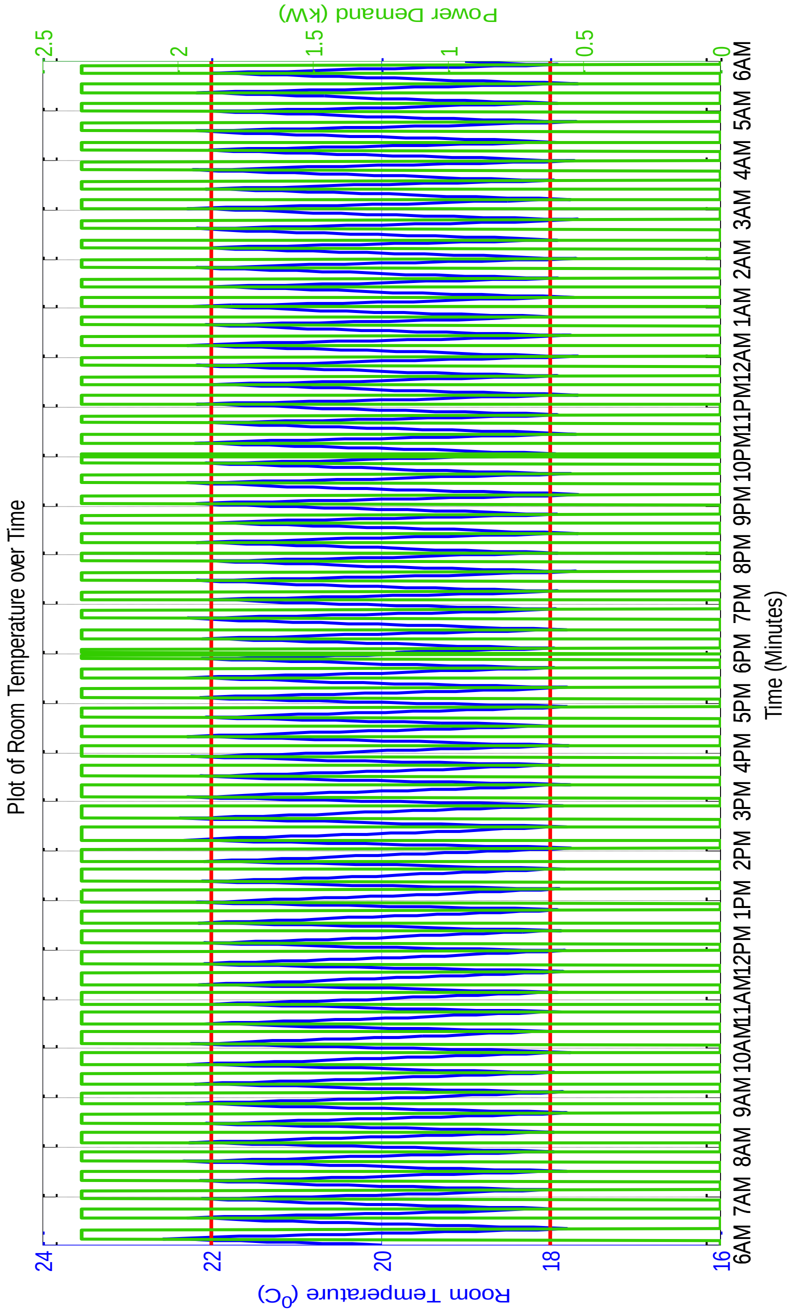

Figure 5.36: Operation of the AC unit with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

