SCHEDULING FOR HOME ENERGY MANAGEMENT SYSTEM

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

MARCH 2018

Approval of the thesis:

SCHEDULING FOR HOME ENERGY MANAGEMENT SYSTEM

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ABSTRACT

SCHEDULING FOR HOME ENERGY MANAGEMENT SYSTEM

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March 2018, 137 pages

This study aims to develop a mathematical model for optimally scheduling usages of home appliances, decisions related to charging and discharging of storage devices and electric vehicles, and energy buying/selling decisions from/to main grid in a smart house. Stochastic optimization approach is employed to obtain less costly consumption policy. The performance of the model is evaluated by comparing the results of the model to the results of a green house which is not supported by an optimization model under same experimental conditions. It is observed that, the model brings a significant saving to the consumer. In numerical experiments, the behavior of the system is analyzed for different price tariffs.

Keywords: Scheduling, Home Energy Management System, Stochastic Programming

ÖZ

EV ENERJİ YÖNETIM SİSTEMİ İÇİN PROGRAMLAMA

Merdanoğlu, Hakan
Yüksek Lisans, Endüstri Mühendisliği Bölümü
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Ortak Tez Yöneticisi : Yrd. Doç. Dr. Ertan Yakıcı

Mart 2018, 137 sayfa

Bu çalışmada, akıllı evlerde ev cihazlarının kullanımının, batarya ve elektrikli arabaların şarj ve deşarj kararlarının, ve ana şebekeden enerji satınalma ve bu şebekeye enerji satış kararlarının optimal olarak çizelgelenmesini sağlayan bir matematiksel modelin geliştirilmesi amaçlanmıştır. En az masraflı kullanım politikasının elde edilmesinde stokastik optimizasyon yaklaşımı benimsenmiştir. Modelin performansı model sonuçlarının aynı şartlar altında matematiksel model tarafından desteklenmeyen bir yeşil evin sonuçları ile karşılaştırılarak değerlendirilmiştir. Modelin tüketiciye büyük ölçüde tasarruf sağladığı gözlemlenmiştir. Sayısal deneyler kapsamında sistemin davranışı farklı fiyat tarifeleri için de analiz edilmiştir.

Anahtar Kelimeler: Çizelgeleme, Ev Enerji Yönetim Sistemi, Stokastik Programlama

to my family

ACKNOWLEDGMENTS

I would first like to thank my thesis advisor Assoc. Prof. Dr.Serhan Duran and co-advisor Assist. Prof. Dr.Ertan Yakıcı for their continuous support during my study. My thanks also goes to Assoc. Prof. Dr. Cem İyigün. I am grateful to him for his help. I thank my office mate Dr.Osman Tufan Doğan, Yaprak Küçükgül, Fırat Onar, Sedat Sarıkaya and my friend, Alaz Toker for their encouragement, and useful comments.

Finally, I would like to thank my family Deniz, Ali Ege, Erhan and Mehmet.

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CHAPTER 1

INTRODUCTION

It is a fact that demand for the energy grows rapidly while the limited natural resources are diminishing day by day. Industrialization and urbanization create a drastic demand for energy. The main fuel sources; coal, oil and gas has been reached 82% of the current energy consumption. As a result of this, the carbon dioxide emissions that are released into Earth's atmosphere critically increased and it is thought to be the cause of the rising global temperatures and climate changes. Despite the fact that Turkey has a vast variety of fossil fuel reserves for the next couple of decades (the brown coal/lignite or hard coal reserves all over Anatolia), most of the fossil fuel resources are going to be exhausted throughout the world in the near future. People need to find new alternatives/clean solutions in order to overcome these problems and prevent the possible energy crisis in the near future. Over-consumption, over-population, poor infrastructure, poor distribution systems, insuffiecient investments for renewable energy are the main topics that are to be discussed and solved by the scientists worldwide.

In Turkey, a similar scenario is expected. Starting a decade ago, all of the thermal power plants are privatised which were supplying the 44% of the energy need of the country. Synchronically, private sector is supported by government supported financial loans and quarantee of purchase in the short-middle run for both fosil fuel and hydro investments. Nowadays (according to the 2017 Q4 figures), 89% of the Turkey's electricity needs are met by three main sources; coal, hydro and natural gas.

Last but not the least; thanks to the environmentalist NGO’s and governments’ additional support for environment friendly technologies; the contribution of the wind, solar and geothermal energies are also increased in the last two decades. As a result of this approach, like the counterparts in the world, Turkey also started to take significant steps regarding the usage of smart energy.

Throughout the world, energy industry moves into a new era, called “smart energy”, in order to use/store/produce/transmit/distribute energy efficiently and energy will become more sustainable, reliable, continuous, secure, green and autonomous by using new Information and Communicaton Technology (ICT). Using innovative technologies to change the energy components and the responsibility of the actors, is the “smartest” way to solve the possible forthcoming crisis. Energy market, inevitably, is going to transform into a more decentralized and transparent market since the companies (professionals) and the home users (households) are going to produce and use their own energy, and therefore they will become so called ‘prosumers’- with the new terminology.

Smart Grid, Demand Response, Micro Grid, Smart Home are the main concepts in the smart energy field today. All these concepts along with their relationship to Home Energy Management System (HEMS) are going to be explained in the following sections of this thesis.

In order to decrease the energy consumption, the first step that the home appliance manufacturers consider to develop is the energy efficient products. As technology improves, more and more electrical devices are introduced and it is observed these advancements are not the solution. Today- in order to monitor, control and conserve the energy usage and to reduce the electricity bills without sacrificing the comfort levels, the most prominent and promising solution is the Home Energy Management System.

In the following part of the chapter, smart energy is explained thoroughly. A literature review is given in Chapter 2. In Chapter 3, proposed model and the input/output of this model are discussed. In Chapter 4, software development for saving, solving and gathering result of experiment are explained. In Chapter 5, the benefit from the usage of the model is measured and the results of the experiments are presented. In Chapter 6, the thesis is concluded with the future work and conclusion.

1.1 SMART ENERGY

A smart energy system is a cost efficient system which utilizes green renewable resources. It is a system in which energy production, storage, distribution, transmission and consumption are integrated intelligently.

Closely related to the continuously increasing energy consumption trend; environmental, economic and sustainability challenges are present all over the world. Fossil energies are becoming more expensive as they approach to the end of their possible exploitation, and the pollution caused by fossil-based energy are becoming less and less acceptable by the society and unbearable for the ecosystem.

Energy efficiency and sustainability can only be improved via facilitating and increasing usage of distributed and renewable energy generation (e.g. solar, wind, geothermal, biomass) near or at the consumption sites, in order to avoid energy losses from long-distance energy transmission, conversion and distribution.

Information and Communication Technology (ICT) based solutions will play an important role for collecting the data, controlling, monitoring and coordinating energy networks, which can be characterized by low-carbon generation, storage, efficient distribution/transmission system, and optimized consumption. However, it should be kept in mind that since the decentralized small-scale renewable energy resources, such as solar and wind power have uncontrollable natures, it is of utmost importance to use the storage technology in order to balance supply and demand.

ICT and automation market players will undertake a major role for enabling and supporting the new smart energy value chain via provisioning of digital services, ICT and automation infrastructure, enabling the smart energy infrastructure for the energy market players. At the same time, digital service providers will guide the energy market players to stimulate the cost efficient streamline to their business processes and to expand their business with new services for consumers. New services will also enable consumers to play roles that are more active in energy consumption.

The existing “energy value chain” is designed in a unilateral way and based on a hierarchical system from top to down, in other words, from producer to consumer. It was not constructed in for a bi-directional traffic. In order to fulfill the rapidly changing society needs, current energy market needs to be more democratic by all means.

1.2 SMART GRID

Smart grid upgrades today’s inefficient and centralized power grids into smart and quick responsive electricity networks that offers new technological services for the energy industry. Smart Grid has some tempting key features for all the players in the market.

Decentralization of Power Generation (DPG) supports end node participation, not only for the consumption side but also for the generation. Energy is produced close to the place where it will be used. By this way, small size local generators are prefered rather than the national large size power plants. This will also help to reach the low carbon emissions that are set by the EU, and is going to reduce the transmission losses too.

Demand Response (DR) is another important aspect of the smart grid. DR manages consumption of electricity in response to supply conditions, such as having customers reduce their consumption at critical times or in response to market prices. It is also related with load shifting that deals with unstability of demand. Total demand can vary from time to time. Smart grid can convince customers to temporarily reduce their consumption during peak demand periods to match balance between total supply and demand in the power grid.

Smart Meter (SM) provides customers to learn their real time energy usage and cost information. Before the smart meter application, it was very hard to determine which activities were high energy consumption activities. By using smart phone, tablet or any smart device applications, customers can track their energy consumption and with their available historic data they will be able to carry out numerous analysis.

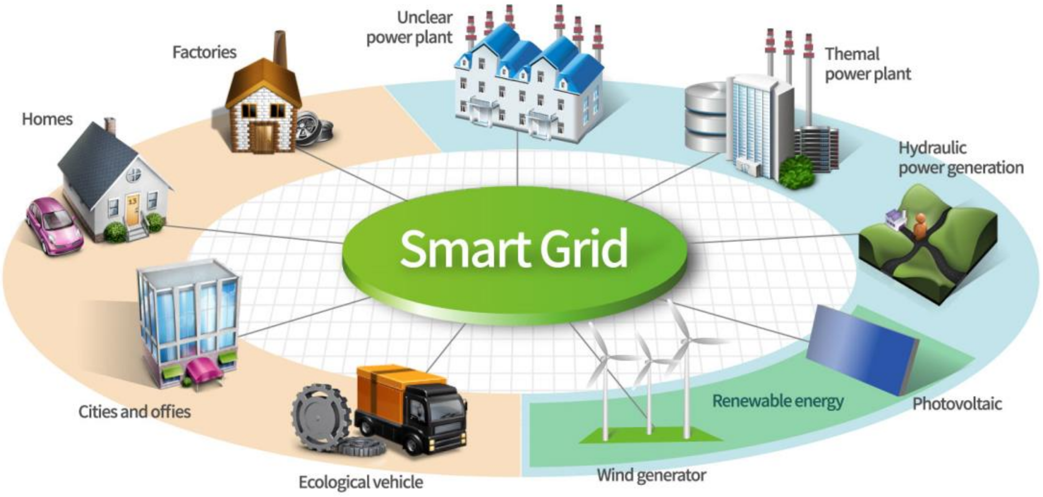


Figure 1.1: Smart Grid

The advantages of the Smart Grid are; more efficient operations that reduces management costs, reduction at energy prices from the consumer’s side, allowing consumers to play a pro-active role in the operating system, efficiency and transparency at electricity transmission or distribution, repairing itself, ensuring power quality and harmonics, smart metering and feedback, reducing peak demand, better integration of all factors, better integration of large scale renewable energy systems (RES), better integration of residential power generations and better security.

1.3 DEMAND RESPONSE

Demand Response (DR) programs provide effective means of control to customers within the Smart Grids (SG). Customers have an opportunity to monitor, reduce, or shift the associated consumption to achieve the minimum consumption payment. Public tariff/tax regulations and DR programs indirectly lead to Peak-to-Average Ratio (PAR) decline, which is a key indicator reflecting efficiency of the entire generation, transmission, and distribution hierarchy. While the public enterprises manage demand and supply in a more coordinated and efficient way, the customers benefit from the financial incentives of the program. There are two types of DR programs:

Price based DR programs, dynamically change electricity prices (selling or buying) to effect the customer energy consumption behaviour. Block price is a type of program in which block period is determined and fixed. Critical peak pricing is a pricing policy applied on critical peak periods. Variable peak pricing is based on "time of use" and "real time pricing", which is the commonly used program where pricing vary by hourly basis. Real market conditions determine the prices of energy.

In Incentive based DR programs, grid operators give customers financial incentives or rewards. Direct load control is a program where power companies or smart grid operators can run or shut down customer's devices, such as air conditioners or water heaters during periods of peak demand in exchange for lower electricity bills. Interruptible service is another program where a firm contract between customer and grid operators can be designed in order to achieve the incentives. For example, a penalty system may be put into operation if the required energy consuption cannot be reached. In the emergency price program, during emergency situations, customers accept to lower their energy consumption in order to take the incentives.

1.4 MICRO GRID

Microgrid is a localized group of electricity sources and loads that normally operates connected to and synchronous with the traditional centralized electrical grid (macrogrid), but can also disconnect to "island mode" and function autonomously as physical and/or economic conditions dictate.

