OPTIMAL SCHEDULING OF HOME ELECTRICAL APPLIANCES AND POWER RESOURCES

Master of Science Thesis

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MASTER OF SCIENCE THESIS

Graduate School of Sciences
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ABSTRACT

OPTIMAL SCHEDULING OF
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Department of Electrical and Electronics Engineering

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In this thesis, an offline home energy management system is proposed to minimize electrical cost and reduce high peak demand while maintaining user comfort. The system is composed of smart electrical appliances, which are divided into three subclasses as uncontrollable, semi-controllable and controllable, power resources (grid, backup battery, photovoltaic system), communication network, plug-in hybrid electrical vehicle and a main controller. At the beginning of each day, the main controller gathers user requests, power resources and smart electrical appliances information and solves a mixed integer linear programming problem that is subject to smart and energy efficient operation constraints defined for appliances and power resources. The interruption is also allowed in controllable appliances while maintaining user comfort. The solution of this problem provides cost minimizing schedules of controllable appliances and power resources. Simulation results demonstrate that the proposed home energy management system significantly reduces the electrical costs and peak demand.

Keywords: Energy management, smart electrical appliances, renewable energy resources, plug-in hybrid electrical vehicle, mixed integer linear programming

ÖZET

ELEKTRİKLİ CİHAZLARIN
VE GÜÇ KAYNAKLARININ
OPTİMAL ZAMANLANDIRILMASI

Hasan İZMİTLİGİL

Elektrik-Elektronik Mühendisliği Anabilim Dalı

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Danışman: Yard. Doç. Dr. Hanife APAYDIN ÖZKAN

Bu tezde, elektrik maliyetinin azaltılması ve anlık yüksek güç talebinin önlenmesini amaçlayan ve bunu yaparken kullanıcı konforunu da dikkate alan çevrim-dışı bir ev enerji yönetim sistemi önerilmiştir. Önerilen sistem kontrol edilebilir, yarı-kontrol edilebilir ve kontrol edilemez olarak sınıflandırılan akıllı elektrikli cihazlar, güç kaynakları (şehir şebekesi, akü bankası, fotovoltaik sistem), haberleşme ağı, merkezi kontrolcü ve şarj edilebilen hibrid elektrikli araçtan oluşmaktadır. Her günün başında kullanıcı talep, güç kaynağı ve akıllı elektrikli cihazların durum bilgilerinin merkezi kontrolcü tarafından toplandığı bu sistemde, güç kaynaklarının ve akıllı elektrikli cihazların verimli kullanımı için kısıtlar tanımlanmıştır. Güç kaynaklarının ve akıllı elektrikli cihazların kontrolü, bu kısıtlar ve durum bilgileri çerçevesinde maliyeti düşürmeyi amaçlayan tam sayılı doğrusal programlama yöntemi ile çevrim-dışı olarak sağlanmaktadır. Ayrıca kontrol edilebilir akıllı elektrikli cihazlara kullanıcı konforunu bozmadan duraklatma imkanı verilmiştir. Yapılan benzetim çalışmaları önerilen ev enerji yönetim sisteminin elektrik maliyetini ve anlık yüksek güç taleplerini önemli ölçüde azalttığını göstermiştir.

Anahtar Kelimeler: Enerji yönetimi, akıllı elektrikli cihazlar, yenilenebilir enerji kaynakları, şarj edilebilen hibrid elektrikli araç, tam sayılı doğrusal programlama

28/12/2016

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Anadolu University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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Hasan İZMİTLİGİL

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NOTATION

t	time slot (or time)
T	total number of times in a day
$\mathcal{T}$	set of uniform times {1, 2, ..., T}
Δ_t	length of each time t
$\mathcal{L}$	set of appliances
$\mathcal{L}_{\mathcal{UC}}$	set of uncontrollable appliances
$\mathcal{L}_{\mathcal{SC}}$	set of semi-controllable appliances
$\mathcal{L}_{\mathcal{C}}$	set of controllable appliances
$\mathcal{S}_{\mathcal{P}}$	set of program modes
a	appliance
i	program mode
$\hat{t}$	internal time of appliances ($\Delta_{\hat{t}} = \Delta_t$)
$\boldsymbol{X}^a(t)$	status vector of the appliance a at time t
$p_i^a(\hat{t})$	power consumption of the appliance a operating at a program mode $i \in \mathcal{S}_{\mathcal{P}}$
$P_i^a(\hat{t})$	average power consumption of the program mode i of the appliance a at $\hat{t}^{th}$ internal time of appliances
T_i^a	duration of the program mode i of the appliance a
$P^{\mathcal{L}}(t)$	total power consumption of appliances at time t
t_s^a	starting time of the operation of the appliance a
t_f^a	finishing time of the operation of the appliance a
$T_{s,i}^a$	user defined earliest start time of the appliance a of the program mode i
$T_{f,i}^a$	user defined latest finish time of the appliance a of the program mode i
$n_{i_{max}}^a$	maximum number of interruptions of the appliance a at the program mode i
$T_{i_{max}}^a$	total maximum interruption duration of the appliance a at the program mode i

$T_{i,k}^{a}$	duration of the k^{th} interruption at the program mode i of the appliance a
n_i^a	number of interruptions of the appliance a at the program mode i
$SOC_{EV}(t)$	state-of-charge of the PHEV at time t
$E^{EV}(t)$	current energy capacity for the PHEV at time t
$E_{cap}^{EV}(t)$	nominal energy capacity for the PHEV at time t
η_{evc}	charge efficiency of the PHEV
η_{evd}	discharge efficiency of the PHEV
$SOC_{EV_{min}}$	minimum SOC level for the PHEV
$SOC_{EV_{max}}$	maximum SOC level for the PHEV
$SOC_{EV_{ini}}$	initial SOC level for the PHEV
$P^{EVc}(t)$	charging rate for the PHEV at time t
$P^{EVd}(t)$	discharging rate for the PHEV at time t
P_{max}^{EVc}	maximum charging rate for the PHEV
P_{max}^{EVd}	maximum discharging rate for the PHEV
$x^{EVc}(t)$	binary decision variable indicating whether the PHEV is charging at time t
$x^{EVd}(t)$	binary decision variable indicating whether the PHEV is discharging at time t
$P^{\mathcal{B}c}(t)$	backup battery charge power at time t
$P^{\mathcal{G}}(t)$	power drawn from the grid at time t
$P^{\mathcal{PV}}(t)$	power obtained from the PV system at time t
$P^{\mathcal{B}d}(t)$	backup battery discharge power at time t
$P^{\mathcal{S}}(t)$	power injected to grid at time t
$x^{\mathcal{S}}(t)$	binary decision variable indicating whether power is injected to the grid at time t
$x^{\mathcal{G}}(t)$	binary decision variable indicating whether power is drawn from the grid at time t
$P_{lim}^{\mathcal{G}}(t)$	maximum power that can be drawn from the grid at time t
$P_{lim}^{\mathcal{S}}(t)$	maximum power that can be injected to the grid at time t

$P_{EV}^{\mathcal{G}}(t)$	grid power used for PHEV charging at time t
$P_{\mathcal{L}}^{\mathcal{G}}(t)$	grid power used for appliance demand at time t
$SOC(t)$	SOC of the backup battery at time t
$E^{\mathcal{B}}(t)$	current energy capacity for the backup battery at time t
$E_{cap}^{\mathcal{B}}(t)$	nominal energy capacity for the backup battery at time t
η_c	charge efficiency of the backup battery
η_d	discharge efficiency of the backup battery
SOC_{min}	minimum SOC level for the backup battery
SOC_{max}	maximum SOC level for the backup battery
SOC_{ini}	initial SOC level for the backup battery
$P_{max}^{\mathcal{B}c}$	maximum charging rate for the backup battery
$P_{max}^{\mathcal{B}d}$	maximum discharging rate for the backup battery
$x^{Bc}(t)$	binary decision variable indicating whether the backup battery is charging at time t
$x^{Bd}(t)$	binary decision variable indicating whether the backup battery is discharging at time t
$P_{\mathcal{B}c}^{\mathcal{PV}}(t)$	PV power used for the backup battery charging at time t
$P_{\mathcal{S}}^{\mathcal{PV}}(t)$	PV power used for power injection to grid at time t
$P_{\mathcal{L}}^{\mathcal{PV}}(t)$	PV power used for supporting the power demand of appliances at time t
$C^{\mathcal{G}}(t)$	electricity tariff for power drawn from the grid at time t
$C^{\mathcal{S}}(t)$	electricity tariff for power injected to the grid at time t

ACRONYMS

CPP	Critical Peak Pricing
GAMS	General Algebraic Modeling System
HEMS	Home Energy Management System
HEM	Home Energy Management
IP	Integer Programming
MC	Main Controller
MILP	Mixed Integer Linear Programming
OF-HEM	Offline Home Energy Management System
PHEV	Plug-in Hybrid Electrical Vehicle
PVGIS	Photovoltaic Geographical Information System
RTP	Real-Time Pricing
SOC	State-Of-Charge
TEDAS	Turkish Electricity Distributor Company
TOU	Time-Of-Use Pricing

1. INTRODUCTION

1.1. Overview and Motivation

Increase in the population results in increasing energy demand which raises the utilization of fossil fuels yielding severe environmental damage. Both the depletion risk of fossil fuels and environmental damages result in an acceleration of the research on efficient use of the energy. Conventional grids are transformed into smart grids that enable efficient use of the energy through control mechanisms constructed between the utility company and the user.

A significant amount of energy consumption occurs in the residentials. In order to prevent grid problems that are caused by the residential peak demands, utility companies prefer to reduce the consumption during peak grid power use in smart grids and provide incentives in exchange for the reduction they provide [1], [2], and conduct different tariff implementations such as critical peak pricing (CPP), real-time pricing (RTP), time-of-use pricing (TOU) [3]. In this thesis, TOU pricing that applies higher unit prices during high energy consumption periods and lower prices during low energy consumption periods, which encourages the users to shift the usage to low-cost periods.

The most significant factor in efficient energy use at homes is Home Energy Management Systems (HEMS). The efficient energy use is provided by these systems, and it is possible to reduce high electrical costs and prevent instantaneous high energy consumption. Thus, low cost provides significant advantages for the user, while prevention of grid problems by avoiding instantaneous energy demand provides benefits for the utility company.

Integration of renewable energy resources that are sustainable and environmentally non-pollutant into HEMS is an important factor increasing the efficiency of the system. Furthermore, expansion of Plug-in Hybrid Electrical Vehicle (PHEV) use, which has the capability of recharging the batteries as an alternative to fuelled vehicles, make it inevitable to consider PHEV integration to HEMS.

There are several studies in the literature on HEMS. In optimization-based studies, in [4], [5], linear programming and in [6] mixed integer linear programming methods were used to schedule appliances to minimize the electrical cost. A computationally feasible and automated residential appliance control scheme was proposed in a retail electricity market with real-time pricing combined with inclining block rates in [7].

Furthermore, some studies presented heuristic methods for home energy management. In [8], energy consumption was scheduled by a game theoretic approach for reducing both the total electrical cost and high peak demand. In [9], a method using Q-learning approach to learn user behaviour and the corresponding changes in tariff prices was presented, while genetic algorithm was applied for energy use for scheduling in [10]. In [11], a rule-based algorithm was developed to control both appliances and power resources. In [3], particle swarm optimization method that requires energy use prediction was used for co-ordinately scheduling controllable appliances.

Apart from these studies, certain optimization-based and heuristic-based studies used the prioritization approach: In [12], appliances were scheduled based on assigned priorities to keep the total energy consumption below a predefined limit. In [13], priority order of appliances was determined according to their features and user comfort, then the energy management was handled with the proposed Appliance-based Rolling Wave Planning algorithm with the aim of reducing electrical cost and improving energy efficiency while maintaning user comfort. In [14], a price-based HEMS framework was designed to incorporate the priority of operating different appliances in the optimization model of a HEMS, while in [15], resource priorities instead of appliance priorities were considered in HEMS.

Studies on use and integration of PHEVs in HEMS have increased in the literature along with the advances in PHEV technology. In one of these studies [16] that proposed online methods, the coordinated PHEV charging with home appliances using an appliance coordination scheme was proposed, while in [17] sensor web services were used for PHEV charging management to increase the administration ability of the utility overload. Although flexible user behaviour was tolerated in these studies, the obtained solutions were sub-optimal.

In this thesis, an Offline Home Energy Management system (OF-HEM) that aims to reduce high peak demand and electrical costs, while providing user comfort is proposed. In this system, energy use in a home equipped with smart electrical appliances that are classified as uncontrollable, semi-controllable and controllable and with PHEV integration is addressed. Photovoltaic system, grid and a backup battery are used as power resources. It is also allowed to sell the energy obtained in the photovoltaic system back to the grid. Furthermore, PHEV is fed from the grid with control, besides it supports other power resources in fulfilling the demand of the home, again in a controlled manner. Management of smart electrical appliances and power resources is conducted by a main controller (MC). Thanks to the communication structure of the system, MC is in communication with all the abovementioned components. In the beginning of each day, MC learns information about the user demands, the status of power resources, grid tariff information and the power demand of the home. Management of power resources and smart electrical appliances is provided by the offline solution of a mixed integer linear programming that utilizes the defined constraints and aims to reduce electrical costs for the data collected at the beginning of the day. Based on the obtained solution and user preferences, appliances are controlled by delaying or stopping their operation within allowed limits, moreover the periods of charging and discharging of PHEV and backup battery, drawing from the grid or injection to grid are determined based on efficiency concern. Conducted simulation work demonstrates that the proposed OF-HEM reduces electrical costs significantly.