Clothes Dryer

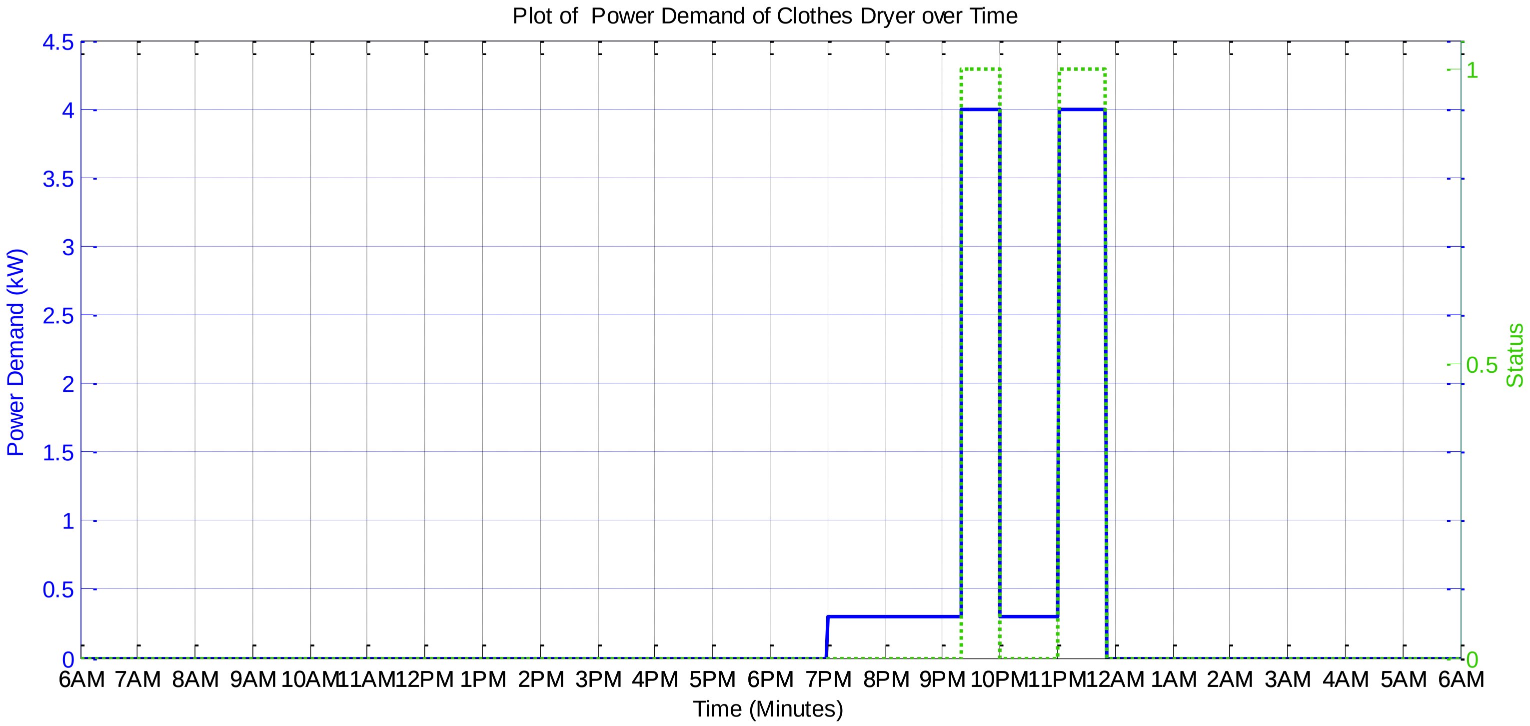

Figure 5.37: Operation of the clothes dryer with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