The main aim is to supply autonomous, reliable, continous, high quality and secure energy for all communities; commercial, industrial, and rural customers. Like the normal (macro) power grid, it has a generation unit, a distribution system, a thermal storage, voltage and frequency regulation, storage, smart meter and distributed controllable loads. It integrates with distributed energy resources (DER), mainly renewable energy resources, solar and wind power, combined heat and power (CHP) generator, hydro and geothermal systems.

Microgrid allow customers to make decisions about consumption, time and quantity adjustment. Demand response programs are based on the agreements between the microgrid operator and load owner, household or the factory owner.

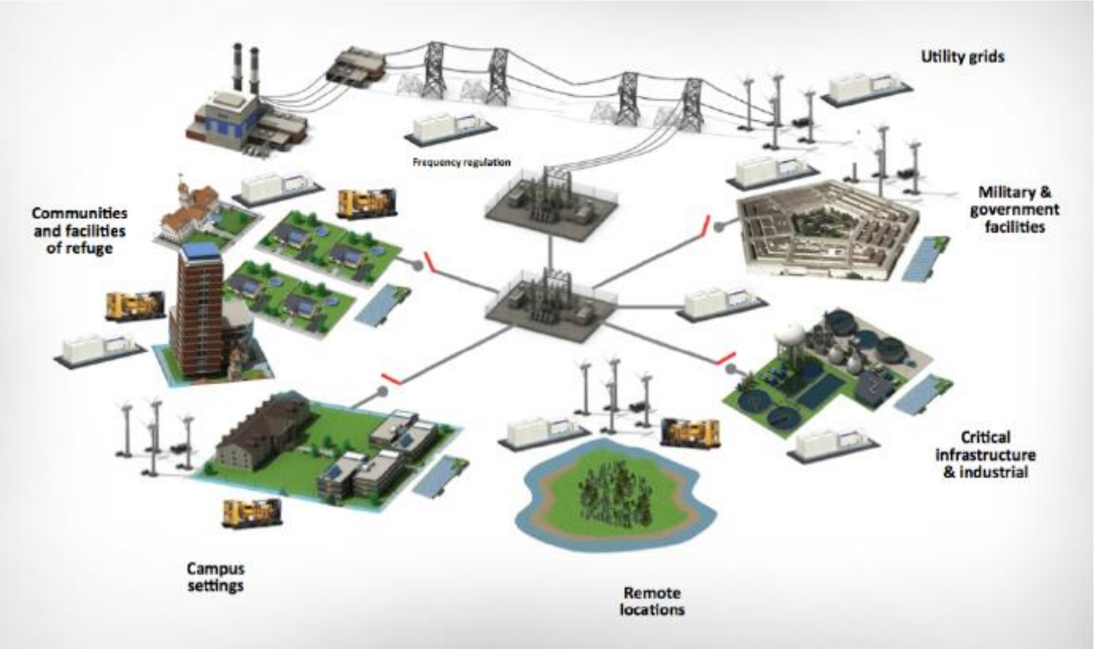


Figure 1.2: Micro Grid.

There are many cases, mostly in developed and developing countries where microgrids are designed and used at university campuses, industrial parks, military bases, residential areas and farms (Figure 1.2). Each entity has its own peculiarities such as the military based microgrid needs more cybersecurity whereas the green farm microgrid uses more solar panel or residential microgrid uses more CHP based energy solutions including both electricity and thermal energy delivery.

1.5 SMART HOME

For the last couple of decades humanity took a huge leap in terms of technology when it is compared with the previous centuries. In the near future, the devices will have more intelligence, they will understand our emotional state and needs and may even speak with us. Internet of Things (IoT) and Artifical Intelligence (AI) will change everything. When an ordinary home is considered, smart lighting reacts automatically or in response to one’s voice, TV opens and lighting color changes according to the TV’s content etc.

Smart home is a technological platform that consists both hardware and software components. Hardware primarily acts as a communications base. Home-area network (HAN), that connects digital devices into a common network by wireless or wired technology, provides a gateway to the other WAN or smart grid networks.

Home controller and automation system gives access to control devices from remote, anywhere that has the internet connection. It has the capability of programming and scheduling activities for the home applications that are connected to the home area network, such as start or stop commands of a washing machine at pre-determined time period that is related with the energy prices. Another example is the situation where a device or events trigger another device by setting designed activity based on the customer preferences. For example, at an emergency case, lighting system turns on immediately, arranges the power in critical position, open/unlock all doors and activates the emergency telephone.

Smart meters are electronic units that monitor and record electricity consumption. Public enterprises have removed old type analog meters and installed new smart meters to measure and keep records of real-time consumption data to balance supply and demand. From the customer’s side, these data/feedback’s may help to adjust their demand to lower their electricity bill. Today, one can easily check how much energy is used and how much it costs, for a given period.

Smart plugs are both energy meter and remote switch, connected to home area networks and can be monitored and controlled from remote locations. They can measure different energy values, energy, current, voltage, power etc. It is the simplest and the most convenient way to transform an ordinary home to a smart one. These users, who uses smart plugs, will not only benefit from turning applications on or off state but even to define some automatic rules on smart plug infrastructure and to monitor each appliance consumption individually.

Smart appliances combine different new technologies and functions to enpower home appliance that has specific tasks for homes. For example, smart refrigerators can read barcodes of the foods and beverages to keep real time inventory information and to give automatic order for not falling under minimum level of temperatures. Mobile applications may support this service by showing the refrigerators' content and giving basic informaton about the ingredients situation.

When the home environment is considered; most of the 'smart applications', lighting controls and HVAC (Heating, Ventilating and Air Conditioning) systems are relatively new technologies for the household, still at testing stages, but are expected to be embedded into the market over the next two decades. It seems that smart homes offer new market opportunities not only for contractors and some equipment manufacturers, but also for one of the the most valuable players -namely HVAC systems and applications- when global energy preservation issues come to the table as illustrated in Figure 1.3

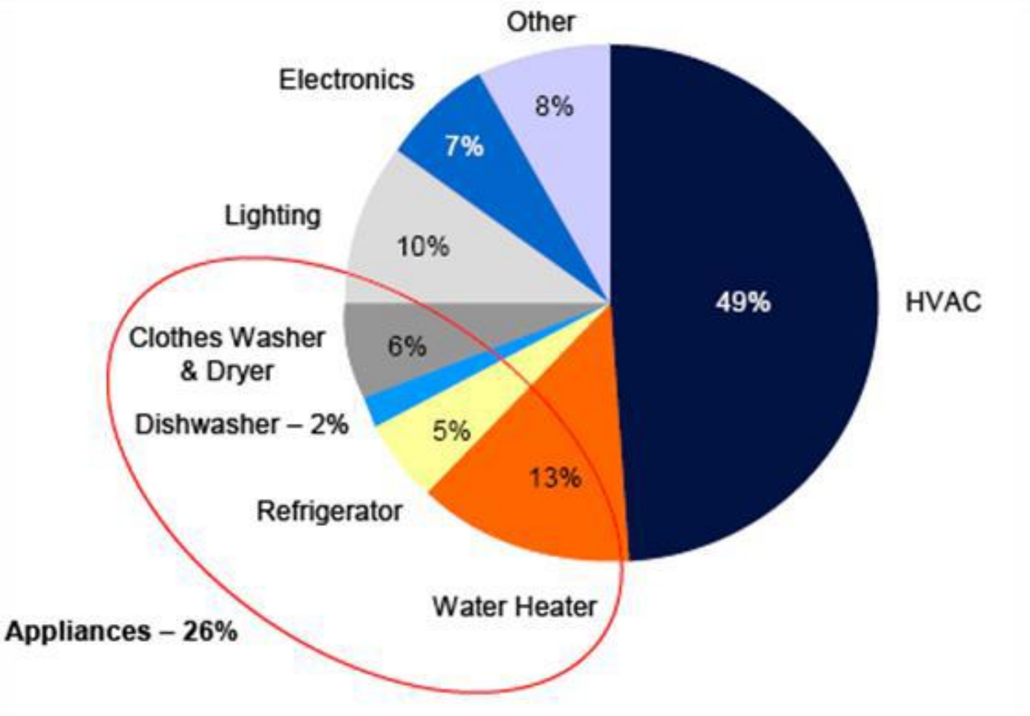


Figure 1.3: Global average energy usage share in homes by appliance

Energy saving is an important side of the home automation technology, which will reduce the whole house operation costs inevitably. Unfortunately, due to the complexity of the automation systems, this technology cannot be coordinated well in many projects, mostly due to pure engineering and lack of complete modelling systems. As a result of this, energy consumption in smart homes may be higher than standart house for a while more. Even though this may have the danger to suspend the customers from the “smart home concept”, the technology-inventors stil can offer good incentives and promotions for the householders, in order to promote the positive effects of energy consumption and its advantages.

1.6 HOME ENERGY MANAGEMENT SYSTEM (HEMS)

Home energy management system (HEMS) makes all of the decisions at a smart house. ‘Smart house’ and ‘home energy management system’ is used in place of one another interchangeably in practice. In order to prevent this confusion, it is of utmost importance to define both concepts thoroughly.

Basically; smart home deals with the infrastructure side, whereas HEMS deals with the decision support side. Not only smart home means more infrastructure, base platform and hardware concepts but also home energy management system simply works on smart house infrastructure as a decision support system. Thus, the home user can make better decisions about reducing energy consumption, managing energy resources by changing energy consumption behavior.

HEMS is the interface that allows the user to monitor, control and manage household electricity consumption and generation efficiently. From the public institutions’ point of view, it reduces peak demand load and prevent blackouts by demand response program. On the other hand, from the enviromental perspective; decreasing gas emission per person is an important achievement when combined with decreasing energy consumption, using clean renewable energy resources and electrical vehicles. HEMS is also accessible through home inside panel, home computer, tablet or smartphones. It increases the energy effectiveness of smart house and has various advantages.

It minimizes energy consumption, electricity bill and maximize customer’s comfort. It shows and predicts electricity usage considering the price of the energy bought from the electricity grid, the amount that the customer sells to grid in real time, the amount of energy generation from renewable energy resources, the devices that are on/off, the amount of energy each device uses etc. In addition, it views and tracks the 'flow of energy' from generation to consumption phases, home energy costs and revenues. It provides energy saving tips giving insights to the customer. Using optimization models, it schedules devices and storages, gives reliable advice to home users to change their consumption behaviour, may even give tips to improve it.

HEMS optimization model focuses on inside of a smart house (see Figure 1.4); namely, smart home devices, such as the dishwasher, washing machine, lighting system, garden irrigatiton system plus the storage, electrical vehicles, renewable energy resources, solar panels/wind turbines, heaters and the air conditioners. HEMS needs to model some characteristics of these house items in order to arrange a balance between the energy usage and the household's comfortable lifestyle.

While carrying out such a task, some questions must be kept in mind with concrete answers: "How much energy is consumed for operating this device? How often does the household use these devices? What are the minimum and maximum energy levels for the energy storages available in home? How much energy will be produced in solar panels if the next day would be sunny? Can the arrival and departure times of the household's electrical cars determined/controlled daily? etc."