1.2. Thesis Outline

In Chapter 2, significant background definitions are presented. In Section 2.1, mathematical programming techniques that linear programming, mixed integer linear programming and nonlinear programming are provided. In Section 2.2, GAMS model that used in scenarios is introduced. From Subsection 2.2.1 to Subsection 2.2.6, the structure of GAMS model is presented.

In Chapter 3, the Offline Home Energy Management system is proposed. In Section 3.1, smart electrical appliances are introduced. From Subsection 3.1.1 to Subsection 3.1.3, type of appliances is presented. In Section 3.2, power resources are introduced. In addition to this introduction, from Subsection 3.2.1 to Subsection 3.2.3, type of power resources are also presented. In Section 3.3, integration to the

Plug-in Hybrid Electric Vehicle is introduced. After that, in Section 3.4, the Main Controller is presented.

In Chapter 4, four different scenarios are presented in order to illustrate the efficiency of the proposed OF-HEM in the GAMS model.

In Chapter 5, the concluding remarks are given.

2. BACKGROUND

2.1. Mathematical Programming Techniques

Mathematical Programming is the use of mathematical models, especially optimization models, to assist in taking decisions. The term ”Programming” is not mean to computer programming. The programming is a synonym for planning.

Many decision problems can be identified in the following steps:

1. Identifying the problem variables for making the possible decisions. These variables aims to an optimize objective function.
2. Identifying the set of constraints for deciding which decisions are acceptable.
3. Identifying the objective function for calculating cost/benefit ratio that is essential for each decision. Thus, the data set is composed of each set of all these elements.

2.1.1. Linear Programming

Linear programming is the mathematical modeling technique for describing the problem. The functions are required to be linear in this model. According to the mathematical model, linear programming aims to obtain an optimal result for the planning of activities among all feasible alternative ways.

An example of a linear programming problem would be:

$$\begin{aligned} \text{minimize} \quad & H = \textstyle\sum_{\mathcal{T}} f_t x_t \\ \text{s.t.} \quad & \textstyle\sum_{\mathcal{T}} d_{it} x_t \leq e_i, \ \{for\ i = 1,\ 2,\ ...,\ m\} \\ & x_t \geq 0, \ \{for\ t = 1,\ 2,\ ...,\ n\} \end{aligned} \tag{2.1}$$

where total measurement value, H, the decision variables, $x_1, x_2, ..., x_n$, parameters of the mathematical model, e_i, f_t, d_{it}.

The decision variables make sense if they only have integer values. If the problem is an integer programming (IP) problem, the decision variables need to be integer values.

2.1.2. Mixed Integer Linear Programming

There is restriction that the variables must have integer values. Some of the variables are just needed to have integer values, this mathematical model is called as mixed integer linear programming (MILP).

An example of a mixed integer linear programming problem would be:

$$\begin{aligned} \text{minimize} \quad & H = \textstyle\sum_{\mathcal{T}} f_t x_t + \sum_{\mathcal{N}} g_r y_r \\ \text{s.t.} \quad & \textstyle\sum_{\mathcal{T}} d_{it} x_t + \sum_{\mathcal{N}} g_{ir} y_r \le e_i, \ \{for \ i = 1, \ 2, \ ..., \ m\} \\ & x_t \ge 0, \ \{for \ t = 1, \ 2, \ ..., \ n\} \\ & y_r = 0, 1, 2, \cdots, \ \{for \ r = 1, \ 2, \ ..., \ p\} \end{aligned} \tag{2.2}$$

where the integer variables are $y_1, y_2, ..., y_p$, parameter of the MILP model is g_r.

"*Yes* or *no* decisions" have greater importance in optimization problems. Thus, the decision variables are restricted to two values (0 and 1). These variables are referred to as binary variables. If the IP problems contain only binary variables, they are called binary integer programming (BIP) problems.

2.1.3. Nonlinear Programming

In nonlinear systems, some of the constraints or the objective function are nonlinear.

The nonlinear programming problem is to find $x = (x_1, x_2, ..., x_n)$ so as to:

$$\begin{aligned} \text{minimize} \quad & f(x) \\ \text{s.t.} \quad & g_i(x) \le e_i, \ \{for \ i = 1, \ 2, \ ..., \ m\} \\ & x \ge 0, \ \{for \ t = 1, \ 2, \ ..., \ n\} \end{aligned} \tag{2.3}$$

where $f(x)$ and the $g_i(x)$ are given functions of the n decision variables.

2.2. GAMS

General Algebraic Modeling System (GAMS) software with high-level language features is used to create mathematical models, especially optimization models, and to solve them easily.

Structure of a GAMS model consists of different parts:

2.2.1. Sets

Sets are main parts in the GAMS model. The connection between variables and equations is provided by *Sets*.

Sets $\mathcal{L}$ *Appliances* /TV, Lamp, AC, REF, WM, DW/;

2.2.2. Scalars, Parameters and Tables

Scalars, *Parameters* and *Tables* are zero, one or multi-dimensional matrices, respectively. These are data in GAMS model and *Sets* specify the indices of these data.

Scalars	η_c	: charging efficiency of the backup battery /0.95/;
Parameters	$P^{PV}(t)$	: obtained power by the PV ;
Tables	$P(un,t)$	: power consumption for uncontrollable appliances

2.2.3. Variables

Different type of variables can be used in GAMS models are given in the following:

Variable	: The value of the variable takes from minus to plus infinity.
Positive Variable	: The value of the variable takes from zero to plus infinity.
Negative Variable	: The value of the variable takes from minus infinity to zero.
Integer Variable	: The value of the variable takes integer values only, i.e., 1,2,..
Binary Variable	: The value of the variable takes integer values either 0 and 1.

$P^{\mathcal{B}c}(t)$	: Backup battery charging power (positive variable)
$x^{\mathcal{G}}(t) = 1$	: iff power is provided from the grid at time t (binary variable)

2.2.4. Equations

In GAMS model, equations are constructed in two steps:

1- The names of equations are declared:

Objective	: define objective function
constraint(t)	: power balance constraint

2- The equation structure is defined:

Objective.. $H = e = \text{sum}(\text{t}, ((P^{\mathcal{G}}(t) * C^{\mathcal{G}}(t) - P^{\mathcal{S}}(t) * C^{\mathcal{S}}(t);$

constraint(t).. $P^{\mathcal{B}c}(t) = \text{l} = P^{\mathcal{B}c}_{max} * x^{\mathcal{B}c}(t);$

2.2.5. Assembling a Model

Sets, *Parameters*, *Variables* and *Equations* consist of a *Model* and the collection of these is given a name and expressed as follows:

Model name /all/;

Model scheduler /all/;

2.2.6. Solving a Model

When the model is defined, it can be solved with *Solve* statement.

Solve name using type of solver minimizing objective ;

Solve scheduler using mip minimizing H ;

3. OFFLINE HOME ENERGY MANAGEMENT SYSTEM

The proposed Offline Home Energy Management system (OF-HEM) is composed of power resources, smart electrical appliances (shortly, appliances), communication network, Main Controller (MC) and a PHEV. In this scheme, MC controls the home power demand and the use of power resources for efficient use of energy, thus minimizing the electrical cost. In the following section, the appliances, power resources and their proposed operation constraints will be presented, then, the electrical cost minimizing optimization problem subject to these constraints will be given. Note that, in this thesis, one day is discretized into a prescribed number T of uniform time slots, i.e., $t \in \mathcal{T} = \{1,\ 2,\ ...,\ T\}$, so that the total number of time slots in a day is $T = 24/\Delta_t$ where Δ_t represents the length of each time slot.

3.1. Appliances

In the proposed OF-HEM, smart electrical appliance concept developed in [15] is used. Due to user comfort concerns, appliances are divided into three subclasses; namely uncontrollable, semi-controllable and controllable appliances. The set of appliances is represented by $\mathcal{L} = \mathcal{L}_{\mathcal{UC}} \cup \mathcal{L}_{\mathcal{SC}} \cup \mathcal{L}_{\mathcal{C}}$ where $\mathcal{L}_{\mathcal{UC}}$, $\mathcal{L}_{\mathcal{SC}}$, $\mathcal{L}_{\mathcal{C}}$, are the sets of uncontrollable, semi-controllable and controllable appliances, respectively. Each appliance has 4 program modes each of which offers different functionality and features, such as operation duration, energy consumptions and more.

The sets of program modes are represented $\mathcal{S}_{\mathcal{P}} = \{1,\ 2,\ 3,\ 4\}$, respectively. The status of an appliance $a \in \mathcal{L}$ operating in a program mode $i \in \mathcal{S}_{\mathcal{P}}$ at time slot $t \in \mathcal{T}$ is represented by the status vector, which is defined as $\boldsymbol{X}^a(t) \in \{0,1\}^{1\times 4}$. Here, $\boldsymbol{X}^a(t) \in \{0,1\}^{1\times|\mathcal{S}_{\mathcal{P}}|}$ is the program mode vector at time slot t in which i^{th} element of the vector, $X_i^a(t)$, is 1 others are zero when the i^{th} program mode is active. For example, the status vector of an appliance a operating in program mode 3 at time slot t is $\boldsymbol{X}^a(t) = [0\ 0\ 1\ 0]$.

Power consumption of an appliance a operating at a program mode $i \in \mathcal{S}_{\mathcal{P}}$ is given by the discretized power profile vector:

$$p_i^a(\hat{t}) = \begin{cases} P_i^a(\hat{t}) & ,\ \text{if } \hat{t} \in [0\ \ T_i^a] \\ 0 & ,\ \text{otherwise} \end{cases} \tag{3.1}$$

where $\hat{t}$ represents the internal time slot of appliances, $(\Delta_{\hat{t}} = \Delta_t)$, $P_i^a(\hat{t})$ represents the average power consumption of the program mode i of the appliance a at $\hat{t}^{th}$ internal time slot and T_i^a is the operation duration of that program mode. Hence, the total power consumption of appliances at time slot t, i.e. $P^{\mathcal{L}}(t)$, is calculated by:

$$P^{\mathcal{L}}(t) = \sum_{\forall a \in \mathcal{L}} P_i^a(t - t_s^l) X_i^a(t) \tag{3.2}$$

where t_s^a is the starting time of the operation of the appliance a.

3.1.1. Uncontrollable Appliances

Appliances, whose operation starting time and finishing time (in short, operation time) and program modes effect user comfort directly, are classified as uncontrollable appliances, e.g., TV and lamps. Both operation time and program modes of these appliances are selected only by the user.

3.1.2. Semicontrollable Appliances

Appliances, whose operation time effect user comfort directly, are classified as semi-controllable appliances. Thermostat controlled appliances (i.e. water heater, fan heater, air conditioner, refrigerator and etc.) are in this type. Hence, operation time of these type of appliances is strictly selected by the user (except for refrigerator which works all day long), while their program modes can be switched to the least power consuming setting by their local controller due to the current tariff rate.

Note that, for uncontrollable and semi-controllable appliances, operation time and operation duration are definite and stated with the following constraint:

$$\sum_{t=t_s^a}^{t_f^a} X_i^a(t) = t_f^a - t_s^a + 1 \ , \quad \forall a \in \mathcal{L}_{\mathcal{UC}} \cup \mathcal{L}_{\mathcal{SC}} \tag{3.3}$$

where t_s^a represents the starting time and t_f^a represents the finishing time of operation of the appliance a.

3.1.3. Controllable Appliances

Appliances, whose program modes effect user comfort directly, are classified as controllable appliances (e.g., washing machine, dishwasher). Program modes of these appliances are selected only by the user and can not be changed by any other means.

Some freedom is available for operation duration of controllable appliances, that is, for controllable appliances, user can define an operation time interval instead of an operation time, such as $[T^a_{s,i}\ T^a_{f,i}]$; where $T^a_{s,i}$ and $T^a_{f,i}$ represent the user defined earliest start time and latest finish time, respectively. Thus, the starting time of a controllable appliance can be shifted through the operation time interval by considering the latest finish time. The operation time of a controllable appliance $a \in \mathcal{L}_\mathcal{C}$ at program mode $i \in \mathcal{S}_\mathcal{P}$ is stated with the following constraint:

$$\sum_{t=T^a_{si}}^{T^a_{fi}} X^a_i(t) = T^a_i \ , \quad \forall i \in \mathcal{S}_\mathcal{P}, \quad \forall a \in \mathcal{L}_\mathcal{C} \tag{3.4}$$

where T^a_i is the duration of the program mode i of appliance a.

MC can also interrupt (that is, switches the working mode from on to standby) a controllable appliance during the operation under some constraints associated with the user comfort and the performance of appliances. Thus, for each program mode $i \in \mathcal{S}_\mathcal{P}$ of a controllable appliance $a \in \mathcal{L}_\mathcal{C}$, the maximum number of interruptions $n^a_{i_{max}}$ and the total maximum interruption duration $T^a_{i_{max}}$ are selected by the user according to personal experiences and preferences or proposed by the manufacturers according to their test results, such that:

$$\sum_{t=1}^{n^a_{i_{max}}} T^a_{i,k} \leq T^a_{i_{max}} \ , \quad \forall i \in \mathcal{S}_\mathcal{P}, \quad \forall a \in \mathcal{L}_\mathcal{C} \tag{3.5}$$

where $T^a_{i,k}$ represents the duration of the k^{th} interruption at the program mode i of the appliance a.