Electric Vehicle

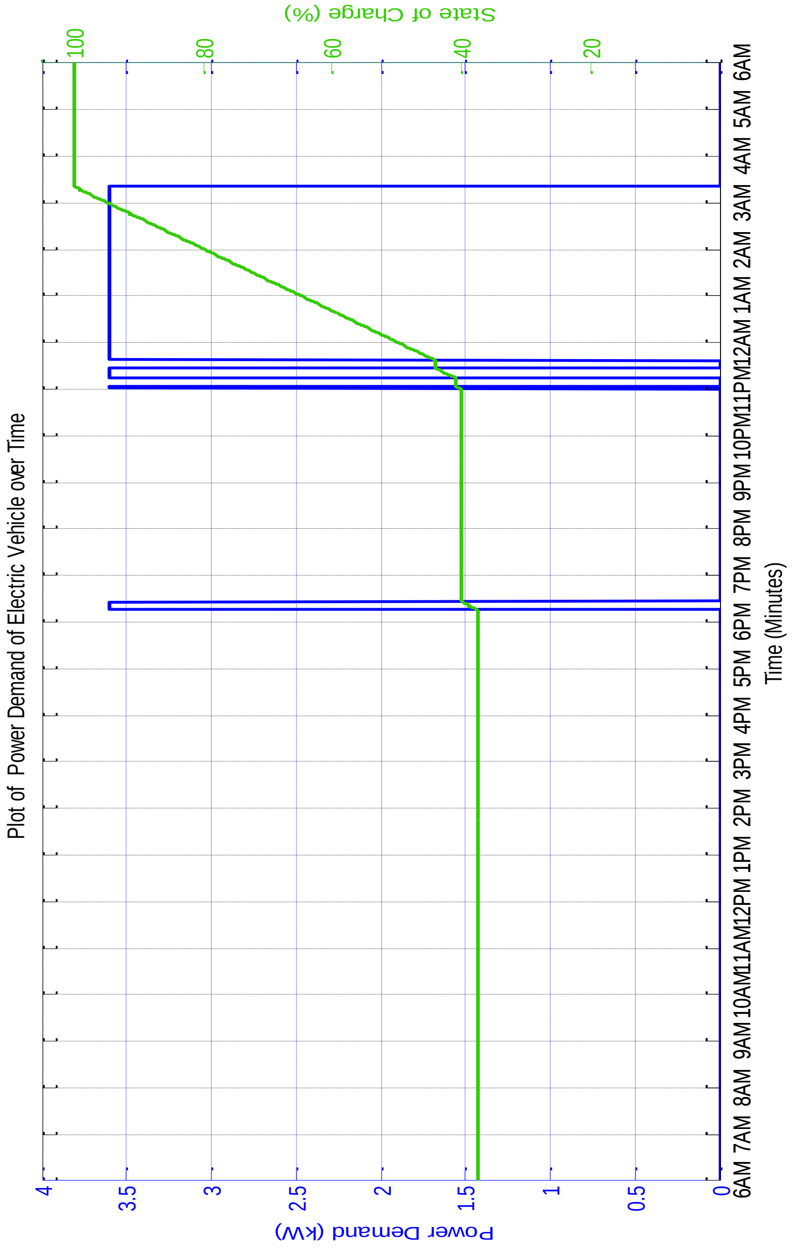

Figure 5.38: Operation of the electric vehicle with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2

Total Household Load

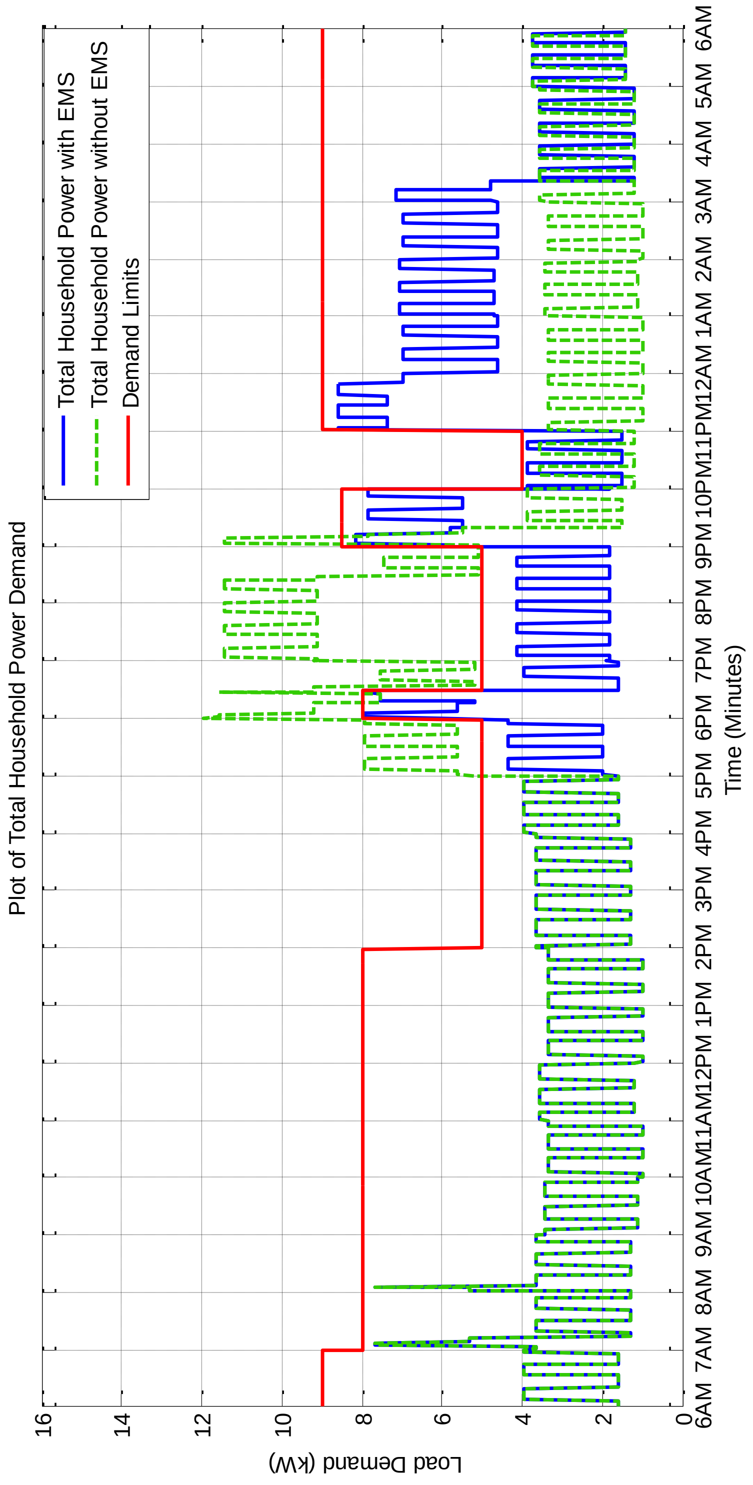

Figure 5.39: Total household load with EMS for RTP mechanism with load pattern changes due to change in user behavior and demand limit set 2