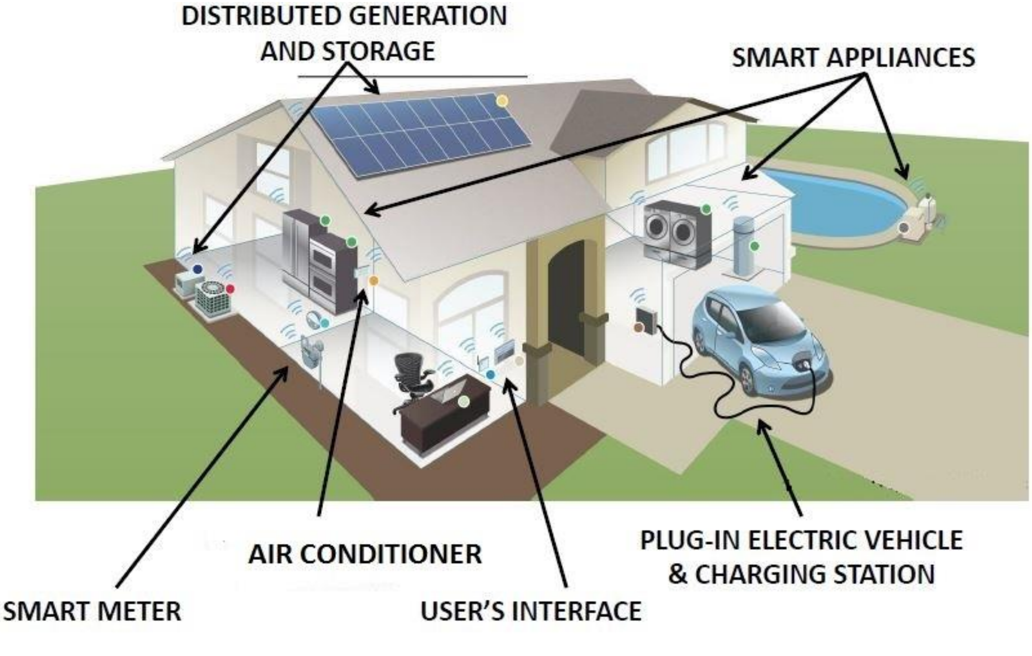


Figure 1.4: Home Energy Management System

HEMS technology is not only developing rapidly and steadily in terms of technology but also gaining popularity towards large mass of people. While for the consumers, HEMS means extra savings and tranquility; for the energy institutions, device manufacturers and connected home platform providers, HEMS means extra growth and possible market opportunities.

1.7 SCOPE OF THE THESIS

The aims of this study are to develop a mathematical model to optimally schedule the usages of in-house devices, make optimal decisions related to charging / discharging of energy storages and EV's and energy buying/selling from/to main grid. We have employed a stochastic programming approach to handle variations in prices (depending on market or regulation conditions), renewable energy resource production (depending on meterological conditions), desired usage time for home devices by the household. Finally, we compare the results given by the model experiments to a green house which is not supported by an optimization model under the same experimental conditions. In these experiments three different price tariffs are assumed.

HEMS Optimization Model solves a scheduling problem taking into account the time-varying prices, energy generation from renewable sources, energy demands for each appliance in the household, battery storage capacities and grid restrictions. Scheduling problem aims to achieve the minimum consumption payment without violating the comfort constraints of the end users. The model faces uncertainties in supply and electricity prices. The randomness in supply comes from uncertainities associated with renewable sources and weather conditions. On the other hand, uncertainities in electricity prices are associated with the market conditions.

The scheduling problem determines schedules of the operating periods of household applications and charging cycles of battery storage and plug-in electric vehicles (EVs). The results are transmitted from Home Controller (HC) to appliances over a home-area network (HAN), which connects in-home digital devices, such as PCs, mobile phones, entertainment technology, thermostats, home security systems and smart applications into a common network. Scheduling problem is solved periodically to determine the decision variables optimal values at equidistant moments. While planning, the typical periods are considered as one day. On the other hand, unexpected events such as drastic changes in meteorological conditions or sudden fluctations on electricity prices are not considered until the final phases, which may of course requires new planning in some cases.

CHAPTER 2

REVIEW OF LITERATURE

In the relevant literature, “Home energy management system (HEMS)”, “Energy management system (EMS)”, “Smart Home Energy Management System (SHEMS)”, “Residential Energy Management System (REMS)”, “Building Energy Management System (BEMS)” are different terms for the same domain. In recent years, several studies are presented which modelled the residential demand response to solve energy load scheduling problem of a smart house optimally considering the energy cost, environmental concerns, load profiles and consumer comfort. Energy scheduling strategies implemented in the decision support tools for residential consumers are reviewed in detail by Zhou et al. (2016). In addition, another detailed review of various home energy management system models introduced since 1970 is deliberately presented in the work of Vega et al. (2015). Here, we limited ourselves with the most relevant studies in the literature.

Since more suitable solutions are investigated for the current problems, rule-based techniques applied on HEMS should be slightly replaced by the optimization-based approaches. But from this point of view, one should not interrogate the validity of rule-based techniques since they are not obsolute -on the contrary- will be used when the smart rules are generated manually or automatically after the analyses of the results of optimization models.

HEMS scheduling optimization models can vary according to; model objective, home appliances/loads, energy storage availability, electrical vehicles (EV) presence, heating, ventilation, air conditioning (HVAC) and water heater usages, renewable energy resources or various grid transactions or time scales. We will investigate the literatue according to these variants of HEMS as subsections in this chapter of the thesis. Although considering all of these elements in the model is possible, the size of the model gets large in that case and this considerably affects the computational complexity. In order to reduce the solution time and make the application process as clear as possible for the household, the model should be constructed with only the proper elements. Adding some extra/additional parameters to the model may cause long run time and may also complicate the visualization of the results by the end users.

2.1 OBJECTIVE FUNCTION

There are many different types of objectives considered in HEMS models in the literature. Basically cost is the commonly used one because it can be measured and defined easily. Start-up cost (Costanzo et al., 2012) is the initial cost for the HEMS. Smart device can provide extra savings, but installation and maintenance costs must be considered when compared to the other devices. Initial cost might be higher at first and this may be a starting barrier for the consumers, but when the long run benefits considered, the consumer will profit from HEMS in the middle to long run.

Deterioration cost is related to working condition of devices. When a storage device is charged or discharged, it lose its ability to store energy gradually in the future. Solar panels also lose thier capabilities over time because of being exposed to sun, rain, snow, birds, and air particles. Wind turbine power generation declines with usage, ageing, wind storms, heavy rainfall, and water splash. I In literature deterioration cost is studied rarely. Zhang et al. (2015) has proposed an optimization model based on net electricity cost considering three terms; buying electricity from the grid, degradation cost of storage battery and overall revenue of selling energy to the grid.

Wellfare or comfort is another alternative objective. Either comfort or discomfort can be directly related to the quality of service obtained from each device. Mainly two categories causes discomfort that leads to the loss of quality in the service: timing and undesirable state. Timing is about delays in the usage of the device due to load shifting. Undesirable state is the issues such as being out of ideal temperature comfort range in house. Zhang et al. (2015) presents an optimization model which uses different comfort indicators for different home applications according to their characteristics and home user’s choices. In their model, the electricity cost is minimized and the comfort levels are maximized by adjusting three variables; the waiting time for the availability of the scheduled home applications, the expected error for the desired indoor temperature for HVAC and the waiting time for the PHEV to be charged completely.

Load profiling is scheduling the usage of devices in a way to reduce the peak demand. Qayyum et al. (2015) formulated an appliance scheduling problem considering the load profiling as their objective. Another objective is the maximization of the usage of energy generated by renewable resources to obtain a house which is self sufficient. Vilar et al. (2016) proposed a residential management model to maximize the use of renewable energy resources, while maximizing the economic benefit and minimizing the power imported from the main distribution grid.

Multi objective optimization methods are also used to optimize objectives simultaneously. A priori approach is selected if a decision-maker wants to determine each objective weights at the beginning.
Otherwise, posteriori approach is suitable for selecting the best solution after analyzing the results. Although multi objective optimization methods are used in the literature, they complicate the usage of HEMS from the end user’s point of view and should be avoided in real life applications.

Weighted sum is one of the best-known a priori methods. Each objective is weighted according to the user preferences but unfortunately, this method is very sensitive to the choice of the weights. The HEMS model in Zhang et al. (2015) minimize the weighted sum of household’s discomfort, total energy cost, peak electricity consumption and carbon footprint.

Pareto optimal is a set of points that provides different best solutions among which the decison maker can choose the more desirable one according to her/his utility measure. Jovanovic et al. (2016) has proposed a model for scheduling residential demand response with consideration of the consumer preferences as a multi-objective mixed integer programming. They examined the relation between the satisfaction of consumers based on the application usage preferences and the electricity cost by using pareto front of the related objective functions. The classification of the recent literature with respect to HEMS optimization model's objective is given in below Table 2.1.

Table 2.1: The classification of recent literature with respect to objective

	Cost	**Discomfort**	**Load Profiling**	**Renewable Energy**	**Single-objective (SO) or Multi-objective (MO)**
Costanzo et al. (2012)	✓				SO
Qayyum et al. (2015)	✓		✓		MO
Jovanovic et al. (2016)	✓	✓			MO (Pareto Front)
Zhang et al. (2015)	✓	✓	✓		MO (Weighted Sum)
Vilar and Affonso (2016)	✓			✓	MO (Simulated Annealing)
Conejo et al. (2010)	✓				SO
Du and Lu (2011)	✓				SO
Salinas et al. (2013)	✓		✓		MO (Pareto Front)
Hu et al. (2016)	✓				SO
Celik et al. (2017)	✓		✓		MO (Weighted Sum)

2.2 DEVICES AND LOADS

Each HEMS model consisting of different devices also has unique characteristics. Demand response behaviour of devices can be classified as: uncontrollable or controllable; continuous, interruptible or uninterruptible and deferrable or undeferrable. There are also other less accepted classification as the one provided by Yu et al. (2013). They classify the home applications into three classes depending on their control types as; power-shiftable, time-shiftable and non-shiftable devices.

Uncontrollable load devices cannot be manipulated mainly due to their high utility value to the household's comfort level such as TV and PC. But usage of the controllable load devices can be shifted for a period of time with little or no loss of comfort, e.g. dishwasher and washing machine. Continuous load devices will be always on, such as refrigerator, outdoor lighting. Usage of the interruptible load devices can be stopped and after the interruption period the usage of the device can continue to complete the work, e.g. water heater. Uninterruptible loads must run without any interruption after they start a task. It should complete all the required consecutive process in a single run. Deferrable loads are of less importance when they work, thus postponement of their operation periods can be accepted, e.g. water pumps. Undeferrable loads are critical and they are not allowed to change in their operation periods.

In literature, there are two types of approaches on dealing with the loads. The first one determines each device’s loads while the second approach focuses total loads, without focusing on any individual device, by grouping devices according to their types. Load forecast is difficult since it should take into consideration the householder’s behaviour. But future load prediction is important for planning of the energy consumption efficiently. Multiple Linear Regression, Exponential Smoothing, Autoregressive Moving Average (ARMA), Autoregressive Integrated Moving Average (ARIMA) and Artificial Neural Network (ANN) are used commonly in future load forecasting. Many researchers compare these techniques with the calculation of forecast error. The prediction period is divided into short, middle and long term. The long time forecast (LTF) is used for making investment in the electricity infrastructure. The middle time forecast (MTF) is used for making a plan for a week or a month. The short time forecast (STF) is the one suitable for providing inputs to HEMS on hour-to-hour basis.

Household devices have different characteristics. The first one is the dependency to other devices. Some studies in literature have included device dependency to strengthen their algorithms. Two types of dependency have been considered in the literature: internal and external. An example for the internal dependency is between the washing machine and clothes dryer: after washing machine completes its work, clothes dryer starts to work. Relationship between devices and environment (e.g weather) are named as external. For example, if air temperature is below normal climate conditions, air conditioner turns on to increase the temperature at home. The second characteristic is priority. Giving priority to home devices based on consumer preferences is used at home energy management systems. Sometimes consumers change their priorities on the selected time periods. HEMS model should compare priority of devices and run the highest priority first in order to meet user preferences. The third characteristic is the flexibility. Time flexibility at devices' start and stop time helps the household to shift the working periods. Working condition's flexibility is also another important issue, e.g. only 1^{o} C temperature above or below the ideal room condition can be tolerated without turning on the airconditioner. Flexibility for each device can be determined by the user's preferences. The classification of the recent literature with respect to loads considered in the HEMS optimization model is given below at Table 2.2.

Table 2.2: Classification of recent literature with respect to loads considered in HEMS

	Control. Loads	**Uncontrol. Loads**	**Continuous / Base Loads**	**Inter. Loads**	**Uninter. Loads**	**Defer. Loads**	**Undefer. Loads**
Mohsenian-Rad & Leon-Garcia (2010)		✓		✓	✓		
Yu T. et al. (2013)				✓	✓	✓	
Zhao et al. (2013)	✓					✓	
Hu et al. (2016)	✓					✓	✓
Giorgio (2012)	✓				✓		
Soares et al. (2013)	✓		✓				
Shao et al. (2013)	✓		✓				✓
Moradi et al. (2016)	✓	✓					
Yu Z. et al. (2013)						✓	✓
Mohsenian-Rad et al. (2012)	✓			✓			

2.3 STORAGE DEVICE AND ELECTRICAL VEHICLES

Since energy storage devices have the ability to charge and discharge energy, they provide flexibility for taking the decisions about when and how much energy should be sold to grid or should be purchased from grid. Charge/discharge rate, maximum/minimum capacity for the stored energy, AC to DC and DC to AC conversion efficiency and levelized cost must be defined with storage constraints while mathematical modelling phase. To calculate the levelized cost of energy, price, cycles, depth of discharge (DoD) and capacity value of storage are needed (Yu et al. 2013). The storage state of charge should be kept within the minimum and maximum allowable storage capacity levels to protect it from damage (Zhang et al. 2015). The charging and discharging speed is constrained to protect the storage device.