Operation of a controllable appliance a working at a program mode i can be shifted to a starting time t^a_s or interrupted by considering duration of the operation T^a_i, in accordance with the following rule,

$$T^a_{fi} - t^a_s \geq T^a_i + \sum_{t=1}^{n^a_i} T^a_{i,k} \ , \quad t^a_s \in [T^a_{si} \ \ T^a_{fi}] \tag{3.6}$$

Here, n_i^a stands for number of interruptions of appliance a working at a program mode i.

A controllable appliance that is interrupted (switched to standby mode) is set to operate by MC at the first convenient time slot, according to the maximum number and maximum duration of interruptions, household power demand and the tariff rate. Note that, an express program mode without interruption is also defined for each of these appliances.

3.2. Power Resources

In the proposed OF-HEM, power resources providing the home power demand are the grid, Photovoltaic system (PV system) and backup battery.

At any time instant $t \in \mathcal{T}$, power demand of home consists of backup battery charge power, i.e., $P^{\mathcal{B}c}(t)$, PHEV charge power, i.e., $P^{EVc}(t)$, power injected to grid, i.e., $P^{\mathcal{S}}(t)$, power consumed by the appliances, i.e., $P^{\mathcal{L}}(t)$, which are provided by power drawn from the grid, i.e., $P^{\mathcal{G}}(t)$, power obtained from the PV system (shortly PV power), i.e., $P^{\mathcal{PV}}(t)$, backup battery discharge power, i.e., $P^{\mathcal{B}d}(t)$ and PHEV discharge power, i.e., $P^{EVd}(t)$. This relationship is given by the following power balance equation:

$$P^{\mathcal{G}}(t) + P^{\mathcal{PV}}(t) + P^{\mathcal{B}d}(t) + P^{EVd}(t) = P^{\mathcal{L}}(t) + P^{\mathcal{B}c}(t) + P^{EVc}(t) + P^{\mathcal{S}}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.7}$$

3.2.1. Grid

Grid is the primary power resource providing power demand of the home. It is possible to inject power to the grid as well as to purchase power from the grid.

Note that, injecting and purchasing from the grid can not be performed at the same time:

$$x^{\mathcal{S}}(t) + x^{\mathcal{G}}(t) \leq 1 \ , \quad \forall t \in \mathcal{T} \tag{3.8}$$

where $x^{\mathcal{S}}(t) \in \{0,1\}$ and $x^{\mathcal{G}}(t) \in \{0,1\}$ are binary decision variables indicating whether power is injected to the grid and power is provided from the grid at time t, respectively. Thus, $x^{\mathcal{S}}(t) = 1$ if and only if power is injected to the grid; similarly $x^{\mathcal{G}}(t) = 1$ if and only if power is provided from the grid at time t.

In order to avoid high peak demand, the maximum power that can be drawn from the grid at any time slot $t \in \mathcal{T}$, i.e., $P^{\mathcal{G}}_{lim}(t)$ is specified as:

$$P^{\mathcal{G}}(t) \leq P^{\mathcal{G}}_{lim}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.9}$$

This limit can be selected higher when the tariff rate is lower and lower when the tariff rate is higher. Thus, the user is encouraged to use lower amount of energy during the expensive tariff period. Injection to grid is also performed within a limit and at any time slot $t \in \mathcal{T}$, i.e., $P^{\mathcal{S}}_{lim}(t)$:

$$P^{\mathcal{S}}(t) \leq P^{\mathcal{S}}_{lim}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.10}$$

In OF-HEM, grid power is used to meet the power demand of home and for PHEV charging. Hence,

$$P^{\mathcal{G}}(t) = P^{\mathcal{G}}_{EV}(t) + P^{\mathcal{G}}_{\mathcal{L}}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.11}$$

where $P^{\mathcal{G}}_{EV}(t)$ and $P^{\mathcal{G}}_{\mathcal{L}}(t)$ represent the grid power used for PHEV charging and appliance demand at time t, respectively.

Moreover, PHEV is charged only by the grid power at any time slot $t \in \mathcal{T}$:

$$P^{\mathcal{G}}_{EV}(t) = P^{EVc}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.12}$$

3.2.2. Backup Battery

Backup battery is used to store energy and used to reduce power purchased from the grid especially when the tariff is expensive.

For a backup battery, one of the most important parameter is State-Of-Charge (SOC). SOC of a backup battery at time slot t, i.e., $SOC(t)$, is defined as the ratio of its current energy capacity $E^{\mathcal{B}}(t)$ to the nominal energy capacity $E^{\mathcal{B}}_{cap}(t)$, i.e., $SOC(t) = E^{\mathcal{B}}(t)/E^{\mathcal{B}}_{cap}(t)$. $SOC(t)$ of the backup battery can be calculated by:

$$SOC(t) = SOC(t-1) + \frac{P^{\mathcal{B}c}(t)\eta_c \Delta t}{E^{\mathcal{B}}_{cap}(t)} x^{\mathcal{B}c}(t) - \frac{P^{\mathcal{B}d}(t)\Delta t}{E^{\mathcal{B}}_{cap}(t)\eta_{dc}} x^{\mathcal{B}d}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.13}$$

Here, η_c and η_{dc} represent the charge and discharge efficiency of the backup battery, respectively.

The simplest and most obvious way of getting the maximum life of a backup battery is to ensure that it always works within its designed operating limits:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \ , \quad \forall t \in \mathcal{T} \tag{3.14}$$

where, SOC_{min} and SOC_{max} are the minimum and maximum SOC limitations for backup battery operation.

In order to provide efficient and well-balanced backup battery usage, charging and discharging rate of the backup battery are limited by maximum charging rate, i.e., $P^{\mathcal{B}c}_{max}$, and maximum discharging rate, i.e., $P^{\mathcal{B}d}_{max}$ as follows:

$$\begin{aligned} P^{\mathcal{B}c}(t) &\leq P^{\mathcal{B}c}_{max} \ , \quad \forall t \in \mathcal{T} \qquad \text{(a)} \\ P^{\mathcal{B}d}(t) &\leq P^{\mathcal{B}d}_{max} \ , \quad \forall t \in \mathcal{T} \qquad \text{(b)} \end{aligned} \tag{3.15}$$

Since backup battery charging and discharging can not be performed at the same time, the following condition must also be satisfied:

$$x^{\mathcal{B}c}(t) + x^{\mathcal{B}d}(t) \leq 1 \ , \quad \forall t \in \mathcal{T} \tag{3.16}$$

where $x^{\mathcal{B}c}(t) \in \{0, 1\}$ and $x^{\mathcal{B}d}(t) \in \{0, 1\}$ are binary decision variables indicating whether backup battery is charging or discharging at time t, respectively. $x^{\mathcal{B}c}(t) = 1$ if and only if the backup battery is charging, similarly $x^{\mathcal{B}d}(t) = 1$ if and only if backup battery is discharging.

3.2.3. PV System

Integrating renewable energy resources to home architecture is an important factor in reducing the power drawn from the grid and the electrical cost. In this thesis, PV system is integrated to OF-HEM as a renewable energy resource.

At any time instant $t \in \mathcal{T}$, PV power can be used for backup battery charging, power injection to grid and for supporting to meet the power demand of appliances. Hence,

$$P^{\mathcal{PV}}(t) = P^{\mathcal{PV}}_{\mathcal{B}c}(t) + P^{\mathcal{PV}}_{\mathcal{S}}(t) + P^{\mathcal{PV}}_{\mathcal{L}}(t) \ , \quad \forall t \in \mathcal{T} \tag{3.17}$$

Here, $P^{\mathcal{PV}}_{\mathcal{B}c}(t)$, $P^{\mathcal{PV}}_{\mathcal{S}}(t)$ and $P^{\mathcal{PV}}_{\mathcal{L}}(t)$ represent the amount of PV power used for backup battery charging, power injection to grid and for supporting the power demand of appliances, respectively.

In OF-HEM, the only plant of backup battery charging and injection to grid is PV power. Hence,

$$P_{\mathcal{B}c}^{\mathcal{PV}}(t) = P^{\mathcal{B}c}(t)\ , \quad \forall t \in \mathcal{T} \tag{3.18}$$

$$P_{\mathcal{S}}^{\mathcal{PV}}(t) = P^{\mathcal{S}}(t)\ , \quad \forall t \in \mathcal{T} \tag{3.19}$$

PV power of the considered day is calculated by using the historically measured PV power:

$$P^{\mathcal{PV}} = P_{hist}^{PV}(t)\frac{G(t)}{G_r(t)}[1 - \hat{\beta}_p(T_C(t) - T_r(t))], \quad \forall t \in \mathcal{T} \tag{3.20}$$

Here, $P_{hist}^{PV}(t)$ is historically measured PV power, $T_r(t)$ and $G_r(t)$ are the panel temperature and solar irradiance at time slot t respectively; $\hat{\beta}_p$ is the temperature coefficient for efficiency of PV panels; $T_C(t)$ is the measured panel temperature and $G(t)$ is the measured solar irradiance at time slot t.

3.3. Plug-in Hybrid Electrical Vehicle (PHEV)

Plug-in Hybrid Electrical Vehicle (PHEV) with a rechargeable battery, has a lower CO_2 emission when compared to fossil fuels. Since there is variation and discontinuity of photovoltaic power in time, it is preferred to charge the PHEV with a lightweight lithium-ion battery via the grid.

PHEV is part of the OF-HEM and charging the PHEV creates an extra load on the grid. Four different charging types are considered for PHEV: uncontrolled charging, delayed charging, off-peak charging and continuous charging: In the uncontrolled charging case, charging starts when PHEV is connected to the home charging station and it stops when PHEV is fully charged. In continuous charging, charging is possible during the day at any charging station in the city. In the delayed charging, charging the PHEV starts after 10 p.m., which is the starting time of low demand period (off-peak). In the off-peak charging, starting time for charging the PHEV is determined by the utility in the off-peak period. In this thesis, instead of continuous and uncontrolled charging which may cause high peak demand, off-peak charging was considered [18].

PHEV is used to reduce electrical cost that is charged from the grid, especially when the tariff is cheap. The PHEV and the other power resources (grid, PV system and backup battery) are coordinated with the smart and energy efficient operation constraints in order to leave adequate energy for driving. Thus, when the PHEV is added to OF-HEM, the mobile nature of storage will be challenged.

Similar to the backup battery, SOC of a PHEV at time slot t, i.e., $SOC_{EV}(t)$, is defined as the ratio of its current energy capacity $E^{EV}(t)$ to its nominal energy capacity $E^{EV}_{cap}(t)$, i.e., $SOC_{EV}(t) = E^{EV}(t)/E^{EV}_{cap}(t)$. $SOC_{EV}(t)$ of the PHEV can be calculated by:

$$SOC_{EV}(t) = SOC_{EV}(t-1) + \frac{P^{EVc}(t)\eta_{evc}\Delta t}{E^{EV}_{cap}(t)} x^{EVc}(t) - \frac{P^{EVd}(t)\Delta t}{E^{EV}_{cap}(t)\eta_{evd}} x^{EVd}(t)\ , \quad \forall t \in \mathcal{T} \tag{3.21}$$

Here, η_{evc} and η_{evd} represent the charge and discharge efficiency of the PHEV, respectively. $SOC_{EV}(t)$ should be within the designed operating limits:

$$SOC_{EV_{min}} \leq SOC_{EV}(t) \leq SOC_{EV_{max}}\ , \quad \forall t \in \mathcal{T} \tag{3.22}$$

where, $SOC_{EV_{min}}$ and $SOC_{EV_{max}}$ are the minimum and maximum SOC_{EV} limitations for PHEV operation.

Charging and discharging rate of PHEV are limited by maximum charging rate, i.e., P^{EVc}_{max}, and maximum discharging rate, i.e., P^{EVd}_{max} as follows:

$$\begin{aligned} P^{EVc}(t) &\leq P^{EVc}_{max}\ , \quad \forall t \in \mathcal{T} \qquad \text{(a)} \\ P^{EVd}(t) &\leq P^{EVd}_{max}\ , \quad \forall t \in \mathcal{T} \qquad \text{(b)} \end{aligned} \tag{3.23}$$

Since charging and discharging can not be performed at the same time, the following condition must also be satisfied:

$$x^{EVc}(t) + x^{EVd}(t) \leq 1\ , \quad \forall t \in \mathcal{T} \tag{3.24}$$

where $x^{EVc}(t) \in \{0,1\}$ and $x^{EVd}(t) \in \{0,1\}$ are binary decision variables indicating whether PHEV is charging and discharging at time t, respectively. $x^{EVc}(t) = 1$ if and only if the PHEV is charging, similarly $x^{EVd}(t) = 1$, if and only if PHEV is discharging.

3.4. Main Controller

MC, communicates and controls appliances and power resources to minimize the electrical cost and reduce high peak demand. At the beginning of each day, MC gathers user requests, power resources and smart electrical appliances information.

For the user request information, MC collects information about the requested operation time and program mode of uncontrollable appliances, requested operation time of semi-controllable appliances, operation time interval and selected program mode, maximum interruption number and maximum interruption duration of controllable appliances.

For the status of power resource information, MC is informed about the initial status of the backup battery, PHEV and the tariff rate for the day of consideration.

By obtaining these information, MC solves the following Mixed Integer Linear Programming (MILP) problem where $C^{\mathcal{G}}(t)$ represents the electricity tariff for power drawn from the grid (€/kWh) and $C^{\mathcal{S}}(t)$ represents electricity tariff for power injected to the grid (€/kWh):

$$\min \sum_{t=1}^{\mathcal{T}} (P^{\mathcal{G}}(t)C^{\mathcal{G}}(t) - P^{\mathcal{S}}(t)C^{\mathcal{S}}(t))\Delta_t \tag{3.25}$$

subject to constraints (3.1) - (3.24):

$$\begin{aligned}
&P^{\mathcal{G}}(t), P^{\mathcal{G}}_{EV}(t), P^{\mathcal{G}}_{\mathcal{L}}(t), P^{\mathcal{PV}}_{\mathcal{S}}(t), P^{\mathcal{PV}}_{\mathcal{L}}(t), P^{\mathcal{PV}}_{\mathcal{B}c}(t),\\
&\qquad P^{\mathcal{B}c}(t), P^{\mathcal{B}d}(t), P^{EVc}(t), P^{EVd}(t), P^{\mathcal{S}}(t) \in \mathbb{R}^+ \ , \quad \forall t \in \mathcal{T}\\
&\quad x^{\mathcal{G}}(t), x^{\mathcal{B}c}(t), x^{\mathcal{B}d}(t), x^{EVc}(t), x^{EVd}(t), x^{\mathcal{S}}(t) \in \{0,1\} \ , \quad \forall t \in \mathcal{T}\\
&\qquad\qquad P^a_i(\hat{t}) \in \mathbb{R}^+ \ , \quad \forall i \in \mathcal{S}_{\mathcal{P}},\ \forall a \in \mathcal{L},\ \hat{t} \in [0 \ \ T^a_i]\\
&\qquad\qquad X^a_i(t) \in \{0,1\} \ , \quad \forall i \in \mathcal{S}_{\mathcal{P}}, \ \ \forall a \in \mathcal{L}, \ \ \forall t \in \mathcal{T}
\end{aligned} \tag{3.26}$$

This MILP problem is solved by CPLEX solver in GAMS software. The solution provides the best operation time of controllable appliances within the user requested time interval and the best timing of backup battery charge and discharge processes, PHEV charge and discharge processes, PV usage, grid power use, power injection to grid operations.

4. CASE STUDY

In this section, the effects of OF-HEM on electrical costs and utilization will be analysed based on different scenarios where operation times of electrical appliances with different occupation times in different seasons are determined by user requests.

In these scenarios, a 60 m^2 home with three occupants is considered. Appliances and their properties are given in Table 4.1. The operation duration, maximum interruption duration and the maximum number of interruptions of each program mode for controllable appliances are also given in Table 4.1. Power consumption of appliances are measured by using Yokowaga WT210 power analyser with the time slot duration of 1 minute, thus $\Delta_t = 1$ min yielding 1440 time slot count per day.

PV system, backup battery and PHEV capacities are specified as 2 kWp, 6 kVAh and 9 kVAh, respectively. The charging and discharging efficiency of the backup battery, PHEV and the efficiency of inverters are assumed 95%. In the scenarios, backup battery and PHEV energy levels are chosen as : $SOC_{EV_{min}} = 30\%$, $SOC_{min} = 10\%$, $SOC_{EV_{max}} = SOC_{max} = 90\%$ and $SOC_{EV_{ini}} = SOC_{ini} = 50\%$.

PV power is calculated based on the historical PV data, which is generated with monthly PV data for Eskisehir (Turkey) in the PVGIS database [19]. Figure 4.1 shows PV power profile used in scenarios for any day of July and for any day of January.

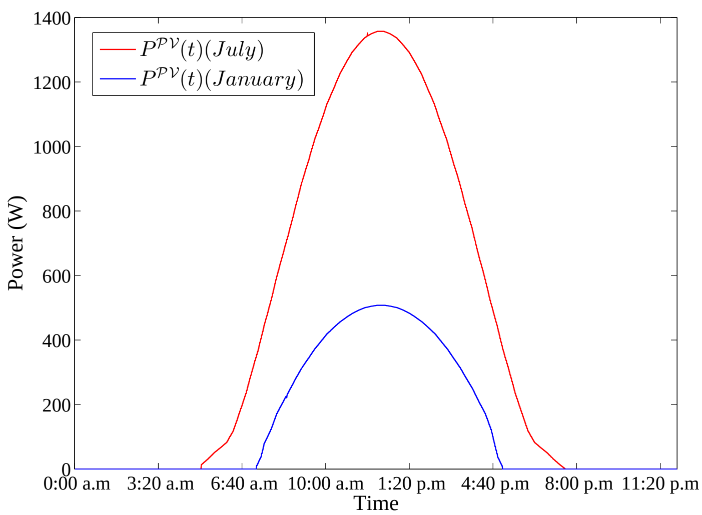

Figure 4.1. Graph of the PV power profile for July and January

Table 4.1. Program Modes and Specifications for Appliances

Type of Appliances					
Uncontrollable Appliances	**Program mode**	**Property**			
2 Lamps	high energy saving	10% illumination			26 W for each
	medium energy saving	30% illumination			
	low energy saving	60% illumination			
	no energy saving	100% illumination			
Television (TV)	high energy saving	10% brightness			116 cm LED TV
	medium energy saving	30% brightness			
	low energy saving	60% brightness			
	no energy saving	100% brightness			
Semi-controllable Appliances	**Program mode**	**Property**			
Air-Conditioner (AC)	cooler-normal	6.74 kW cooling capacity			
	cooler-economic				
	heater-normal	7.03 kW heating capacity			
	heater-economic				
Refrigerator (REF)	low speed	510 lt no-frost			
	moderate speed				
	high speed				
	defrost				
Controllable Appliances	**Program mode**	T_i^a	$n_{i_{max}}^a$	$T_{i_{max}}^a$	**Property**
Washing-Machine (WM)	normal (i=1)	60	3	15	7 kg front-load
	long (i=2)	145	3	30	
	express (i=3)	20	0	0	
	special (i=4)	90	3	25	
Dishwasher (DW)	normal (i=1)	80	4	20	60 cm free standing
	intensive (i=2)	144	4	30	
	express (i=3)	30	0	0	
	special (i=4)	120	4	25	

In Table 4.2, TOU periods and prices set by Turkish Power Distribution Corporation (TEDAS) [20] and the grid limits are given. Here, limit on the power drawn from the grid and the limit on the power injected to grid are chosen as equal.

Note that, although these limits are assumed to be constant throughout a price period, it can also vary even in every time slot depending on system requirements.

Table 4.2. Time-Of-Use Pricing (TOU) Periods, Rates and Grid Limits

Duration	$C^{\mathcal{G}}(t)$ **(€/kWh)**	$C^{\mathcal{S}}(t)$ **(€/kWh)**	**Modes**	$P^{\mathcal{G}}_{lim}(t)$ **(W)**
6 a.m. - 5 p.m.	0.1	0.06	Moderate	3460
5 p.m. - 10 p.m.	0.15	0.12	Expensive	2200
10 p.m. - 6 a.m.	0.06	0.03	Cheap	4500

To identify the effect of OF-HEM on electrical costs and utilization clearly, several scenarios are analysed for three different cases. In Case 1, neither power resources, nor the appliances are controlled. Backup battery is used only during power outages, electrical appliance use (program modes and operation times) are determined only by the user. In Case 2, only power resources (grid, PV system, backup battery) are controlled based on the OF-HEM constraints, all electrical appliances are managed based on user requests. On the other hand, in Case 3, OF-HEM is integrated to the home, in other words, both power resources and electrical appliances are controlled within the limits of determined constraints.

In the following, four of the analysed scenarios will be provided in detail. Others and related analysis results will be given in the Appendix.

4.1. Scenario 1

In Scenario 1, the home is occupied fully on a day in a week in July. The user sets WM to run in the time interval [2:00 p.m. - 6:00 p.m.] at the normal program mode ($T_1^{WM} = 60$ min), and DW to run in the time interval [9:00 p.m. - 11:59 p.m.] at the normal program mode ($T_1^{DW} = 80$ min). AC and REF runs all day long. Operation of TV and lamps are strictly selected by the user, such that the user turns on TV [09:00 p.m. - 11:59 p.m.] at the high energy saving mode and turns on two lamps [8:00 p.m. - 11:59 p.m.] at the low and high energy saving modes. PHEV integration to HEMS isn't considered.

In Cases 1 and 2, WM and DW start with the user defined earliest start time, i.e., 2:00 p.m. and 9:00 p.m. and finish at 3:00 p.m. and 10:20 p.m., respectively. During the whole day AC is operated at cooler-normal mode. REF is operated in the time intervals [0:00 a.m. - 0:30 a.m.] at the defrost mode and [0:31 a.m. - 11:59 p.m.] at the moderate mode. In Case 3, starting time of the operation of WM is delayed for 48 min and its operation starts at 2:48 p.m. The starting time of the operation of DW is delayed for 12 min and its operation starts at 9:12 p.m. Controllable appliances being uninterruptible means that they cannot be switched to standby mode during the operation times. According to their operation starting times, operation of WM finishes at 3:48 p.m., while that of DW ends at 10:32 p.m. AC and REF program modes are switched to cooler economic mode and low speed mode when the tariff switches to the expensive period. Operation properties of all uncontrollable appliances, that is, operation duration, starting time and program modes, are the same for all three cases.

In Table 4.3, total power consumption, grid power and cost values for Scenario 1 are given. The cost of the Scenario 1 would be 1.94 € for Case-1, while it is obtained as 0.97 € with 50% reduction for Case-2. By integrating the OF-HEM to the home, that is for Case-3, the cost is realized as 0.77 €, with an improvement of 21% when compared to Case-2 and with an improvement of 60% when compared to Case-1.

In Figure 4.2, Figure 4.3 and Figure 4.4 graphs of power demand and power drawn from the grid for Scenario 1 are given for Case-1, Case-2 and Case-3,respectively. While sudden increases are observed in the power taken from the grid in Case-1 and Case-2, the power taken from the grid in Case-3 remains below the predefined grid limits.

4.2. Scenario 2

In Scenario 2, the home is occupied fully on a day in a week in July. The user sets WM to run in the time interval [2:00 p.m. - 6:00 p.m.] at the normal program mode (T_1^{WM} = 60 min, $T_{1_{max}}^{WM}$ = 15 min), and DW to run in the time interval [9:00 p.m. - 11:59 p.m.] at the normal program mode (T_1^{DW} = 80 min, $T_{1_{max}}^{DW}$ = 20 min). AC and REF runs all day long. Operation of TV and lamps are strictly selected by the user, such that the user turns on TV [09:00 p.m. - 11:59

Table 4.3. Results of Scenarios

Cases and Results		Scenarios			
		1	**2**	**3**	**4**
Season	January			✓	✓
	July	✓	✓		
Occupancy	full occupancy	✓	✓		
	partial occupancy			✓	✓
$P^{\mathcal{L}}(t)$ (kWh)	Case 1	28.2	28.9	28.51	29.21
	Case 2	28.2	28.9	28.51	29.21
	Case 3	26.46	26.3	27.05	27.51
$P^{\mathcal{G}}(t)$ (kWh)	Case 1	22.24	30.7	26.38	34.8
	Case 2	13	15.6	19.6	20.34
	Case 3	11.27	15.26	18.13	19.9
$P^{\mathcal{G}}_{\mathcal{L}}(t)$ (kWh) (with PHEV)	Case 1	-	22.27	-	26.4
	Case 2	-	7.18	-	11.91
	Case 3	-	6.84	-	11.47
$P^{\mathcal{G}}_{EV}(t)$ (kWh)	Case 1	-	8.42	-	8.42
	Case 2	-	8.42	-	8.42
	Case 3	-	8.42	-	8.42
Cost (€)	Case 1	1.94	2.55	2.6	3.16
	Case 2	0.97	0.9	1.68	1.51
	Case 3	0.77	0.8	1.5	1.44
Cost reduction (%)	Case 2 wrt. Case 1	50	65	35	52.2
	Case 3 wrt. Case 2	21	11.1	11	4.63
	Case 3 wrt. Case 1	60	68.6	42	54.4

p.m.] at the high energy saving mode and turns on two lamps [8:00 p.m. - 11:59 p.m.] at the low and medium energy saving modes. While PHEV $SOC_{EV_{max}} = 90\%$, it leaves the house at 6:00 a.m. in the morning, arrives back at 5:00 p.m. while $SOC_{EV_{min}} = 30\%$.