At the beginning of twentieth century, there was a big debate on the current flow issue, namely Alternative Current (AC) or Direct Current (DC). Tesla won the so called battle. Now, we all use the AC at our homes. However, the battery store energy is still DC. When it charges, it needs to convert main circuit AC to DC by the rectifier, a component of the storage system. When it discharges, it needs to convert the storede DC to the main circuit AC by the inverter, another component of the storage system. Inverter and rectifier is responsible for the 3-4% energy loss during this conversion, in each direction.

The Depth of Discharge (DoD) is one of the most important factor that affects the expected lifetime of a storage device. Another one is the number of discharge and charge recycles. DoD is opposite of the state of charge (SoC). If a fully charged storage device discharges and delivers 30% of stored energy, SoC of storage decreases to 70%, and DoD of storage is 30%. Deeply discharging of storage, high DoD, can reduce the lifetime of a storage device significiantly. The lifetime depends on storage device type. According to this fact, Aksanli and Rosing (2014) build a battery model describing nonlinear properties, but formulate it linearly for the ease of solution. They validate their results using real home usage data from the MIT REDD database.

Electrical Vehicles (EV) run on electrical energy, which is stored in its own battery. EVs can be classified as deferrable and uninterruptible load and energy storage. They can be recharged or used as energy storage device when directly connected to the home electricity grid. When leaving and coming back at home of an EV is specified, the decision about time of leave and amount of charging can be optimallr determined (Yu et al. 2013). Moradi et al. (2016) also proposed a DR model including an EV and in order to have a better evaluation of the impact of EVs on the cost and load profile, they consider three different scenarios were considered for electric vehicle charging profile: uncontrolled, controlled and smart charging. Classification of recent literature with respect to storage device consideration is provided at Table 2.3.

Table 2.3: Classification of recent literature with respect to storage device consideration

	Storage				EV
	Charge Rate	**Capacity**	**Depth of Discharge**	**Efficiency**	
Aksanli and Rosing (2014)	✓	✓	✓	✓	
Moradi et al. (2016)					✓
Yu Z. et al. (2013)					✓
Harb et al. (2016)		✓		✓	
Zhang et al. (2015)		✓		✓	✓
Hu et al. (2016)	✓	✓		✓	✓
Shao et al. (2013)					✓
Yu T. et al. (2013)	✓	✓	✓		
Qayyum et al. (2015)					✓
Giorgio (2012)		✓			

2.4 HEATING, VENTILATION AND AIR CONDITIONING (HVAC) AND WATER HEATER (WH)

Two thermal loads can be considered in a HEMS: Heating, Ventilation and Air Conditioning (HVAC) and Water Heater (WH). HVAC system is responsible for 30-50% of energy consumption in buildings. The second biggest share of home consumption is the WH’s.

Heating, Ventilation and Air Conditioning (HVAC) is commonly considered as controllable appliance in the literature. The HEMS models try to keep the inside temperature within comfort temperature range or to provide as less deviation as possible from the ideal temperature level. Thermal dynamic model uses some thermal parameters of the house to the predict inner temperature. The internal heat energy loss at a house is mostly through walls, floor, windows, doors and ceiling. In many examples, HVAC is used both for cooling and for heating. Yu et al. (2013) formulate a multi-stage stochastic optimization framework for HEMS, which has a linear thermal dynamic model, proposed online model parameter estimation, and compared to real performance of HVAC appliance.

Shao et al. (2016) propose a demand response enabled space cooling and heating load model, together with its validation. Input parameters are divided into three categories: temperatures, building and space cooling or heating properties. Temperatures considered are outside and inside temperatures, building properties are different parts of home areas, and space heating or cooling properties are heating capacity, power consumption and the sizing of building's floor plan, activity, occupants and environment.

The Water Heater (WH) is a closed system. When the temperature of the water is less than the user's preference, the heating system turns on. Water heating model uses water tank volume and surface area, the heat resistance capability of the water tank. Power consumption of the water heating system is estimated by using the thermal model (Shao et al. 2013). Classification of recent literature with respect to Thermal Load consideration is given below at Table 2.4.

Table 2.4: Classification of recent literature with respect to Thermal Load consideration

	HVAC	**WH**
Shao et al. (2013)	✓	✓
Hu et al. (2016)	✓	
Yu Z. et al. (2013)	✓	
Qayyum et al. (2015)	✓	
Zhang et al. (2015)	✓	✓

2.5 RENEWABLE ENERGY RESOURCES

Renewable energy resources such as solar panel and wind turbines are used for clean energy generation. They are green and cost effective solutions to reduce the total house energy costs. Other energy resources for home is mainly power generators that runs on natural gas or fuel (Aki et al. 2016).

Renewable energy resources depend greatly on natural phenomena. Thus, forecasting of solar panel and wind turbine energy production depends significantly on the accurate prediction of weather parameters (solar irradiation, temperature, wind speed etc.) and properties of panel and wind turbine, such as panel size, wind turbine diameter, efficiency etc. In the literature, methods proposed for the photovoltaic production estimation are ARIMA, k-NN, ANN, and ANFIS models.

Solar panel creates an electrical direct current (DC), an inverter converts it to an alternating current (AC), while some energy is lost during the conversion process. Wind turbine produces an AC, but it cannot be used directly at homes, it needs to be converted into usable AC. The efficiency of the solar panel is related with type of the materials (monocrystalline, polycrystalline and thin silicon) that are used in the solar panel. The probable losses are as follows; inverter loss (%5), cable loss (%2), shading loss, snow and dust effect (%1) etc.

Renewable energy systems are commonly assumed to have on-grid connections. It means that, if there will be any time mismatch or surplus energy between the production and demand, then it will be imported or exported to the main grid. Question about how to manage surplus energy is placed on storage side and is not related to the production (Wu et al. 2015). Yu et al. (2013) has formulated two types of the optimization problem including a photovoltaic system with or without storage. Classification of recent literature with respect to Renewable Energy Resource consideration is provided at Table 2.5.

Table 2.5: Classification of recent literature w.r.t. Renewable Energy Resource consideration

	Wind Turbine	**Solar Panel**	**Other**
Qayyum et al. (2015)		✓	
Aki et al. (2016)			Fuel based Combined Heat and Power (CHP)
Vilar and Affonso (2016)		✓	
Wang et al. (2012)	✓	✓	
Wu et al. (2015)			Micro CHP
Harb et al. (2016)		✓	

2.6 PRICE TARIFFS

Electricity energy market price tariff can be divided into a few categories: single-fixed (FP), time of use (TOU), critical peak (CPP), real time (RTP), consumption based (CB) and reward (RP). Single-fixed price tariff has no peak and off-peak periods. Price does not vary with time. Time of use price tariffs charges different prices at different time of the day. Commonly three different rate price periods are defined for balancing the energy consumption: peak, off-peak and shoulder. During peak time, the prices are relatively higher than other periods. Price schedule is fixed and predefined on season, days of week, etc. Critical peak price tariff is a version of TOU. In certain hours, critical peak periods, prices are significantly higher than other periods. Real time price tariff is based on actual market value, emerges as supply and demand matches each other. If supply is greater than demand, price goes downward, otherwise, price goes upward. Price is volatile and customers need to handle the price variations to obtain benefits. Consumption based price tariff is an increasing linear function: if consumption is greater than the threeshold quantity for the determined price, new price bigger than the previous one, is charged to the excess amount of energy. Reward price tariff can be used to encourage customer to change their consumption pattern by giving rewards to them.

Varying energy prices can result in energy arbitrage; users can buy extra energy when the prices are low, store energy in storages, and then use the stored energy and deferrable applications when the price gets higher. Classification of recent literature with respect to the Price Tariffs consideration is given below at Table 2.6.

Table 2.6: Classification of recent literature with respect to the Price Tariffs consideration

	FP	**TOU**	**CPP**	**RTP**	**CB**	**RP**
Aksanli and Rosing (2014)	✓	✓				
Zhao et al. (2013)				✓	✓	
Qayyum et al. (2015)		✓				✓
Moradi et al. (2016)		✓			✓	
Tariq et al. (2017)			✓			
Jovanovic et al. (2016)				✓		
Yu et al. (2013)				✓		
Zhang et al. (2015)				✓		

2.7 TIME SCALE

HEMS models' scheduling time scales have been defined over either future period or real time. In future period models, length of planning horizon, time interval between each period (resolution) and rescheduling frequency determine the complexity of the model. Rescheduling strategy is applied with the optimization models using a rolling horizon approach (Harb et al. 2016).

Planning horizon should be made sufficiently long enough to illustrate the full benefits of the optimal decisions related with the model results. On the other hand, to conform to a new situation, changing input parameters and to support accurate real environment, the horizon length must not be too long. In many studies, one day is taken in the experiments. Classification of recent literature with respect to time scale used in HEMS models is given below at Table 2.7.

Table 2.7 : Classification of recent literature with respect to time scale used in HEMS models

	Planning Horizon	**Resolution**	**Number of Periods**
Giorgio (2012)	1 day	15 minutes	96 periods
Zhao et al. (2013)	1 day	12 minutes	120 periods
Zhang et al. (2015)	1 day	12 minutes	120 periods
Mohsenian-Rad and Leon-Garcia (2010)	1 day	1 hour	24 periods
Du and Lu (2011)	1 day	1 hour	24 periods
Soares et al. (2013)	36 hours	1 hour	36 periods
Qayyum et al. (2015)	1 day	15 minutes	96 periods
Wu et al. (2015)	1 day	15 minutes	96 periods
Shao et al. (2013)	1 day	1 minute	1440 periods
Moradi et al. (2016)	1 days	1 hour	24 periods

2.8 UNCERTAINTY

HEMS models face many uncertain factors such as in real time prices, weather and consumer device consumption behavior. Nevertheless, there are studies in the literature where these problems are solved by deterministic approach. Most of the times deterministic approach results in significant deviations from the actual schedules observed in real life. However, it is easier to formulate and solve the deterministic models compared to the stochastic solution methods. Stochastic approach deals with uncertainties in the input to get more realistic results.

Energy consumption pattern for different household applications are generally considered as stochastic variables. This may give a better representation of the household behavior, but the computational burden increases more when stochastic parameters are used (Wu et al. 2015). In addition, the proposed algorithm should have acceptable robustness for easy decision making. Robust optimization techniques help to minimize the effects of extreme case scenarios to get a smooth result (Le and Ploix. 2016). Harb et al. (2016) presents predictive energy management strategy for optimizing a building's energy system. The approach is based on multi stage stochastic programming that uses continuous value and discrete time hot water and electricity demand forecast. Uncertainty is represented by a set of scenarios. Classification of recent literature with respect to Stochastic Input Variables considered in HEMS models is given below at Table 2.8.

Table 2.8: Classification of recent literature w.r.t. Stochastic Input Variables considered in HEMS

	Price	**Load**	**Generation**	**Temperature**
Harb et al. (2016)		✓		✓
Wu et al. (2015)	✓	✓	✓	✓
Le and Ploix (2016)	✓	✓		
Shafie-khah and Siano (2017)		✓	✓	

2.9 MICROGRID BASED

Distributed HEMS modelling in micro grid environments is another field of study. Nowadays, the optimization modelsin coordinating the smart homes located in the same microgrid community for reducing energy cost of each house individually is a very popular research topic.

Microgrid operator is considered as a leader who decides to what extent of the total demand could be balanced by coordinating different household consumption and common useable renewable energy resources or how the micro grid operator can coordinate all neighbours without interrupting the autonomous decision making mechanism. Each house has different types of appliances, loads, storages and generators and the model should decrease total customer electricity cost of the microgrid area. Both microgrid operator and the households try to meet at some common point and build a pragmatical relationship in order to maximize the profit on both ways (Zhang et al. 2016, Mondal et al. 2015).