For this Scenario, in Cases 1 and 2, WM and DW start with the user defined earliest start time, i.e., 2:00 p.m. and 9:00 p.m. and finish at 3:00 p.m. and 10:20 p.m., respectively. During the whole day AC is operated at cooler-normal

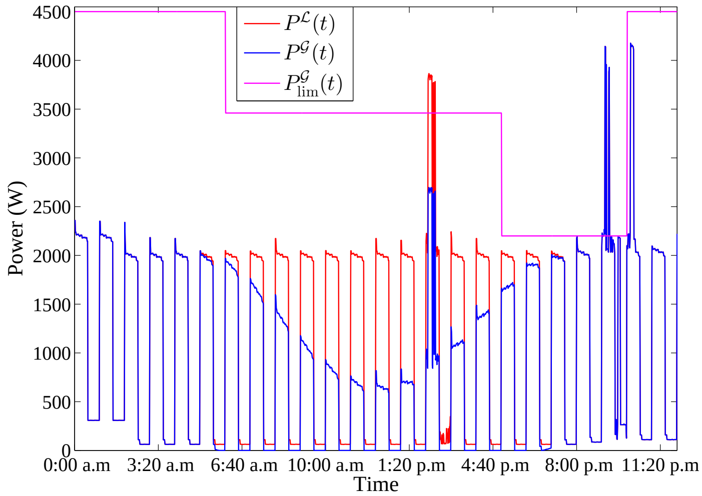

Figure 4.2. Power demand/grid power/grid limit for Case 1 of Scenario 1

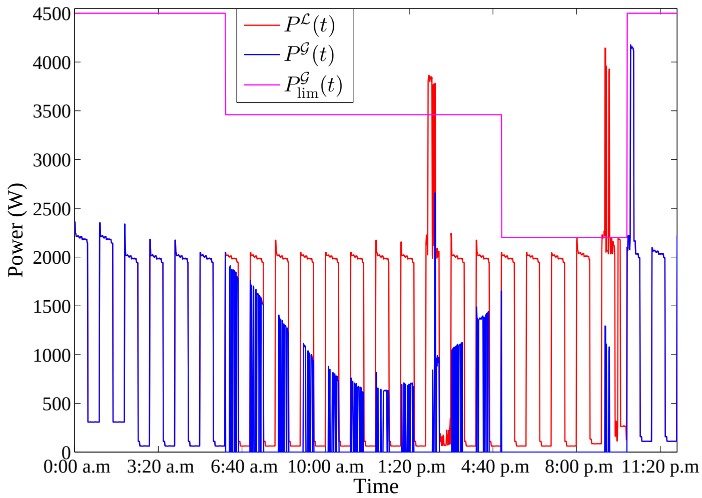

Figure 4.3. Power demand/grid power/grid limit for Case 2 of Scenario 1

mode. REF is operated in the time intervals [0:00 a.m. - 0:30 a.m.] at the defrost mode and [0:31 a.m. -11:59 p.m.] at the moderate mode. In Case 3, starting time of the operation of WM is delayed for 52 min and its operation starts at 2:52 p.m. The starting time of the operation of DW is delayed for 48 min and its operation starts at 9:48 p.m. WM and DW are interrupted for a total of 10 and 20 minutes, respectively to operate at the first convenient time slot. According to their operation starting times and total interruption times, operation of WM finishes at 4:02 p.m., while that of DW ends at 11:28 p.m. AC and REF program modes are switched to cooler economic mode and low speed mode when the tariff switches to

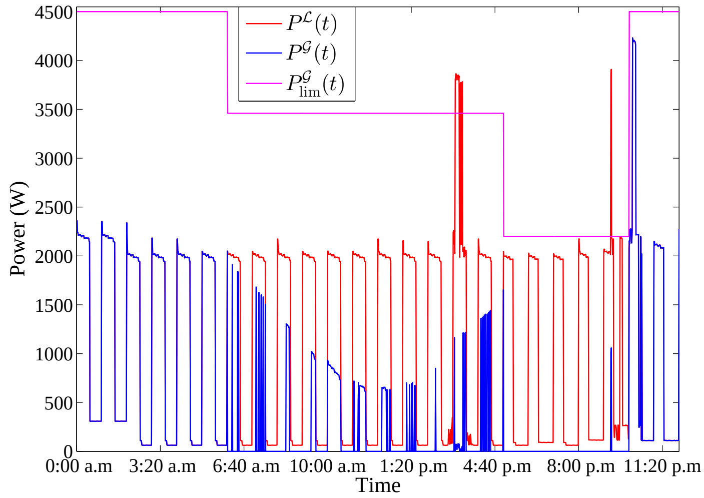

Figure 4.4. Power demand/grid power/grid limit for Case 3 of Scenario 1

the expensive period. Operation properties of all uncontrollable appliances, that is, operation duration, starting time and program modes, are the same for all three cases.

In Table 4.3, total power consumption, grid power and cost values for Scenario 2 are given. The cost of the Scenario 2 would be 2.55 € for Case-1, while it is obtained as 0.9 € with 65% reduction for Case-2. By integrating the OF-HEM to the home, that is for Case-3, the cost is realized as 0.8 €, with an improvement of 11.1% when compared to Case-2 and with an improvement of 68.6% when compared to Case-1.

Graphs of power demand and power drawn from the grid for Scenario 2 are given for Case-1, Case-2 and Case-3 in Figure 4.5, Figure 4.6 and Figure 4.7, respectively.

4.3. Scenario 3

In Scenario 3, the home is occupied partially on a day in a week in January. The user sets WM to run in the time interval [7:30 p.m. -11:59 p.m.] at the special program mode ($T_4^{WM} = 90$ min), and DW to run in the time interval [00:30 a.m. - 04:00 a.m.] at the special program mode ($T_4^{DW} = 120$ min). AC and REF runs all day long. Operation of TV and lamps are strictly selected by the user, such that the user turns on TV [09:00 p.m. - 11:59 p.m.] at the low energy saving mode and

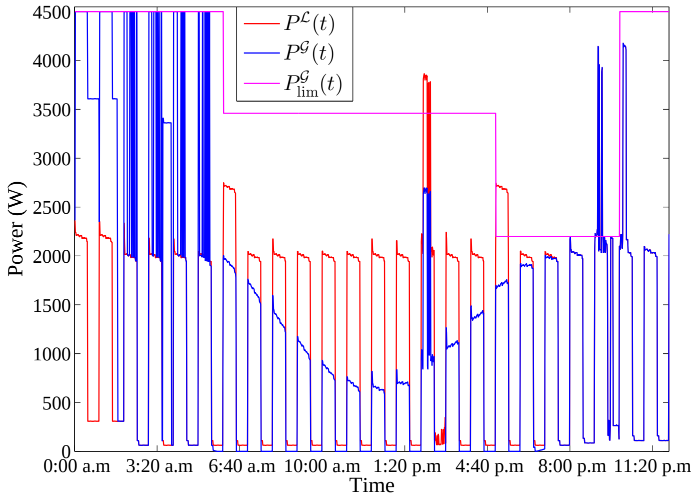

Figure 4.5. Power demand/grid power/grid limit for Case 1 of Scenario 2

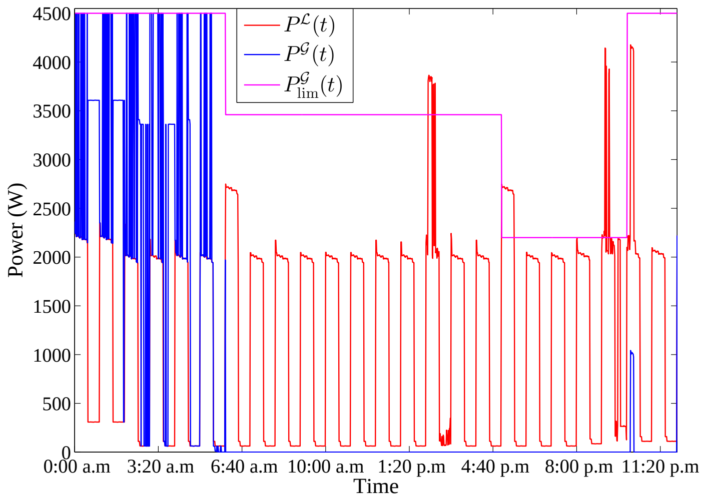

Figure 4.6. Power demand/grid power/grid limit for Case 2 of Scenario 2

turns on two lamps [6:00 p.m. - 11:59 p.m.] at the no and medium energy saving modes. PHEV integration to HEMS isn't considered.

In Cases 1 and 2, WM and DW start with the user defined earliest start time, i.e., 7:30 p.m. and 0:30 a.m. and finish at 9:00 p.m. and 2:30 a.m., respectively. During the whole day AC is operated at heater-normal mode. REF is operated in the time intervals [0:00 a.m. - 0:30 a.m.] at the defrost mode and [0:31 a.m. - 11:59 p.m.] at the moderate mode. In Case 3, starting time of the operation of WM is delayed for 92 min and its operation starts at 9:02 p.m. The starting time of the operation of DW is delayed for 20 min and its operation starts at 0:50 a.m.

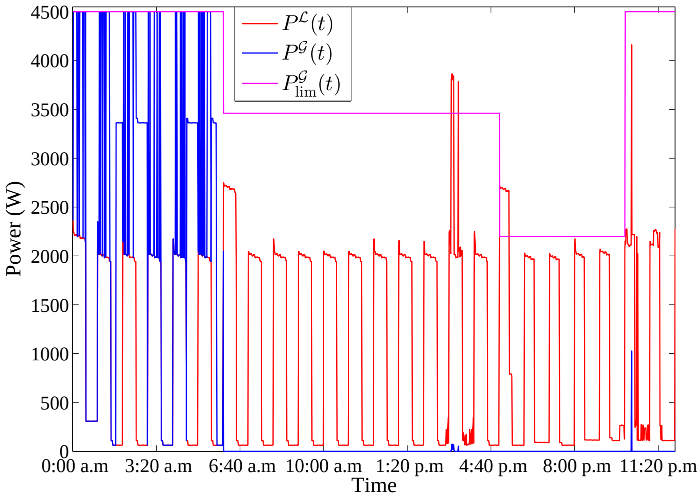

Figure 4.7. Power demand/grid power/grid limit for Case 3 of Scenario 2

Controllable appliances being uninterruptible means that they cannot be switched to standby mode during the operation times. According to their operation starting times, operation of WM finishes at 10:32 p.m., while that of DW ends at 2:50 a.m. AC and REF program modes are switched to heater economic mode and low speed mode when the tariff switches to the expensive period. Operation properties of all uncontrollable appliances, that is, operation duration, starting time and program modes, are the same for all three cases.

In Table 4.3, total power consumption, grid power and cost values for Scenario 3 are given. The cost of the Scenario 3 would be 2.6 € for Case-1, while it is obtained as 1.68 € with 35% reduction for Case-2. By integrating the OF-HEM to the home, that is for Case-3, the cost is realized as 1.5 €, with an improvement of 11% when compared to Case-2 and with an improvement of 42% when compared to Case-1.

In Figure 4.8, Figure 4.9 and Figure 4.10 graphs of power demand and power drawn from the grid for Scenario 3 are given for Case-1, Case-2 and Case-3,respectively. While sudden increases are observed in the power taken from the grid in Case-1 and Case-2, the power taken from the grid in Case-3 remains below the predefined grid limits.

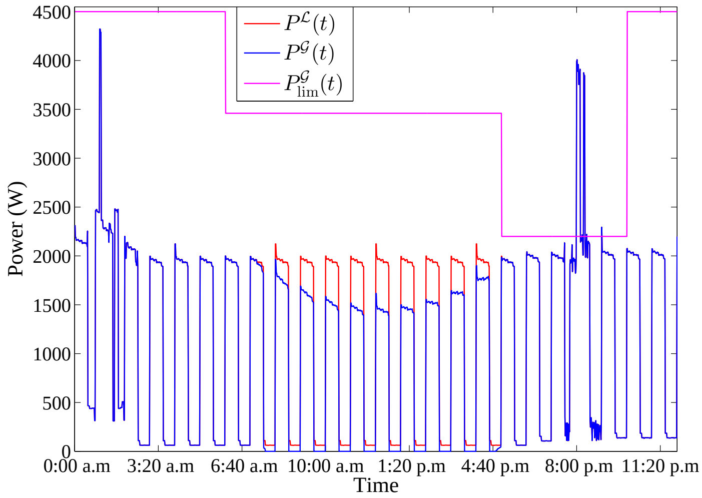

Figure 4.8. Power demand/grid power/grid limit for Case 1 of Scenario 3

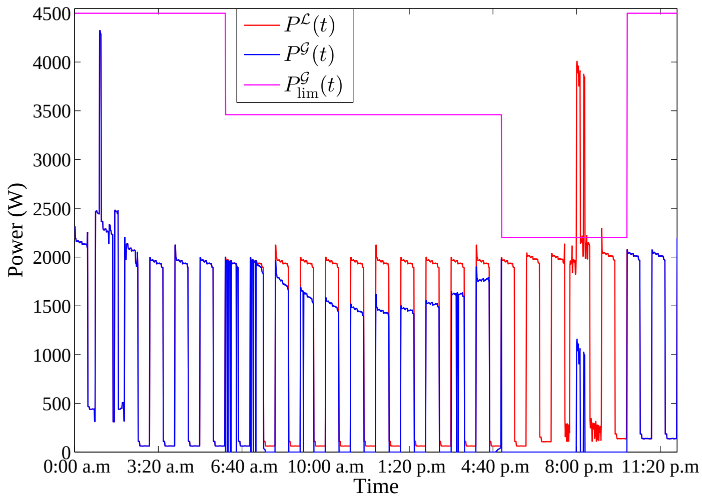

Figure 4.9. Power demand/grid power/grid limit for Case 2 of Scenario 3

4.4. Scenario 4

In Scenario 4, the home is occupied partially on a day in a week in January. The user sets WM to run in the time interval [7:30 p.m. -11:59 p.m.] at the special program mode ($T_4^{WM} = 90$ min, $T_{4_{max}}^{WM} = 25$ min), and DW to run in the time interval [00:30 a.m. - 04:00 a.m.] at the special program mode ($T_4^{DW} = 120$ min, $T_{4_{max}}^{DW} = 25$ min). AC and REF runs all day long. Operation of TV and lamps are strictly selected by the user, such that the user turns on TV [09:00 p.m. - 11:59 p.m.] at the low energy saving mode and turns on two lamps [6:00 p.m. - 11:59

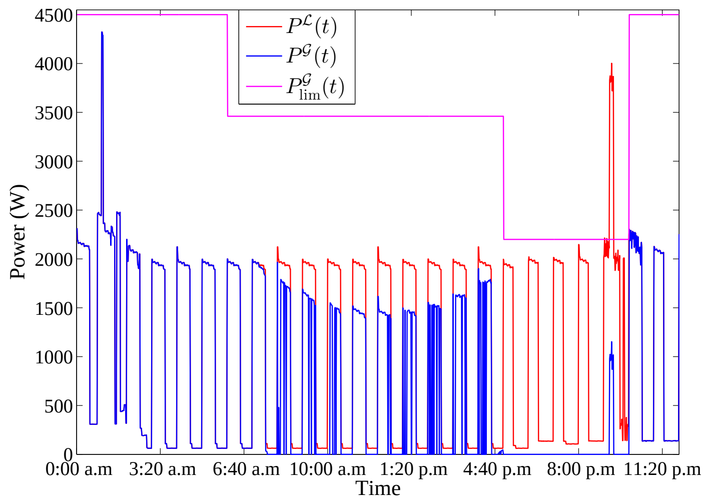

Figure 4.10. Power demand/grid power/grid limit for Case 3 of Scenario 3

p.m.] at the no and medium energy saving modes. While PHEV $SOC_{EV_{max}} = 90\%$, it leaves the house at 6:00 a.m. in the morning, arrives back at 5:00 p.m. while $SOC_{EV_{min}} = 30\%$.