Celik et al. (2017) develop an algorithm in order to reduce the aggregated peak demand power of the neighborhood; in addition to reduce the daily electricity bill of the users by scheduling household appliances and controlling battery (both home and EV) charging/discharging operations through dynamic pricing. Fatima et. al. (2017) propose a grid connected to a microgrid to supply fifteen homes at a residential area and use real time price tariff for calculating the total microgrid energy consumption cost.

2.10 OPTIMIZATION METHODS

Different mathematical optimization techniques, heuristic and non-heuristic methods are applied to HEMS problems. Mixed integer linear programming (MILP) is commonly used to find the best schedule for household activities. Other conventional mathematical optimization techniques such as linear programming (LP), dynamic programming (DP) and quadratic programming can also be preferred. Mohsenian-Rad and Leon-Garcia (2010) propose a linear programming (LP) consumption scheduler that aims to provide an exchange between the minimum cost and minimum delay time for the operation of appliances with respect to pre-determined starting times. A weighted average price prediction capability is also presented in the model. They claim to obtain a significant reduction in the consumer payments and PAR (Peak-to-Average Ratio) in their experiments. Conejo et al. (2010) considers an LP model to maximize the utility (or to reduce the energy cost) of the consumer within the limits of a given energy consumption level and hourly load levels. A case study is also presented to prove the profitability of the proposed method. Mixed integer nonlinear (Stluka et al. 2011), neural networks (Hernandez at al. 2010) and game theory (Mohsenian-Rad et al. 2012) approaches are also implemented to HEMS problems. As an example, Hernandez et al. (2010) schedule only lighting applications at a house by using neural network methods.

When complexity or size of the problem increases beyond computational limits, heuristic and meta-heuristic methods are preferred to overcome the computational load. These methods do not always guarantee to achieve the best results, but offers a close-to-optimal and reliable results in a reasonable time frame. In the meta-heuristic area, swarm (Hernandez et al. 2010), genetic (Zhao et al. 2013, Soares et al. 2013) and evolutionary (Salinas et al. 2013) algorithms are proposed to provide reliable decisions for HEMS models. Giorgio (2012) use a mixed integer linear programming with a greedy heuristic approach for finding finest quality solutions in a short time. Pedrasa et al. (2010) propose an optimization framework for a smart home using Particle

Swarm Optimization (PSO). Their model includes scheduling of a plug-in EV, heaters, pump and photovoltaic energy storage system. The authors compare cases where energy resources are scheduled together and independently in which the scheduling problem is decomposed into sub-problems.

Conejo et al. (2010) consider a simple LP model to maximize the utility (or to reduce the energy cost) of the consumer within the limits of a given energy consumption level and hourly load levels. A case study is presented by them to prove the efficacy of the proposed method. Du and Lu (2011) present a model for minimum cost load scheduling subject to consumer comfort setting for a thermostatically controlled application. Their two-step scheduling process provides adjustments to the schedule to interpret the uncertainties and errors. Rastegar et al. (2012) work on an LC (Load Commitment) framework to achieve the minimum payment for household consumption. The model incorporates the decision of operating status of applications, charging and discharging cycles of energy storage devices and plug-in EVs. Classification of recent literature with respect to the optimization method applied to HEMS models is given below at Table 2.9.

Table 2.9: Classification of recent literature with respect to the optimization method applied

	Optimization Methods	**Metaheuristic/Heuristic Methods**
Conejo et al. (2010)	LP	
Mohsenian-Rad and Leon-Garcia (2010)	LP	
Giorgio (2012)	MILP	Greedy
Zhao et al. (2013)		Genetic
Stluka et al. (2011)	MINLP	
Jovanovic et al. (2016)	MILP	
Salinas et al. (2013)		Evolutionary
Pedrasa et al. (2010)		Particle Swarm
Qayyum et al. (2015)	MILP	
Wu et al. (2015)	MILP	
Moradi et al. (2016)		Genetic
Rastegar et al. (2012)	LP	
Hernandez et al. (2013)		Neural Networks

To the best of our knowledge, there is no study yet which models the scheduling problem of a system including controllable and uncontrollable applications, EVs, storage devices, energy generators (wind turbine and solar panel) and thermostatically controlled devices (ACs), allowing energy sales to the grid and considering stochastic usage of applications, stochastic nature of energy purchase/sales prices and also stochastic weather conditions. We handle all of these issues simultaneously in a detailed formulation for the HEMS scheduling.

CHAPTER 3

MATHEMATICAL MODEL

In this section, we present the required notation and the mathematical model in detail. Since the description of the model takes several pages, it is given in a partitioned way. After the definition of sets and the objective function are given, the constraint modules of the model are explained one by one. In each module, equations or inequalities are declared after the required parameters are described.

The constraint modules are for controllable appliances, uncontrollable appliances, storage devices, electrical vehicle and air conditioner operation. In addition to these modules, there is a set of constraints which represent the balance and limitations on energy purchase, energy sale, energy generation and consumption, which is described along with the objective function. The appliances that work independently like refrigerators and automatic lighting systems are kept separate from the other home appliances which can be controlled by the energy management system or the residents of home. They are named as continual applications and modeled only in objective function, while the others are classified as controllable applications (controllable by energy management system) and uncontrollable applications.

3.1 Sets

The sets employed in the model are as follows:
$S = (1, \dots, |S|)$: set of scenarios,
$T = (1, \dots, |T|)$: set of periods,
$C = (1, \dots, |C|)$: set of $controllable\ appliances,$
$U = (1, \dots, |U|)$: set of $uncontrollable\ appliances,$
$B = (1, \dots, |B|)$: set of $storage\ devices,$

$V = (1, \ldots, |V|)$: set of $electrical\ vehicles$,

$W = (1, \ldots, |W|)$: set of $wind\ generators$,

$P = (1, \ldots, |P|)$: set of $solar\ panels$,

$A = (1, \ldots, |A|)$: set of $air\ conditioners$,

$N_V(v) = (1, \ldots, |N_V(v)|)$: set of $electrical\ vehicle$ usages,

$N_C(c) = (1, \ldots, |N_C(c)|)$: set of $controllable\ appliance$ usages,

$N_U(u) = (1, \ldots, |N_U(u)|)$: set of $uncontrollable\ appliance$ usages,

3.2 Objective Function

Objective function given in Equation (2.1) minimizes the average total cost of possible scenarios.

$$(\boldsymbol{HEMS}) \quad Z_{HEMS} = \min \frac{1}{|S|} \sum_{s \in S} TC(s) \qquad (2.1)$$

Total cost of a scenario s, TC(s), includes the cost of purchased energy, negative cost of sold energy and depreciation cost of several devices, which generate, consume or store energy. Therefore, how much energy will be used from the grid and how much energy will be sold to the grid should be decided. Notation for these two main decision variables are:

$E_{purchase}(s,t)$: energy purchased from grid at period $t \in T$ in scenario $s \in S$,

$E_{sell}(s,t)$: energy sold to grid at period $t \in T$ in scenario $s \in S$.

Energy sold to grid at period t , $E_{sell}(s,t)$, and energy purchased from grid at period t, $E_{purchase}(s,t)$ are related with balance equations. These equations balance the energy consumption of continual, controllable and uncontrollable applications, air conditioner, usage of storage devices and electrical vehicles with energy generation at home and energy purchase from grid.

These two energy values are the results of the following decisions: energy generation from wind turbine(s) and solar panel(s), the usage of storage device(s) and electrical vehicle(s), the schedule of controllable, uncontrollable applications and air conditioner(s). These decisions are included in the balance equations and the whole model by the following decision variables:

$E_{Bc}(t,b)$: charged energy by the $storage\ device\ b \in B$during period$t \in T$,

$E_{Bd}(t,b)$: discharged energy by the $storagedevice\ b \in B$ during period $t \in T$,

$E_{Vc}(t,v)$: charged energy by the $electricalvehicle\ v \in V$ during period $t \in T$,

$E_{Vd}(t,v)$: discharged energy by the $electricalvehicle\ v \in V$ during period t
$\in T$,

$I_W(t,w,s)$: 1 if $windturbinew \in W$ is on during period $t \in T$ in scenario s
$\in S$, 0 o. w.,

$I_P(t,p,s)$: 1 if $solarpanelp \in P$ is on during period $t \in T$ in scenario s
$\in S$, 0 o. w.,

$I_C(t,c,n(c))$: 1 if $controllableappliance\ c \in C$ is on during period $t \in T$
at usage $n(c) \in N_c(c)$, 0 o. w.,

$I_U(s,t,u,n(u))$: 1 if $uncontrollable\ appliance\ u \in U$ is on during period $t \in$
T in scenario $s \in S$ at usage $n(u) \in N_u(u)$, 0 o. w.,

$E_{heat}(t,a)$: consumed energy for heating by the $air\ conditioner\ a$
$\in A$ during period $t \in T$,

$E_{cool}(t,a)$: consumed energy for cooling by the $air\ conditioner\ a$
$\in A$ during period $t \in T$,

In addition to these decision variables, in the energy balance equations we need the following parameters:

$E_W(s,t,v)$: energy generation rate of $wind\ turbine\ w \in$ W at period $t \in$
T in scenario $s \in S$, if wind turbine is on,

$E_P(s,t,p)$: energy generation rate of $solar\ panel\ p \in P$ at period $t \in$
T in scenario $s \in S$, if solar panel is on,

$E_C(c)$: energy consumption rate of $controllable\ appliance\ c$
$\in C$, if appliance is on,

$E_U(u)$: energy consumption rate of $uncontrollable\ appliance\ u \in$
U, if appliance is on,

$E_{continual}(t)$: energy consumption rate of $continual\ appliances$ at period $t \in T$,

$n_{Bc}(b)$: AC to DC efficiency of the $storage\ device\ b \in B$,

$n_{Bd}(b)$: DC to AC efficiency of the $storage\ device\ b \in B$,

$n_{Vc}(v)$: AC to DC efficiency of the $electrical\ vehicle\ v \in V$

$n_{Vd}(v)$: DC to AC efficiency of the $electrical\ vehicle\ v \in V$

$n_W(w)$: efficiency of the $wind\ turbine\ w \in W$,

$n_P(p)$: efficiency of the $solar\ panel\ p \in P$,

$E_{PMax}(t)$: maximum energy that can be purchased at period $t \in T$,

$E_{SMax}(t)$: maximum energy that can be sold at period $t \in T$.

$$
\begin{aligned}
& E_{sell}(s,t) + \sum_{b\in B}\frac{1}{n_{Bc}(b)}E_{Bc}(t,b) + \sum_{v\in V}\frac{1}{n_{Vc}(v)}E_{Vc}(t,v) \\
& \qquad + \sum_{c\in C} E_C(c)\left(\sum_{n(c)\in N_c(c)} I_C\big(t,c,n(c)\big)\right) \\
& + \sum_{u\in U} E_U(u)\left(\sum_{n(u)\in N_u(u)} I_u\big(s,t,u,n(u)\big)\right) + E_{continual}(t) + E_{cool}(t,a) \\
& \qquad + E_{heat}(t,a) \le \\
& E_{purchase}(s,t) + \sum_{b\in B} n_{Bd}(b)E_{Bd}(t,b) + \sum_{v\in V} n_{Vd}(v)E_{Vd}(t,\mathrm{v}) \\
& \qquad + \sum_{w\in W} n_W(w)E_W(s,t,\mathrm{w})\, I_W(s,t,v) \\
& + \sum_{w\in W} n_W(w)E_W(s,t,\mathrm{w})\, I_W(s,t,v) \qquad \forall\ t\in T,\ \forall\ s\in S \qquad (2.2)
\end{aligned}
$$

$$E_{purchase}(s,t) \le E_{PMax}(t) \qquad \forall\ t\in T,\ \forall\ s\in S \qquad (2.3)$$

$$E_{sell}(s,t) \le E_{SMax}(t) \qquad \forall\ t\in T,\ \forall\ s\in S \qquad (2.4)$$

Constraint (2.2), which is referred as the energy balance equation, ensures that the total energy which is used up, charged or sold in a period should be less than or equal to the total energy which is discharged, generated or purchased in that period. The remaining energy between two sides of equation goes to ground, and is removed out of the system.