For this Scenario, in Cases 1 and 2, WM and DW start with the user defined earliest start time, i.e., 7:30 p.m. and 0:30 a.m. and finish at 9:00 p.m. and 2:30 a.m., respectively. During the whole day AC is operated at heater-normal mode. REF is operated in the time intervals [0:00 a.m. - 0:30 a.m.] at the defrost mode and [0:31 a.m. -11:59 p.m.] at the moderate mode. In Case 3, starting time of the operation of WM is delayed for 3 hours and its operation starts at 10:30 p.m. The starting time of the operation of DW is delayed for 40 min and its operation starts at 1:10 p.m. WM is uninterruptible and DW is interrupted for a total of 25 min, to operate at the first convenient time slot. According to their operation starting times and total interruption times, operation of WM finishes at 11:59 p.m., while that of DW ends at 3:35 a.m. AC and REF program modes are switched to heater economic mode and low speed mode when the tariff switches to the expensive period. Operation properties of all uncontrollable appliances, that is, operation duration, starting time and program modes, are the same for all three cases.

In Table 4.3, total power consumption, grid power and cost values for Scenario 4 are given. The cost of the Scenario 4 would be 3.16 € for Case-1, while it is obtained as 1.51 € with 52.2% reduction for Case-2. By integrating the OF-HEM to the home, that is for Case-3, the cost is realized as 1.44 €, with an improvement of 4.63% when compared to Case-2 and with an improvement of 54.4% when compared to Case-1.

Graphs of power demand and power drawn from the grid for Scenario 4 are given for Case-1, Case-2 and Case-3 in Figure 4.11, Figure 4.12 and Figure 4.13, respectively.

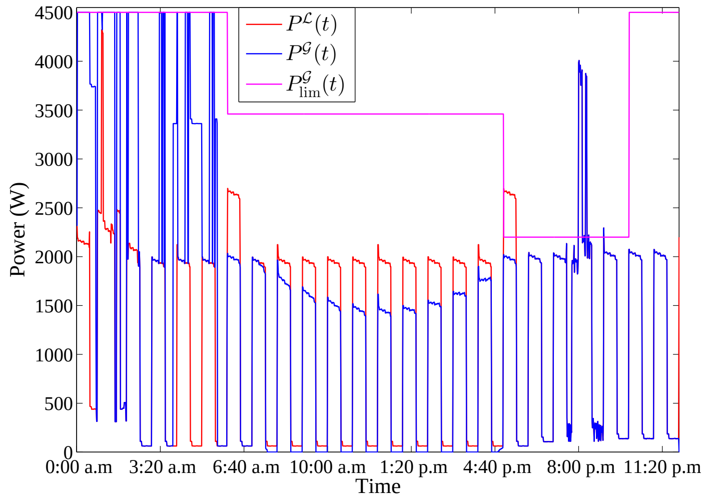

Figure 4.11. Power demand/grid power/grid limit for Case 1 of Scenario 4

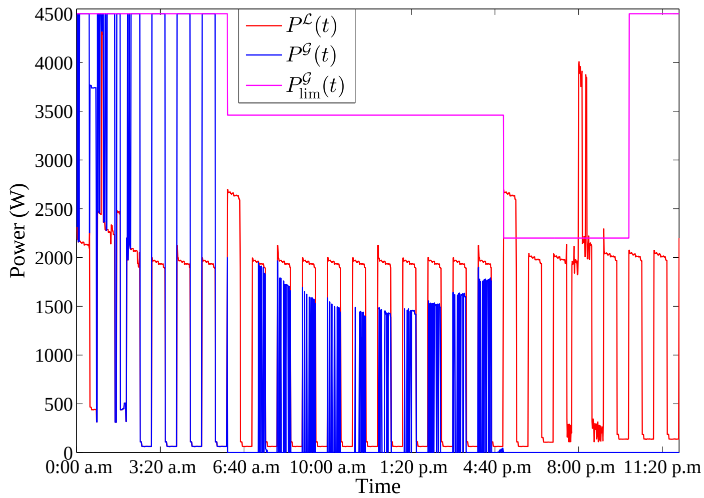

Figure 4.12. Power demand/grid power/grid limit for Case 2 of Scenario 4

In Scenario 2 and Scenario 4, maximum interruption times for controllable

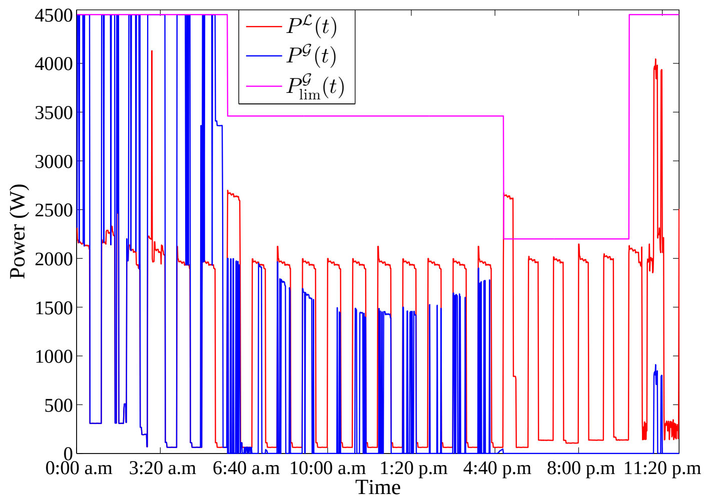

Figure 4.13. Power demand/grid power/grid limit for Case 3 of Scenario 4

appliances in the integration of OF-HEM in the system are selected between 0 to 30 minutes, considering the user comfort (See Table 4.1). By limiting or selecting longer periods, further gains on cost can be obtained such as 9% for Scenario 2 in Case 3 when compared to Case 1 and 5% for Scenario 4 in the same case.

The optimisation-based HEM proposed by the authors in a previous study [21] provided an offline home energy management as well using MILP. Different from the said study, interruption was allowed in controllable appliances in the OF-HEM and a PHEV was integrated to the home system. PHEV could be powered by the grid in a controlled manner, it could also support other power resources in a controlled manner in providing for the energy requirements of the home. Power demand and power drawn from the grid graphs obtained with HEM and OF-HEM applications for the Scenario 1 and Scenario 2 in Case 3 are presented in Figure 4.4 and Figure 4.7, respectively. As could be compared to the graphs, OF-HEM was more effective in preventing instantaneous peak demand.

Comparison of OF-HEM and HEMS based on electrical costs is presented in Table 4.4. The same table also reflects the comparison of the studies based on electrical costs where in [21], an offline home energy management system was proposed, an appliance-based control approach was proposed [13], an autonomous appliance scheduling method was proposed [22], a different demand response approach was used [7], and linear programming methods trade-off between user comfort and energy savings, in terms of electrical cost reduction [14]. As displayed in the table, OF-HEM prioritizes user satisfaction in addition to the better cost optimization it provides when compared to other studies.

Table 4.4. Comparison of Results of the Different Methods

Method	**Cost reduction**
OF-HEM	48%-68%
HEM [21]	40%-60%
Ab-HPMS [13]	10%-24%
Autonomous appliance scheduling [22]	11%
Price based HEM [7]	7.5%
Linear programming-based scheduling [14]	6%-25%

5. CONCLUSION

In this thesis, a home energy management system, namely OF-HEM, is proposed to minimize electrical costs and reduce high peak demand while maintaining user comfort. The system is composed of smart electrical appliances, power resources, communication network, MC and a PHEV. In the system, appliances are divided into three subclasses as uncontrollable, semi-controllable and controllable based on user comfort and appliance properties. Power resources providing the home power demand are the grid, PV system and backup battery. Smart and energy efficient operation constraints are defined and used for appliances and power resources. Power demand when charging the PHEV is supplied from the grid, which also supports other power resources to meet the home power demand in a controlled manner. MC controls the home power demand and the usage of power resources and appliances for efficient use of energy, thus minimizing the electrical cost. At the beginning of each day, MC gathers user requests, appliances and power resources information and solves the MILP problem formulated with the aforementioned constraints for appliances and power resources. The solution of this problem provides cost minimizing schedule for controllable appliances and power resources, thus, it provides cost minimizing times for the backup battery and PHEV charges and discharges, PV usage, grid power usage, power injection to grid processes. Simulations of various scenarios demonstrated that OF-HEM provided 48%-68% reduction in electrical costs when compared to the uncontrolled case in January and July, respectively and also improved the results obtained by similar studies in the literature.

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APPENDIX

Scenarios without PHEV and uninterruptible controllable appliances:

Scenario 1 - the user sets	2 Lamps	: low energy saving [8:00 p.m. - 11:59 p.m.]
		: high energy saving [8:00 p.m. - 11:59 p.m.]
	TV	: high energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: normal [2:00 p.m. - 6:00 p.m.]
	DW	: normal [9:00 p.m. - 11:59 p.m.]
Case 1-2 - $\mathcal{L}$ operates	2 Lamps	: low energy saving [8:00 p.m. - 11:59 p.m.]
		: high energy saving [8:00 p.m. - 11:59 p.m.]
	TV	: high energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: normal [2:00 p.m. - 3:00 p.m.]
	DW	: normal [9:00 p.m. - 10:20 p.m.]
Case 3 - $\mathcal{L}$ operates	2 Lamps	: low energy saving [8:00 p.m. - 11:59 p.m.]
		: high energy saving [8:00 p.m. - 11:59 p.m.]
	TV	: high energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 5:00 p.m.]
		: cooler-economic [5:01 p.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 5:01 p.m.]
		: low speed [5:01 p.m. - 11:59 p.m.]
	WM	: normal [2:48 p.m. - 3:48 p.m.]
	DW	: normal [9:12 p.m. - 10:32 p.m.]

Scenario 3 - the user sets	2 Lamps	: no energy saving [6:00 p.m. - 11:59 p.m.]
		: medium en. saving [6:00 p.m.-11:59 p.m.]
	TV	: low energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: special [7:30 p.m. - 11:59 p.m.]
	DW	: special [0:30 a.m. - 04:00 a.m.]
Case 1-2 - $\mathcal{L}$ operates	2 Lamps	: no energy saving [6:00 p.m. - 11:59 p.m.]
		: medium en. saving [6:00 p.m. - 11:59 p.m.]
	TV	: low energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: special [7:30 p.m. - 9:00 p.m.]
	DW	: special [0:30 a.m. - 02:30 a.m.]
Case 3 - $\mathcal{L}$ operates	2 Lamps	: no energy saving [6:00 p.m. - 11:59 p.m.]
		: medium en. saving [6:00 p.m. - 11:59 p.m.]
	TV	: low energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 5:00 p.m.]
		: heater-economic [5:01 p.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 5:01 p.m.]
		: low speed [5:01 p.m. - 11:59 p.m.]
	WM	: special [9:02 p.m. - 10:32 p.m.]
	DW	: special [0:50 a.m. - 2:50 a.m.]

Scenario 5 - the user sets	2 Lamps	: low energy saving [6:00 p.m. - 11:59 p.m.]
		: high energy saving [6:00 p.m. - 11:59 p.m.]
	TV	: high energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: normal [2:00 p.m. - 6:00 p.m.]
	DW	: normal [9:00 p.m. - 11:59 p.m.]
Case 1-2 - $\mathcal{L}$ operates	2 Lamps	: low energy saving [6:00 p.m. - 11:59 p.m.]
		: high energy saving [6:00 p.m. - 11:59 p.m.]
	TV	: high energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: normal [2:00 p.m. - 3:00 p.m.]
	DW	: normal [9:00 p.m. - 10:20 p.m.]
Case 3 - $\mathcal{L}$ operates	2 Lamps	: low energy saving [6:00 p.m. - 11:59 p.m.]
		: high energy saving [6:00 p.m. - 11:59 p.m.]
	TV	: high energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 5:00 p.m.]
		: heater-economic [5:01 p.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 5:01 p.m.]
		: low speed [5:01 p.m. - 11:59 p.m.]
	WM	: normal [2:48 p.m. - 3:48 p.m.]
	DW	: normal [9:12 p.m. - 10:32 p.m.]

Scenario 7 - the user sets	2 Lamps	: no energy saving [8:00 p.m. - 11:59 p.m.]
		: medium en. saving [8:00 p.m. - 11:59 p.m.]
	TV	: low energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: special [7:30 p.m. - 11:59 p.m.]
	DW	: special [0:30 a.m. - 04:00 a.m.]
Case 1-2 - $\mathcal{L}$ operates	2 Lamps	: no energy saving [8:00 p.m. - 11:59 p.m.]
		: medium en. saving [8:00 p.m. - 11:59 p.m.]
	TV	: low energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: special [7:30 p.m. - 9:00 p.m.]
	DW	: special [0:30 a.m. - 02:30 a.m.]
Case 3 - $\mathcal{L}$ operates	2 Lamps	: no energy saving [8:00 p.m. - 11:59 p.m.]
		: medium en. saving [8:00 p.m. - 11:59 p.m.]
	TV	: low energy saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 5:00 p.m.]
		: cooler-economic [5:01 p.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 5:01 p.m.]
		: low speed [5:01 p.m. - 11:59 p.m.]
	WM	: special [9:34 p.m. - 11:04 p.m.]
	DW	: special [1:42 a.m. - 3:42 a.m.]

Scenario 9 - the user sets	2 Lamps	: medium en. saving [8:00 p.m. - 11:59 p.m.]
		: low energy saving [8:00 p.m. - 11:59 p.m.]
	TV	: medium en. saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: express [5:50 p.m. - 10:30 p.m.]
	DW	: intensive [7:30 p.m. - 11:59 p.m.]
Case 1-2 - $\mathcal{L}$ operates	2 Lamps	: medium en. saving [8:00 p.m. - 11:59 p.m.]
		: low energy saving [8:00 p.m. - 11:59 p.m.]
	TV	: medium en. saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: express [5:50 p.m. - 6:10 p.m.]
	DW	: intensive [7:30 p.m. - 9:54 p.m.]
Case 3 - $\mathcal{L}$ operates	2 Lamps	: medium en. saving [8:00 p.m. - 11:59 p.m.]
		: low energy saving [8:00 p.m. - 11:59 p.m.]
	TV	: medium en. saving [9:00 p.m. - 11.59 p.m.]
	AC	: cooler-normal [0:00 a.m. - 5:00 p.m.]
		: cooler-economic [5:01 p.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 5:01 p.m.]
		: low speed [5:01 p.m. - 11:59 p.m.]
	WM	: express [8:02 p.m. - 8:22 p.m.]
	DW	: intensive [8:58 p.m. - 11:22 p.m.]

Scenario 11 - the user sets	2 Lamps	: medium en. saving [6:00 p.m.-11:59 p.m.]
		: low energy saving [6:00 p.m. - 11:59 p.m.]
	TV	: medium en. saving [9:00 p.m.-11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: express [5:50 p.m. - 10:30 p.m.]
	DW	: intensive [7:30 p.m. - 11:59 p.m.]
Case 1-2 - $\mathcal{L}$ operates	2 Lamps	: medium en. saving [6:00 p.m.-11:59 p.m.]
		: low energy saving [6:00 p.m. - 11:59 p.m.]
	TV	: medium en. saving [9:00 p.m.-11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 11:59 p.m.]
	WM	: express [5:50 p.m. - 6:10 p.m.]
	DW	: intensive [7:30 p.m. - 9:54 p.m.]
Case 3 - $\mathcal{L}$ operates	2 Lamps	: medium en. saving [6:00 p.m.-11:59 p.m.]
		: low energy saving [6:00 p.m. - 11:59 p.m.]
	TV	: medium en. saving [9:00 p.m.-11.59 p.m.]
	AC	: heater-normal [0:00 a.m. - 5:00 p.m.]
		: heater-economic [5:01 p.m. - 11:59 p.m.]
	REF	: defrost [0:00 a.m. - 0:30 a.m.]
		: moderate speed [0:31 a.m. - 5:01 p.m.]
		: low speed [5:01 p.m. - 11:59 p.m.]
	WM	: express [7:34 p.m. - 7:54 p.m.]
	DW	: intensive [7:41 p.m. - 10:05 p.m.]

Scenarios with PHEV and interruptible controllable appliances:

For all scenarios - the user drives	PHEV	: to work [6:00 a.m. - 6:30 a.m.]
		: to home [5:00 p.m. - 5:30 p.m.]
Scenario 2 - the user sets	WM	: normal [2:00 p.m. - 6:00 p.m.]
	DW	: normal [9:00 p.m. - 11:59 p.m.]
Case 3 - $\mathcal{L}$ operates	WM	: normal [2:52 p.m. - 4:02 p.m.]
	DW	: normal [9:48 p.m. - 11:28 p.m.]
Scenario 4 - the user sets	WM	: special [7:30 p.m. - 11:59 p.m.]
	DW	: special [0:30 a.m. - 4:00 a.m.]
Case 3 - $\mathcal{L}$ operates	WM	: special [10:29 p.m. - 11:59 p.m.]
	DW	: special [1:10 a.m. - 3:35 a.m.]
Scenario 6 - the user sets	WM	: normal [2:00 p.m. - 6:00 p.m.]
	DW	: normal [9:00 p.m. - 11:59 p.m.]
Case 3 - $\mathcal{L}$ operates	WM	: normal [4:48 p.m. - 6:00 p.m.]
	DW	: normal [9:20 p.m. - 10:57 p.m.]
Scenario 8 - the user sets	WM	: special [7:30 p.m. - 11:59 p.m.]
	DW	: special [0:30 a.m. - 4:00 a.m.]
Case 3 - $\mathcal{L}$ operates	WM	: special [7:30 p.m. - 9:22 p.m.]
	DW	: special [0:30 a.m. - 2:53 a.m.]
Scenario 10 - the user sets	WM	: express [5:50 p.m. - 10:30 p.m.]
	DW	: intensive [7:30 p.m. - 11:59 p.m.]
Case 3 - $\mathcal{L}$ operates	WM	: express [7:35 p.m. - 7:55 p.m.]
	DW	: intensive [8:24 p.m. - 11:13 p.m.]
Scenario 12 - the user sets	WM	: express [5:50 p.m. - 10:30 p.m.]
	DW	: intensive [7:30 p.m. - 11:59 p.m.]
Case 3 - $\mathcal{L}$ operates	WM	: express [7:39 p.m. - 7:59 p.m.]
	DW	: intensive [7:50 p.m. - 10:33 p.m.]

GAMS code of OF-HEM:

Sets	*a Appliances*	/TV, Lamps, AC, REF, WM, DW/
	i Modes	/10% illumination, 30% illumination, 60% illumination, 100% illumination, 10% brightness, 30% brightness, 60% brightness, 100% brightness, low speed, moderate speed, high speed, defrost, cooler-normal, cooler-economic, heater-normal, heater-economic, express, intensive, long, special/
	t Time	/0*1440/;

Scalar	η_c	: charging efficiency of the backup battery /0.95/
	η_{evc}	: charging efficiency of the PHEV /0.95/
	$P_{max}^{\mathcal{B}c}$	: maximum charging rate for the backup battery /3000/
	P_{max}^{EVc}	: maximum charging rate for the PHEV /3300/
	η_{dc}	: discharging efficiency of the backup battery /0.95/
	η_{evd}	: discharging efficiency of the PHEV /0.95/
	$P_{max}^{\mathcal{B}d}$	: maximum discharging rate for the backup battery /3000/
	P_{max}^{EVd}	: maximum discharging rate for the PHEV /3300/
	SOC_{ini}	: initial state of charge of the backup battery /7500/
	$SOC_{EV_{ini}}$	: initial state of charge of the PHEV /8000/
	SOC_{max}	: maximum state of charge of the backup battery/15000/
	$SOC_{EV_{max}}$	: maximum state of charge of the PHEV /16000/
	SOC_{min}	: minimum state of charge of the backup battery /1580/
	$SOC_{EV_{max}}$	: minimum state of charge of the PHEV /4800/
	TS	: time slot /60/ ;

$Parameters$

$P^{\mathcal{G}}_{lim}(t)$	: maximum power that can be drawn from the grid
$P^{\mathcal{S}}_{lim}(t)$	: maximum power that can be injected to the grid
$P^{PV}(t)$	: power obtained from the PV system
$C^{\mathcal{G}}(t)$	: electricity tariff for power drawn from the grid
$C^{\mathcal{S}}(t)$	: electricity tariff for power injected to the grid
$Op(un)$	: operation time for uncontrollable appliances
$Op(sc)$	: operation time for semicontrollable appliances
$Op(co)$	: operation time for controllable appliances
Table $P(un, t)$	: power consumption for uncontrollable appliances
Table $P(sc, t)$	: power consumption for semicontrollable appliances
Table $P(co, t)$	: power consumption for controllable appliances
Table $CP(un, t)$	: the consumer preference for uncontrollable appliances
Table $CP(sc, t)$	: the consumer preference for semicontrollable appliances
Table $CP(co, t)$	: the consumer preference for controllable appliances

$Variables$ H : the total electrical cost for operating the appliances

Positive Variables

$P^{\mathcal{B}c}(t)$	: backup battery charging power
$P^{EVc}(t)$	: PHEV charging power
$P^{\mathcal{B}d}(t)$	: backup battery discharging power
$P^{EVd}(t)$	: PHEV discharging power
$P^{\mathcal{G}}(t)$	: power drawn from the grid
$P^{\mathcal{G}}_{EV}(t)$	: grid power used for the PHEV charging
$P^{\mathcal{G}}_{\mathcal{L}}(t)$	: grid power used for the power demand of appliances
$P^{EVc}(t)$	: charging rate for the PHEV
$P^{EVd}(t)$	: discharging rate for the PHEV
$P^{\mathcal{PV}}_{\mathcal{S}}(t)$	: PV power used for power injection to grid
$P^{\mathcal{PV}}_{\mathcal{L}}(t)$	: PV power used for supporting the power demand of appliances
$P^{\mathcal{B}}_{\mathcal{L}}(t)$	: backup battery used for supporting the power demand of appliances

$P_{\mathcal{B}c}^{\mathcal{PV}}(t)$: PV power used for the backup battery charging

$P^{\mathcal{L}}(t)$: total power consumed by the appliances

$P^{\mathcal{S}}(t)$: total power injected to the grid

$UNC(t)$: total power consumed from the uncontrollable appliances

$SCO(t)$: total power consumed from the semicontrollable appliances

$CON(t)$: total power consumed from the controllable appliances

$SOC(t)$: state of charge of the backup battery

$SOC_{EV}(t)$: state of charge of the PHEV ;

Binary Variables

$x^{\mathcal{B}c}(t)$: 1 if the backup battery is charging during time t

$x^{EVc}(t)$: 1 if the PHEV is charging during time t

$x^{\mathcal{G}}(t)$: 1 if the grid is suppyling power during time t

$x(un, t)$: 1 if the uncontrollable appliance is operating during time t

$y(sc, t)$: 1 if the semi-controllable appliance is operating during time t

$w(co, t)$: 1 if the controllable appliance is operating during time t

$u(un, t)$: sequential uncontrollable appliances

$s(sc, t)$: sequential semicontrollable appliances

$c(co, t)$: sequential controllable appliances

$h(co, t)$: interruption ;

Equations

Objective : define objective function

$constraint1(t)$: power balance constraint

$constraint2(t)$: backup battery appliance constraint

$constraint3(t)$: PHEV appliance constraint

$constraint4(t)$: backup battery charge constraint

$constraint5(t)$: backup battery discharge constraint

$constraint6(t)$: PHEV charge constraint

$constraint7(t)$: PHEV discharge constraint

$constraint8(t)$: initial state of charge constraint

$constraint9(t)$: maximum state of charge constraint

$constraint10(t)$: minimum state of charge constraint

$constraint11(t)$: initial state of PHEV constraint

$constraint12(t)$: maximum state of PHEV constraint

$constraint13(t)$: minimum state of PHEV constraint

$constraint14(t)$: maximum PHEV battery level

$constraint15(t)$: Backup battery is charged by PV

$constraint16(t)$: PHEV charge constraint

$constraint17(t)$: grid supplied power constraint

$constraint18(t)$: PV power produced constraint

$constraint19(t)$: PV power sold constraint

$constraint20(t)$: grid limit constraint

$constraint21(t)$: sold limit constraint

$constraint22(un)$: uncontrollable operational time constraint

$constraint23(sc)$: semicontrollable operational time constraint

$constraint24(co)$: controllable operational time constraint

$constraint25(un, t)$: sequential uncontrollable constraint one

$constraint26(un, t)$: sequential uncontrollable constraint two

$constraint27(un, t)$: sequential uncontrollable constraint three

$constraint28(sc, t)$: sequential semicontrollable constraint one

$constraint29(sc, t)$: sequential semicontrollable constraint two

$constraint30(sc, t)$: sequential semicontrollable constraint three

$constraint31(co, t)$: sequential controllable constraint one

$constraint32(co, t)$: sequential controllable constraint two

$constraint33(co, t)$: sequential controllable constraint three

$constraint34(un, t)$: uncontrollable consumer preference constraint

$constraint35(sc, t)$: semicontrollable consumer preference constraint

$constraint36(co, t)$: controllable consumer preference constraint

$constraint37(t)$: uncontrollable internal power constraint

$constraint38(t)$: semicontrollable internal power constraint

$constraint39(t)$: controllable internal power constraint

$constraint40(t)$: total appliance power constraint

$constraint41(t)$: state of charge backup battery constraint

$constraint42(t)$: state of charge PHEV constraint

$constraint43(t)$: interruption constraint one

$constraint44(t)$: interruption constraint two

$constraint45(t)$: interruption constraint three

$constraint46(t)$: interruption constraint four

$constraint47(t)$: interruption constraint five

$constraint48(co, t)$: interruption constraint six

$constraint49(co, t)$: interruption constraint seven

$constraint50(co, t)$: interruption constraint eight

$constraint51(co, t)$: interruption constraint nine

$constraint52(co, t)$: interruption constraint ten

$constraint53(co)$: maximum interruption time constraint

$constraint54(co)$: minimum interruption time constraint ;