While deciding on the optimum values of the above mentioned decision variables to minimize the average total cost, usage costs and energy prices should also be considered in the model. This information are included in the objective function using the following additional parameters;

$PP(s,t)$: purchase price at period $t \in T$ in scenario $s \ \in S$,

$SP(s,t)$: sale price at period $t \in T$ in scenario $s \ \in S$,

$m_{Bc}(b)$: depreciation cost per unit charge of $storage\ device\ b \in B$,

$m_{Vc}(v)$: depreciation cost per unit charge of $electrical\ vehicle\ v \in V$,

$m_{Bd}(b)$: depreciation cost per unit discharge of $storage\ device\ b \in B$,

$m_{Vd}(v)$: depreciation cost per unit discharge of $electrical\ vehicle\ v \in V$,

$m_W(w)$: depreciation cost per unit energy generation of $wind\ turbine\ w \in W$,

$m_P(p)$: depreciation cost per unit energy generation of $solar\ panel\ p \in P$,

Therefore, Equation (2.5) gives the total cost of scenario $s \in S$ accordingly.

$$TC(s) = \sum_{t\in T} PP(s,t)E_{purchase}(s,t) - SP(s,t)\,E_{sell}(s,t) + \\ \sum_{b\in B}\sum_{t\in T} m_{Bc}(b)E_{Bc}(t,b) + \sum_{v\in V}\sum_{t\in T} m_{Vc}(v)E_{Vc}(t,v) + \\ \sum_{b\in B}\sum_{t\in T} m_{Bd}(b)E_{Bd}(t,b) + \sum_{v\in V}\sum_{t\in T} m_{Vd}(v)E_{Vd}(t,v) + \\ \sum_{w\in W}\sum_{t\in T} m_W(w)E_W(s,t,\mathrm{w})I_W(s,t,\mathrm{w}) + \sum_{p\in P}\sum_{t\in T} m_P(p)E_P(s,t,\mathrm{p})I_P(s,t,\mathrm{p}) \quad (2.5)$$

3.3 Constraints

The constraints of the scheduling problem for HEMS will be presented in modules for ease of understanding.

3.3.1 Constraints for the Air Conditioner

The operation of the the air conditioner is modelled by considering the internal temperature of the building with its thermal inertia, the transmittance of its walls/floor/roof/windows and the power injections given by air conditioner systems and of solar radiation as illustrated in Figure 3.1. Air conditioner has capabilities of cooling and heating. Heating and cooling demand of the building is explained in the Appendix. Constraint (2.6) represent this model utilizing the following parameters;

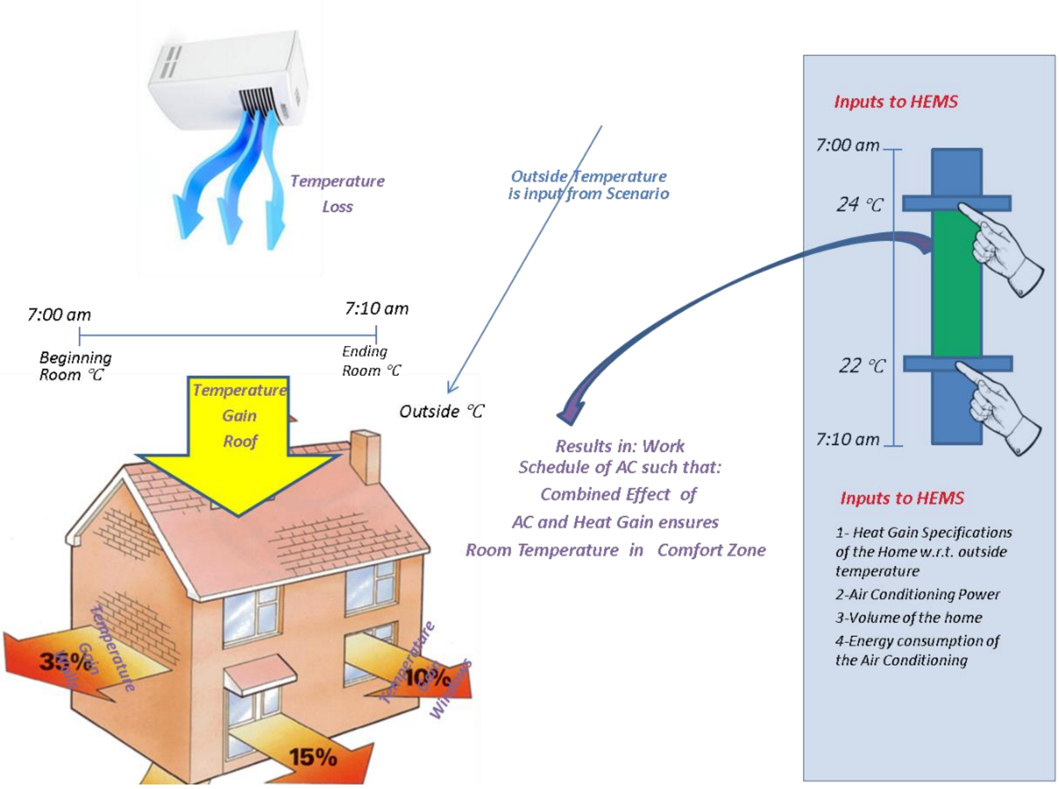


Figure 3.1: Air Conditioner Thermal Model

C: is the heat capacity,

Δt: is the length of a period,

U: thermal transmittance of the building,

$E_{hrad}(t)$: global horizontal radiation at period t,

S_{sun}: surface exposed to sun,

$F_{cool}(a)$: energy efficiency ratio for cooling by *air conditioner a*,

$F_{heat}(a)$:energy efficiency ratio for cooling by *air conditioner a*,

and the decision variables;

$T_{in}(t)$: inside temperature at the end of period t ,$T_{in}(0)$ is given,

$T_{ex}(t)$: outside temperature at the end of period t.

In addition, for the remaining constraints, we define the following decision variables;

$I_{heat}(t,a)$: 1 if *air conditioner a* heats during period t, 0 o.w.,

$I_{cool}(t,a)$: 1 if *air conditioner a* cools during period t, 0 o.w., and parameters;

$T_{min}(t)$: allowed minimum inside temperature at the end of period t,
$T_{max}(t)$: allowed maximum inside temperature at the end of period t.

Thus, we need the following constraints to model the work mechanics of the air conditioner:

$$T_{in}(t)\frac{C}{\Delta \mathrm{t}} - T_{in}(t-1)\left(\frac{C}{\Delta \mathrm{t}} - U\right) + \sum_{a \in A}\left(F_{cool}(a)E_{cool}(t,a) - F_{heat}(a)E_{heat}(t,a)\right)$$
$$= T_{ex}(t)\mathrm{U} + E_{hrad}(t)S_{sun} \qquad \forall\ t \in T \qquad (2.6)$$

$$I_{cool}(t,a) + I_{heat}(t,a) <= 1 \qquad \forall\ a \in A, \forall\ t \in T \qquad (2.7)$$

$$I_{cool}(t,a) * \frac{1}{M} \leq E_{cool}(t,a) \leq I_{cool}(t,a) * M \qquad \forall\ a \in A, \forall\ t \in T \qquad (2.8)$$

$$I_{heat}(t,a) * \frac{1}{M} \leq E_{heat}(t,a) \leq I_{heat}(t,a) * M \qquad \forall\ a \in A, \forall\ t \in T \qquad (2.9)$$

$$T_{min}(t) \leq T_{in}(t) \leq T_{max}(t) \qquad \forall\ t \in T \qquad (2.10)$$

Constraints make the temperature inside the house equal to sum of beginning level of temperature and gained/lost temperature up to corresponding time, while the remaining constraints keep the temperature between defined limits. Heat capacity C, and thermal transmittance U, are obtained by the formulas given in Equations (2.11and 2.12), respectively, where;

$S_{horizontal}$: horizontal surface (floor) area of the building,
$C_{thermal}$: the per unit daily thermal capacity coeffcient,
$U_{wall}, U_{roof}, U_{floor}$ and $U_{windows}$: the transmittance of walls, roof, floor and windows, respectively,
S_{wall} and $S_{windows}$: the surface area of walls and windows, respectively,
A_{fresh}: parameter taking into account the circulation of fresh air into the building, and
V : volume of the building.

$$C = S_{horizontal}\, C_{thermal} \qquad (2.11)$$

$$U = U_{wall}\, S_{wall} + U_{roof}\, S_{horizontal} + U_{floor}\, S_{horizontal} + U_{windows}\, S_{windows}$$
$$+ A_{fresh}\, V \qquad (2.12)$$

3.3.2 Constraints for the Storage Device

The operation of the storage device is modelled as shown in Figure 3.2. Below the decision variables are defined as;

$E_B(t,b)$: energy level of storage device $b \in B$ at the end of period $t \in T$, $E_B(0,b)$ is given $\forall b \in B$,
$I_{Bc}(t,b)$: 1 if storage device $b \in B$ charges during period $t \in T$, 0 o.w.,
$I_{Bd}(t,b)$: 1 if storage device $b \in B$ discharges during period $t \in T$, 0 o.w.,

and the parameter is defined as follows;

$E_{Bmax}(b)$: maximum energy level of storage device $b \in B$.

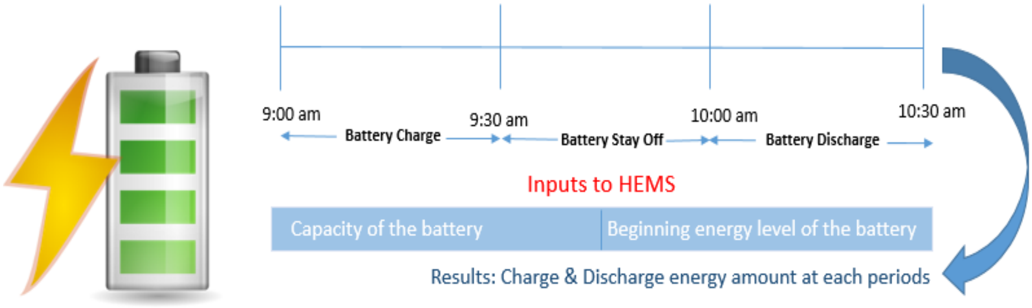


Figure 3.2: Storage Model

Thus, the following constraints are needed to model the work mechanics of the storage device where M is a big number:

$$I_{Bd}(t,b) + I_{Bc}(t,b) <= 1 \qquad \forall\ b \in B, \forall\ t \in T \qquad (2.13)$$

$$I_{Bc}(t,b) * \frac{1}{M} \leq E_{Bc}(t,b) \leq I_{Bc}(t,b) * M \qquad \forall\ b \in B, \forall\ t \in T \qquad (2.14)$$

$$I_{Bd}(t,b) * \frac{1}{M} \leq E_{Bd}(t,b) \leq I_{Bd}(t,b) * M \qquad \forall\ b \in B, \forall\ t \in T \qquad (2.15)$$

$$E_{Bd}(t,b) \leq E_B(t-1,b) \qquad \forall\ b \in B, \forall\ t \in T \qquad (2.16)$$

$$E_B(t,b) = E_B(0,b) + \sum_{t' \leq t} E_{Bc}(t',b) - E_{Bd}(t',b) \quad \forall \; b \in B, \forall \; t \in T \qquad (2.17)$$

$$E_B(t,b) \leq E_{Bmax}(b) \qquad \forall \; b \in B, \forall \; t \in T \qquad (2.18)$$

Constraint (2.13) forces storage device either charge, discharge or stay off in a given period, while Constraint (2.14) and (2.15) connects binary and continuous decision variables related to charging and discharging, respectively. Constraint (2.16) ensures that in a given period, storage device can discharge at most as much as the energy stored. Constraint (2.17) make the energy level equal to sum of beginning level of energy and charged/(-)discharged energy up to corresponding time. Constraint (2.18) limits the device such that it can store up to its maximum capacity.

3.3.3 Constraints for the Electric Vehicle

The operation of the electric vehicle is modelled in a way, which is very similar to the case in storage device as illustrated in Figure 3.3.

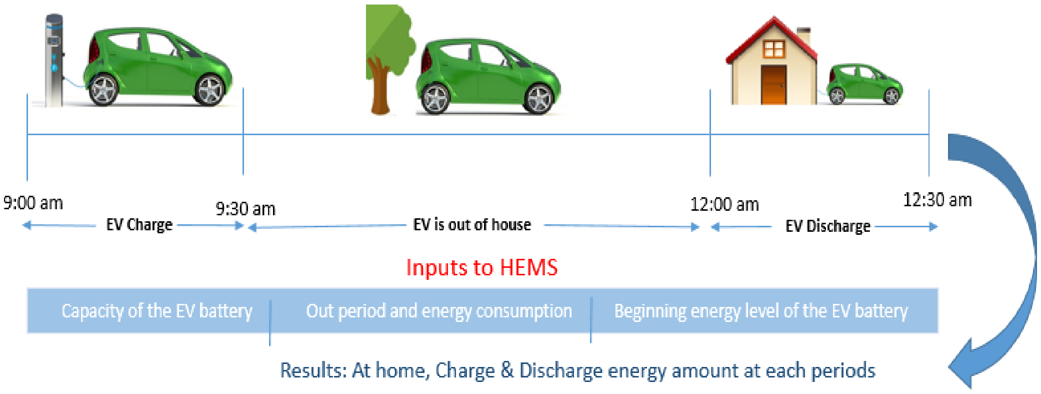


Figure 3.3: EV Model

Below, the decision variables are defined;

$E_V(t,v)$: energy level of electric vehicle $v \in V$ at the end of period $t \in T$, $E_V(0,v)$ is given $\forall v \in V$,

$I_{Vc}(t,v)$: 1 if electric vehicle $v \in V$ charges during period $t \in T$, 0 o.w.,

$I_{Vd}(t,v)$: 1 if electric vehicle $v \in V$ discharges during period $t \in T$, 0 o.w., and the parameters are defined as follows;

$E_{Vmax}(v)$: maximum energy level of electric vehicle $v \in V$,

$E_{Vout}(t, v, n(v))$: energy consumption of electric vehicle $v \in V$ outside at the usage $n(v) \in N_V(v)$ at period $t \in T$, 0 o.w.,

$bV(v, n(v))$: beginning of out period for electric vehicle $v \in V$ at the usage $n(v) \in N_V(v)$,

$eV(v, n(v))$: ending of out period for electric vehicle $v \in V$ at the usage $n(v) \in N_V(v)$.

Thus, the following constraints are needed to model the work mechanics of the electric vehicle where M is a big number:

$$I_{Vd}(t,v) + I_{Vc}(t,v) <= 1 \qquad \forall\, v \in V, \forall\ t \in T \qquad (2.19)$$

$$I_{Vc}(t,v) * \frac{1}{M} \leq\ E_{Vc}(t,v) \leq\ I_{Vc}(t,v) * M \qquad \forall\ v \in V, \forall\ t \in T \qquad (2.20)$$

$$I_{Vd}(t,v) * \frac{1}{M} \leq\ E_{Vd}(t,v) \leq\ I_{Vd}(t,v) * M \qquad \forall\ v \in V, \forall\ t \in T \qquad (2.21)$$

$$E_{Vd}(t,v) \leq\ E_V(t-1,v) \qquad \forall\ v \in V, \forall\ t \in T \qquad (2.22)$$

$$E_V(t,v) =\ E_V(0,v) + \sum_{t' \leq t} (E_{Vc}(t',v) -\ E_{Vd}(t',v)) - \sum_{t' \leq t} \sum_{n(v) \in N_V(v)} E_{Vout}(t', v, n(v)) \qquad \forall\, v \in V, \forall\ t \in T \quad (2.23)$$

$$E_V(t,v) \leq\ E_{Vmax}(v) \qquad \forall\ v \in V, \forall\ t \in T \qquad (2.24)$$

$$\sum_{bV(v,n(v)) \leq\, t \leq eV(v,n(v))} I_{Vc}(t,v) = 0 \qquad \forall\, n(v) \in N_V(v), \forall\ v \in V \qquad (2.25)$$

$$\sum_{bV(v,n(v)) \leq\, t \leq eV(v,n(v))} I_{Vd}(t,v) = 0 \qquad \forall\, n(v) \in N_V(v), \forall\ v \in V \qquad (2.26)$$

Constraints (2.19-2.24) function similarly for electric vehicle as the Constraints (2.13-2.18) do for storage device. In constraint (2.23), energy usage at outside reduces electrical vehicle energy level. Constraints (2.25) and (2.26) prevent charge and discharge while the electric vehicle is out of home.

3.3.4 Controllable Appliances

The scheduling of the controllable applications is modelled as shown in Figure 3.4:

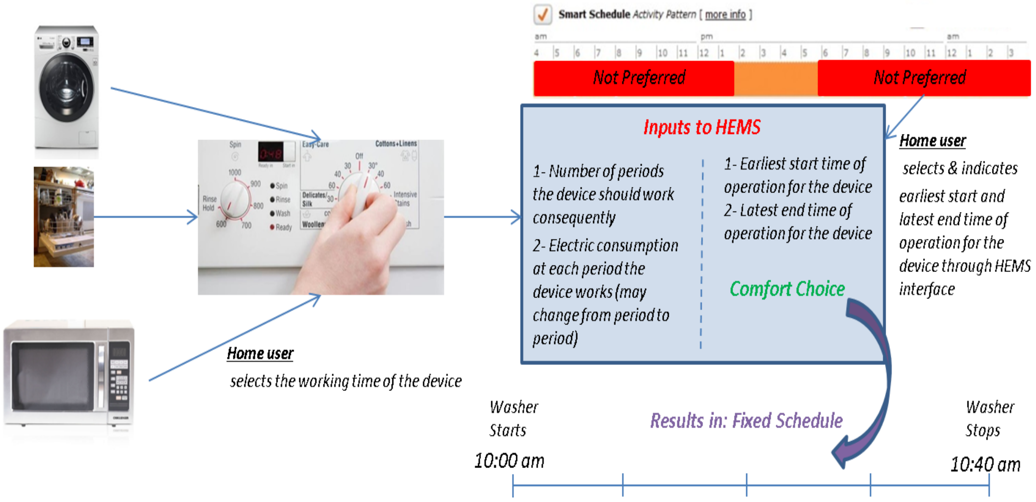


Figure 3.4: Controllable Appliances Model

Below, the decision variables are defined;

$y_C(t, c, n(c))$: 1 if appliance $c \in C$starts in period $t \in T$ at usage $n(c) \in N_C(c)$, 0 o.w.,

and the parameters are defined as follows:

$D_C(c, n(c))$: work duration of appliance $c \in C$ in number of periods at usage $n(c) \in N_C(c)$

$b(c, n(c))$: earliest start time for appliance $c \in C$ at usage $n(c) \in N_C(c)$

$e(c, n(c))$: latest stop time for appliance $c \in C$ at usage $n(c) \in N_C(c)$

Thus, the following constraints are needed to schedule the controllable applications:

$$\sum_{b(c,n(c)) \leq t \leq e(c,n(c))} I_C(t, c, n(c)) = D_C\big(c, n(c)\big) \;\; \forall\, c \in C, \forall\, n(c) \in N_C(c) \quad (2.27)$$

$$\sum_{b(c,n(c)) \leq t \leq e(c,n(c))} y_C(t, c, n(c)) = 1 \qquad \forall\, c \in C, \forall\, n(c) \in N_C(c) \quad (2.28)$$

$$\sum_{t \leq t' \leq t + D_C(c,n(c)) - 1} I_C\big(t', c, n(c)\big) \geq D_C\big(c, n(c)\big)\, y_C\big(\mathrm{t}, \mathrm{c}, \mathrm{n(c)}\big)$$

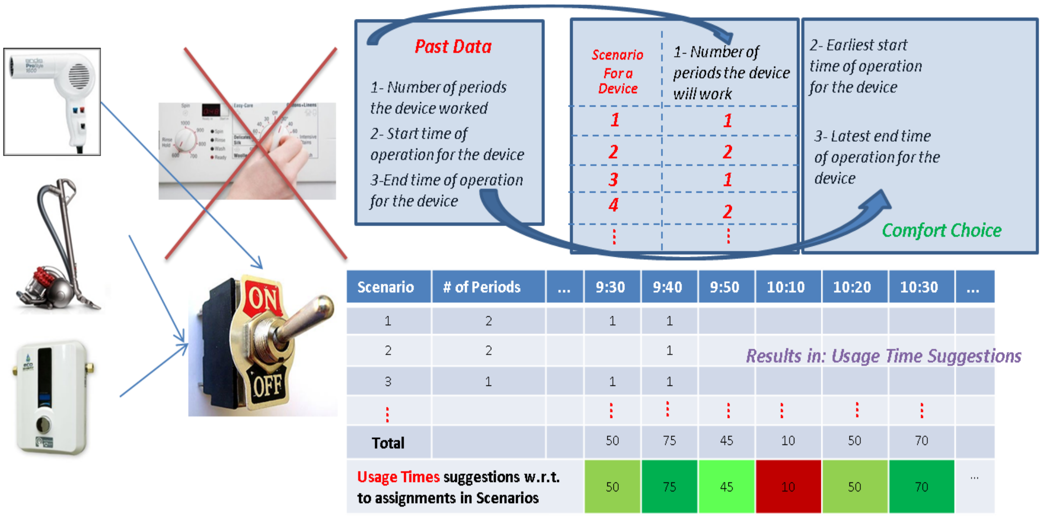
$$\forall\, c \in C, \forall\, t \in T : t \leq T - D_C\big(c, n(c)\big), \forall\, n(c) \in N_C(c) \quad (2.29)$$

$$\sum_{n(c)=1}^{|N_C(c)|} I_C\big(t,c,n(c)\big) \le 1 \qquad \forall\, c \in C, \forall\, t \in T \qquad (2.30)$$

Constraints (2.27 and 2.29) ensure that the required work duration should be satisfied without any interruption. Constraints (2.30) ensure that an appliance can be in only one usage case at a time.

3.3.5 Uncontrollable Appliances

The model for scheduling of the uncontrollable applications is similar to the model for controllable applications.



Scenario For a Device	1- Number of periods the device will work
1	1
2	2
3	1
4	2
⋮	⋮

Scenario	# of Periods	...	9:30	9:40	9:50	10:10	10:20	10:30	...
1	2		1	1					
2	2			1					
3	1		1	1					
⋮			⋮	⋮	⋮	⋮	⋮	⋮	
Total			50	75	45	10	50	70	
Usage Times suggestions w.r.t. to assignments in Scenarios			50	75	45	10	50	70	...

Figure 3.5: Uncontrollable Appliances Model

Below, the decision variables are defined;

$y_U(s,t,u,n(u))$: 1 if appliance $u \in U$starts in period $t \in T$ in scenario $s \in S$ at usage $n(u) \in N_U(u)$, 0 o.w.,

and the parameters are defined as follows:

$D_U(s,u,n(u))$: work duration of appliance $u \in U$ in number of periods in scenario $s \in S$ at usage $n(u) \in N_U(u)$,

$b(s,u,n(u))$: earliest start time for appliance $u \in U$ at usage $n(u) \in N_U(u)$

$e(s,u,n(u))$: latest stop time for appliance $u \in U$ at usage $n(u) \in N_U(u)$

Thus, the following constraints are needed to schedule the uncontrollable applications:

$$\sum_{b(s,u,n(u)) \leq t \leq e(s,u,n(u))} I_U(s,t,u,n(u)) = D_U(s,u,n(u))$$

$$\forall\, u \in U, \forall\, s \in S, \forall\, n(u) \in N_U(u) \qquad (2.31)$$

$$\sum_{b(s,u,n(u)) \leq t \leq e(s,u,n(u))} y_U(s,t,u,n(u)) = 1$$

$$\forall\, u \in U, \forall\, s \in S, \forall\, n(u) \in N_U(u) \qquad (2.32)$$

$$\sum_{t \leq t' \leq t + D_U(s,u,n(u)) - 1} I_U(s,t',u,n(u)) \geq D_U(s,u,n(u))\, y_U(s,t,u,n(u))$$

$$\forall\, u \in U, \forall\, s \in S, \forall\, t \in T : t \leq T - D_U(s,u,n(u)), \forall\, n(u) \in N_U(u) \quad (2.33)$$

$$\sum_{n(u)=1}^{|N_U(u)|} I_U(s,t,u,n(u)) \leq 1 \qquad \forall\, u \in U, \forall\, t \in T, \forall\, s \in S \qquad (2.34)$$

All of the constraints above (Equations 2.31-2.34) function as Constraints (2.27-2.30) do, for the applications, which are not controllable by the system. Note that, differently, uncontrollable applications depend on the scenario.