$Objective..$ $H = e =$sum(t, $((P^{\mathcal{G}}(t) * C^{\mathcal{G}}(t) - P^{\mathcal{S}}(t) * C^{\mathcal{S}}(t))/TS * 0.001)$;

$constraint1(t)..$ $P^{\mathcal{G}}_{EV}(t)$+$P^{\mathcal{G}}_{\mathcal{L}}(t)$+$P^{\mathcal{PV}}_{\mathcal{L}}(t)$+$P^{\mathcal{PV}}_{\mathcal{B}c}(t)$+$P^{\mathcal{B}}_{\mathcal{L}}(t)$+$P^{EV}_{\mathcal{L}}(t)$
=e=$P^{\mathcal{L}}(t)$+$P^{\mathcal{B}c}(t)$+$P^{EVc}(t)$;

$constraint2(t)..$ $P^{\mathcal{B}}_{\mathcal{L}}(t)$=e=$P^{\mathcal{B}d}(t)$*$\eta_{dc}$;

$constraint3(t)..$ $P^{EV}_{\mathcal{L}}(t)$=e=$P^{EVd}(t)$*η_{dc};

$constraint4(t)..$ $P^{\mathcal{B}c}(t)$=l=$P^{\mathcal{B}c}_{max}$*$x^{\mathcal{B}c}(t)$;

$constraint5(t)..$ $P^{\mathcal{B}d}(t)$=l=$P^{\mathcal{B}d}_{max}$*(1-$x^{\mathcal{B}c}(t)$);

$constraint6(t)..$ $P^{EVc}(t)$=l=P^{EVc}_{max}*$x^{EVc}(t)$;

$constraint7(t)..$ $P^{EVd}(t)$=l=$P^{\mathcal{B}d}_{max}$*(1-$x^{EVc}(t)$);

$constraint8(t)..$ $SOC(t)$=e=SOC_{ini};

$constraint9(t)..$ $SOC(t)$=l=SOC_{max};

$constraint10(t)..$ $SOC(t)$=g=SOC_{min};

$constraint11(t)..$ $SOC_{EV}(t)$=e=$SOC_{EV}ini$;

$constraint12(t)..$ $SOC_{EV}(t)$=l=SOC_{EVmax};

$constraint13(t)..$ $SOC_{EV}(t)$=g=SOC_{EVmin};

$constraint14(t)..$ $SOC_{EV}(t)$=e=SOC_{EVmax};

$constraint15(t)..$ $P^{\mathcal{PV}}_{\mathcal{B}c}(t)$=e=$P^{\mathcal{B}c}(t)$;

$constraint16(t)..$ $P^{\mathcal{G}}_{EV}(t)$=e=$P^{EVc}(t)$;

$constraint17(t)..$ $P^{\mathcal{G}}(t)$=e=$P^{\mathcal{G}}_{EV}(t)$+$P^{\mathcal{G}}_{\mathcal{L}}(t)$;

$constraint18(t)..$ $P^{\mathcal{PV}}_{\mathcal{L}}(t)$+$P^{\mathcal{PV}}_{\mathcal{B}c}(t)$+$P^{\mathcal{PV}}_{\mathcal{S}}(t)$=e=$P^{PV}(t)$;

$constraint19(t)..$ $P^{\mathcal{S}}(t)$=e=$P^{\mathcal{PV}}_{\mathcal{S}}(t)$;

$constraint20(t)..$ $P^{\mathcal{G}}(t)$=l=$P^{\mathcal{G}}_{lim}(t)$*$x^{\mathcal{G}}(t)$;

$constraint21(t)..$ $P^{\mathcal{S}}(t)$=l=$P^{\mathcal{S}}_{lim}(t)$*(1-$x^{\mathcal{G}}(t)$);

$constraint22(un)..$ $sum(t$,$x(un,t))$=e=$Op(un)$;

$constraint23(sc)..$ $sum(t$,$y(sc,t))$=e=$Op(sc)$;

$constraint24(co)..$ $sum(t$,$w(co,t))$=e=$Op(co)$;

$constraint25(un,t)..$ $x(un,t)$=l=1-$U(un,t)$;

$constraint26(un,t)..$ $x(un,t-1)$-$x(un,t)$=l=$u(un,t)$;

$constraint27(un,t)..$ $u(un,t-1)$=l=$u(un,t)$;

$constraint28(sc,t)..$ $y(sc,t)$=l=1-$s(sc,t)$;

$constraint29(sc,t)..$ $y(sc,t-1)$-$y(sc,t)$=l=$s(sc,t)$;

$constraint30(sc,t)..$ $s(sc,t-1)$=l=$s(sc,t)$;

$constraint31(co,t)..$ $w(co,t)$=l=1-$c(co,t)$;

$constraint32(co,t)..$ $w(co,t-1)$-$w(co,t)$=l=$c(co,t)$;

$constraint33(co,t)..$ $c(co,t-1)$=l=$c(co,t)$;

$constraint34(un,t)..$ $x(un,t)$=l=$CP(un,t)$;

$constraint35(sc,t)..$ $y(sc,t)$=l=$CP(sc,t)$;

$constraint36(co,t)..$ $w(co,t)$=l=$CP(co,t)$;

$constraint37(t)..$ $sum(un$,$P(un,t)$*$x(un,t))$=e=$UNC(t)$;

$constraint38(t)..$ $sum(sc$,$P(sc,t)$*$y(sc,t))$=e=$SCO(t)$;

$constraint39(t)..$ $sum(co$,$P(co,t)$*$w(co,t))$=e=$CON(t)$;

$constraint40(t)..$ $P^{\mathcal{L}}(t)$=e=$UNC(t)$+$SCO(t)$+$CON(t)$;

$constraint41(t)..$ $SOC(t)$=e=$SOC(t-1)$+(η_c*$P^{\mathcal{B}c}(t)) - P^{\mathcal{B}d}(t))/TS$;

$constraint42(t)..$ $SOC_{EV}(t)$=e=$SOC_{EV}(t-1)$+(η_c*$P^{EVc}(t)) - P^{EVd}(t))/TS$;

$constraint43(t)..$ $w('WMregulartwo', t)$=l=$c('WMregularone', t)$;

$constraint44(t)..$ $w('WMregularthree', t)$=l=$c('WMregulartwo', t)$;

$constraint45(t)..$ $w('DWnormaltwo', t)$=l=$c('DWnormalone', t)$;

$constraint46(t)..$ $w('DWnormalthree', t)$=l=$c('DWnormaltwo', t)$;

$constraint47(t)..$ $w('DWnormalfour', t)$=l=$c('DWnormalthree', t)$;

$constraint48(co, t)..$ $h('WMregulartwo', t)$=e=$c('WMregularone', t)$
-($w('WMregulartwo', t)$+$c('WMregulartwo', t)$);

$constraint49(co, t)..$ $h('WMregularthree', t)$=e=$c('WMregulartwo', t)$
-($w('WMregularthree', t)$+$c('WMregularthree', t)$);

$constraint50(co, t)..$ $h('DWnormaltwo', t)$=e=$c('DWnormalone', t)$
-($w('DWnormaltwo', t)$+$c('DWnormaltwo', t)$);

$constraint51(co, t)..$ $h('DWnormalthree', t)$=e=$c('DWnormaltwo', t)$
-($w('DWnormalthree', t)$+$c('DWnormalthree', t)$);

$constraint52(co, t)..$ $h('DWnormalfour', t)$=e=$c('DWnormalthree', t)$
-($w('DWnormalfour', t)$+$c('DWnormalfour', t)$);

$constraint53(co)..$ $sum(t$,$h(co, t))$=l=10;

$constraint54(co)..$ $sum(t$,$h(co, t))$=g=2;

Model scheduler /all/;

option lp = cplex ;

Solve scheduler using mip minimizing H ;

Table A.1. Results of Scenarios - 1 to 6

Cases and Results Scenario 1 to 6		Scenarios 1	2	3	4	5	6
Season	January			✓	✓	✓	✓
	July	✓	✓				
Occupancy	full occupancy	✓	✓			✓	
	partial occupancy			✓	✓		✓
$P^{\mathcal{L}}(t)$ (kWh)	Case 1	28.2	28.9	28.51	29.21	27.6	28.3
	Case 2	28.2	28.9	28.51	29.21	27.6	28.3
	Case 3	26.46	26.3	27.05	27.51	26.13	26.52
$P^{\mathcal{G}}(t)$ (kWh)	Case 1	22.24	30.7	26.38	34.8	25.43	33.9
	Case 2	13	15.6	19.6	20.34	18.68	19.84
	Case 3	11.27	15.26	18.13	19.9	17.21	19.28
$P^{\mathcal{G}}_{\mathcal{L}}(t)$ (kWh)	Case 1	-	22.27	-	26.4	-	25.46
	Case 2	-	7.18	-	11.91	-	11.42
	Case 3	-	6.84	-	11.47	-	10.86
$P^{\mathcal{G}}_{EV}(t)$ (kWh)	Case 1	-	8.42	-	8.42	-	8.42
	Case 2	-	8.42	-	8.42	-	8.42
	Case 3	-	8.42	-	8.42	-	8.42
Cost (€)	Case 1	1.94	2.55	2.6	3.16	2.5	3.06
	Case 2	0.97	0.9	1.68	1.51	1.6	1.5
	Case 3	0.77	0.8	1.5	1.44	1.43	1.41
Cost reduction (%)	Case 2 wrt. Case 1	50	65	35	52.2	36	51
	Case 3 wrt. Case 2	21	11.1	10.7	4.63	10.6	6
	Case 3 wrt. Case 1	60	68.6	42.3	54.4	42.8	54

Table A.2. Results of Scenarios - 7 to 12

Cases and Results Scenario 7 to 12		Scenarios					
		7	**8**	**9**	**10**	**11**	**12**
Season	January					✓	✓
	July	✓	✓	✓	✓		
Occupancy	full occupancy	✓		✓		✓	
	partial occupancy		✓		✓		✓
$P^{\mathcal{L}}(t)$ (kWh)	Case 1	29.1	29.8	28.4	29.1	27.8	28.51
	Case 2	29.1	29.8	28.4	29.1	27.8	28.51
	Case 3	27.3	27.73	26.65	26.81	26.34	27.17
$P^{\mathcal{G}}(t)$ (kWh)	Case 1	23.15	31.57	22.46	30.87	25.67	34.1
	Case 2	13.91	15.5	13.22	15.45	18.9	19.65
	Case 3	12.16	14.2	11.43	15.42	17.43	19.37
$P^{\mathcal{G}}_{\mathcal{L}}(t)$ (kWh)	Case 1	-	23.15	-	22.45	-	25.67
	Case 2	-	7.05	-	7.04	-	11.23
	Case 3	-	6.92	-	6.99	-	10.95
$P^{\mathcal{G}}_{EV}(t)$ (kWh)	Case 1	-	8.42	-	8.42	-	8.42
	Case 2	-	8.42	-	8.42	-	8.42
	Case 3	-	8.42	-	8.42	-	8.42
Cost (€)	Case 1	2.03	2.66	2.02	2.58	2.58	3.13
	Case 2	1.02	0.9	1	0.86	1.64	1.46
	Case 3	0.82	0.86	0.8	0.8	1.49	1.4
Cost reduction (%)	Case 2 wrt. Case 1	49.8	65.4	50.5	66.6	36.43	53.3
	Case 3 wrt. Case 2	19.6	4.4	20	6.97	9.1	4.1
	Case 3 wrt. Case 1	59.6	66.9	60.3	69	42.2	55.3

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Curriculum Vitae

PERSONAL DETAILS

Birth	November 10, 1988
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EDUCATION

MSc. Electrical and Electronics Engineering Program 2014-2016
Anadolu University

BSc. Electrical and Electronics Engineering 2006-2012
Gaziantep University

WORK EXPERIENCE

Research Assistant 2014-present
Anadolu University

I am working as a research assistant in the Department of Electrical and Electronics Engineering in Anadolu University.

SKILLS

Languages	Turkish (mother tongue)
	English (very good)
	German (basic)
Software	MATLAB, SIMULINK, LaTeX, MICROSOFT OFFICE