CHAPTER 4

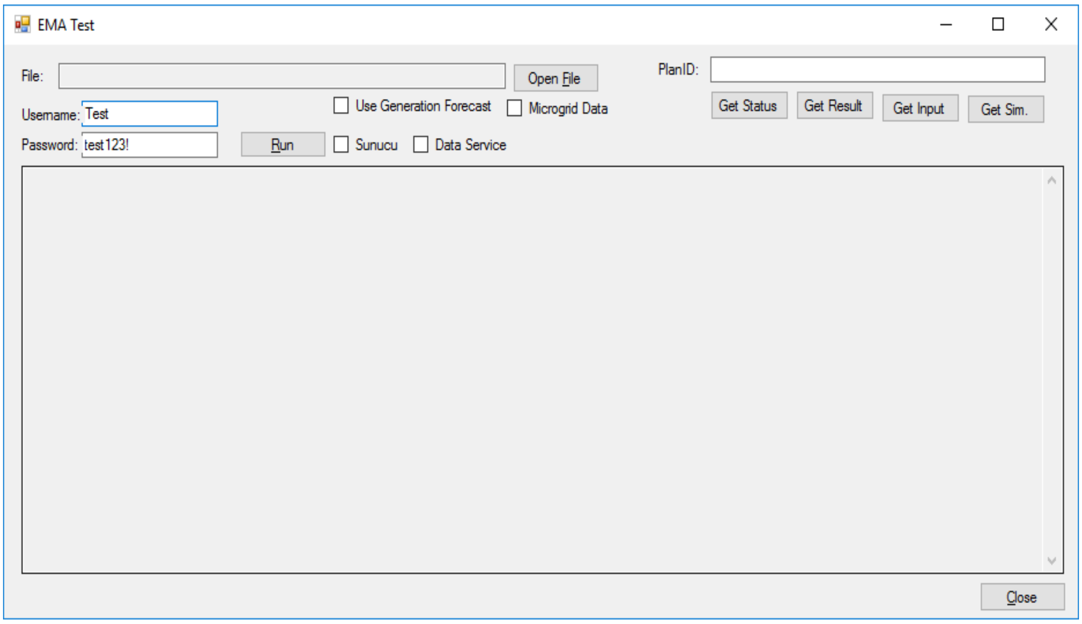
SOFTWARE DEVELOPMENT

Five applications has been developed: 1 - User Interface, 2 - ASP.Net WCF Restful Web Service, 3 - Optimization Console, 4 - Chart Module and 5 - Simulation. These five applications will be describef in this Chapter one by one, respectively.

4.1 User Interface

User Interface is a simple windows form application as seen in Figure 4.1. It imports an excel file and decodes the uploaded excel file to class data. After saving the input to the server database successfully, web service gives a unique number, unique identifier, describing the entire plan entity. In application message panel, the plan unique number or validation error message can be seen.

The status and result of plan can be queried by filling “PlanID” text control and hitting “Get Status” or “Get Result” button in the left side of form. The result of query can be seen on the message panel to follow the status of the plan or get information about the plan’s input data errors.



Username: Test

Password: test123!

☐ Use Generation Forecast ☐ Microgrid Data

☐ Sunucu ☐ Data Service

Figure 4.1: User Interface

4.2 ASP.Net WCF Restful Web Service

A web service is a function that is accessible via standart web protocol, http or https. XML and Json are the most common used formats to support transaction between the server and client. The Rest (Representational State Transfer) technology is simple and popular in developing web services, because it does not need the client to know anything about structure of web services. ASP.Net Web API is an ideal platform for building restful services.

There are three methods in this developed web service. The web service is published and available for usage on the following address and the snapshot is provided in Figure 4.2. Appendix C describe the format of web service request and response Json data.

(https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc/help)

Operations at https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc

This page describes the service operations at this endpoint.

Uri	Method	Description
/GetScheduleInput/{PlanID}	GET	Service at https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc/GetScheduleInput/{PLANID}
/GetScheduleResult/{PlanID}	GET	Service at https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc/GetScheduleResult/{PLANID}
/GetScheduleStatus/{PlanID}	GET	Service at https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc/GetScheduleStatus/{PLANID}
/ScheduleHomeResources	POST	Service at https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc/ScheduleHomeResources
/ValidatePlanData	POST	Service at https://seasdemo.innova.com.tr/HemsOptServices/OptimizationService.svc/ValidatePlanData

Figure 4.2: Web Service

ScheduleHomeResources: This method takes Json type of plan input data to save input to the database. Before saving the data, it validates the input data by using input validator layer. For example, each usage period of specific home devices cannot be intersect with the usage of the same device. Earliest start time period and latest stop time period data should obey this basic rule. The method returns “succesfully saved” message with plan’s identification number or “not saved” message with error information.

GetScheduleStatus: This method takes plan identification number. There are four types of status: 1- saved (not scheduling yet), 2- scheduled (has an optimal result), 3- scheduling (optimization console try to solve plan, but not finished yet), and 4- error (saved, when scheduling, optimization console gave an error and stopped to solve it). The method returns one of these status types.

GetScheduleResult: This method takes plan identification number. If the status of the plan is scheduled, then there is an optimal solution and it returns Json type of plan results.

To reach the methods, the user should be registered on the authorized user list. Service authentication is based on an authentication layer service using ASP.Net Membership framework. To reach SQL database, MS Sql 2012 version database layer was developed. It uses the Entity Framework which is a popular Net ORM (Object Relational Mapping) technology. In Appendix D, Database diagram is provided.

4.3 Optimization Console

This console is an application that runs on the server side. It tries to solve a plan, with the ILOG CPLEX (version 12.6.1) C# Api. After solving a plan, it takes the next plan in the queue and starts to solve. The pseudo code, summarizing working principles of the optimization console, is described below at Figure 4.3.

```
Database.Listen() //Console application periodically listen database and query new
//plans
{
        List<Plan> PlanList=GetPlan(Status.Saved); // Get only saved plans

        for (i=1;i<=PlanList.Count;i++)
        {
                CreateModel(); // Create optimization model for each plan
                {

                        List<Scenario>(PlanData.nScenarios)ScenarioList=
                        GenerateScenarios(); // Produce random variable list from
                        //the plan stochastic variables

                        CreateDesicionVariables(); //Create model decision
                                        variables, //integer or binary
                        AddObjective(); // Add objective function to optimization
                        model, // for scenario based parameters, it uses
                        ScenarioList
                        AddConstraints(); // Add model constraints to optimization
                        model
                        {
                                AddBalanceConstraint();
                                AddStorageConstraints();
                                AddControllableApplianceConstraints();
                                AddUnControllableApplianceConstraints();
```

```
                AddGridConstraints();

                AddElectricVehicleConstraints();

                AddAirConditionerConstraints();

            }

            ExportModel() // Save cplex lp file to one specified folder

        }

        SolveModel(t); // Cplex runs, limit t seconds

        WriteOutput(); // Write results to txt file in one specified folder

        WriteSolution(); // Write results to server database, some of the
        //scenario based results reduced or eliminated

        UpdatePlanStatus(); // Update plan status, “Scheduled”, if cplex
        gives a //solution

    }

}
```

Figure 4.3: Pseudo Code for Optimization Model

4.4 Chart Module

Chart module shows the optimization model results. It uses Google Chart Api which is a user friendly tool. It has a cross browser feature and portability which adopts the module to the mobile environment easily. There are seven charts: 1 - Price Chart shows the information of price versus time, 2 - Energy Generation Chart shows the renewable energy resources generation versus time, 3 - Grid Chart shows sold and purchased energy amounts from the grid versus time, 4 - Storage Chart shows the energy level of the storage (home battery or the electric vehicle) versus time, 5 -Temperature Chart shows the temperature of the system versus time, 6 - Air Conditioner Chart shows the air conditioner’s energy consumption versus time, 7 - Gantt Chart shows applications usage results as; controllable, uncontrollable and continuous applications in gantt chart. For controllable applications, earliest start time, latest stop time and optimum working period can be seen in one block. For uncontrollable applications, an alternative working period, determined at the beginning of plan, where the results that have the same earliest start time and latest stop time, can be displayed on different blocks. The chart module can be called as putting planID at the end of web adress in the format below: https://seasdemo.innova.com.tr/SeasChartWeb/PriceChart.html?PlanID={PlanID}

4.5 Simulation

The simulation framework has been developed on a Java platform. It is used to validate the performance of the mathematical model. The system is illustrated in Figure 4.4:

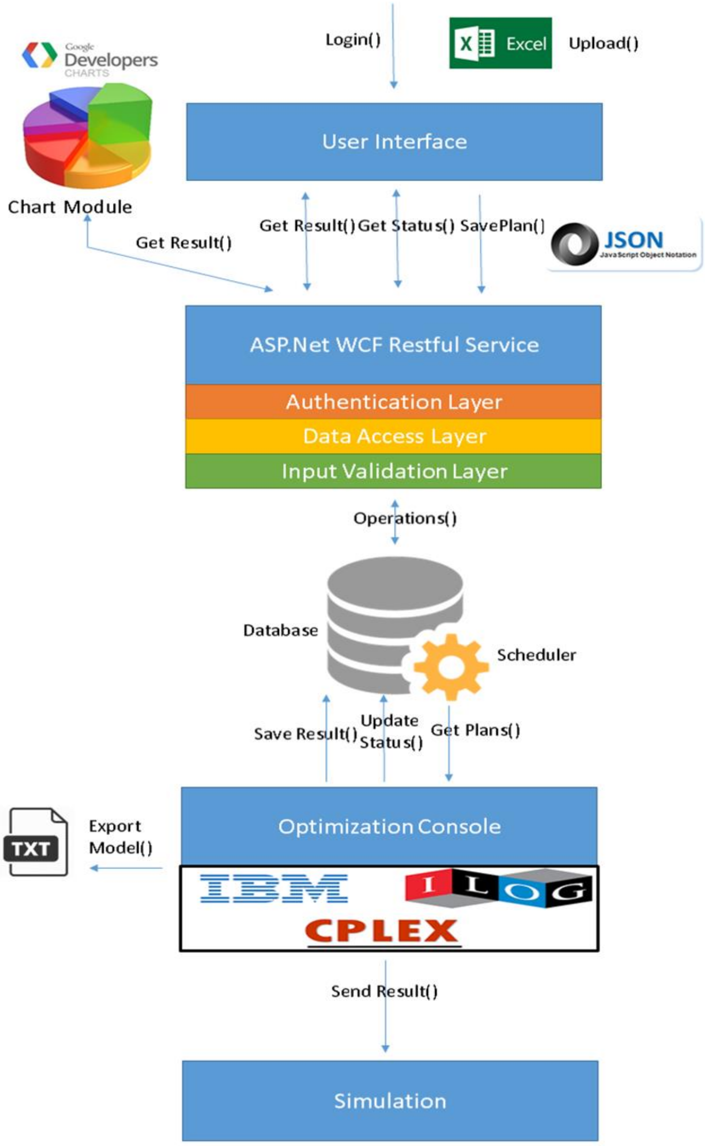


Figure 4.4: System Architecture of Applications

CHAPTER 5

NUMERICAL EXPERIMENTS

By conducting numerical experiments, we aim to investigate whether there is a significant benefit of utilizing the HEMS under the presence of uncertainty. Our mathematical model takes into account the uncertainty in prices, weather conditions and usage of the devices through the use of scenarios. First, we describe the settings for the experiments and then the results are presented. The explanations for the abbreviations used in this section are given in Table A.1 in the Appendix. Numerical experiments are run on a 64-bit computer possessing Intel(R) Xeon(R) CPU E5645 2.40 GHz, with 32 GB of memory and operated by Windows Server 2008 R2 Enterprise Edition.

5.1. Settings

We compare two cases of a green house in terms of energy consumption control. The first case deals with a house that has a home energy management system, while in the second case the same house is not supported by a decision support system. In the green house, there are 5 controllable, 7 uncontrollable and 2 continual appliances, a wind turbine, a solar panel, a storage device, an electric vehicle and an air conditioner.

In order to analyze the effect of price tariffs, the experiments are executed under three different price tariffs given in Figure 5.1. In these tariffs, the mean sale price to the grid is always less than the mean purchase price from the grid. Therefore, we have two patterns; either a constant pattern throughout the whole planning horizon or a fluctuating pattern mimicking the main trend in the purchase price. Purchase price from the grid is considered to have again two patterns; either a stepwise or a fluctuating version of the stepwise pattern. In Price Tariff 1, both the purchase and sale prices are fluctuating and the difference between them is small. In Price Tariff 3, the stepwise version of the purchase price in Tariff 1 is considered keeping the sale price same as in Tariff 1. And in Price Tariff 2, the purchase price is stepwise and the sale price is constant with a larger difference between them.

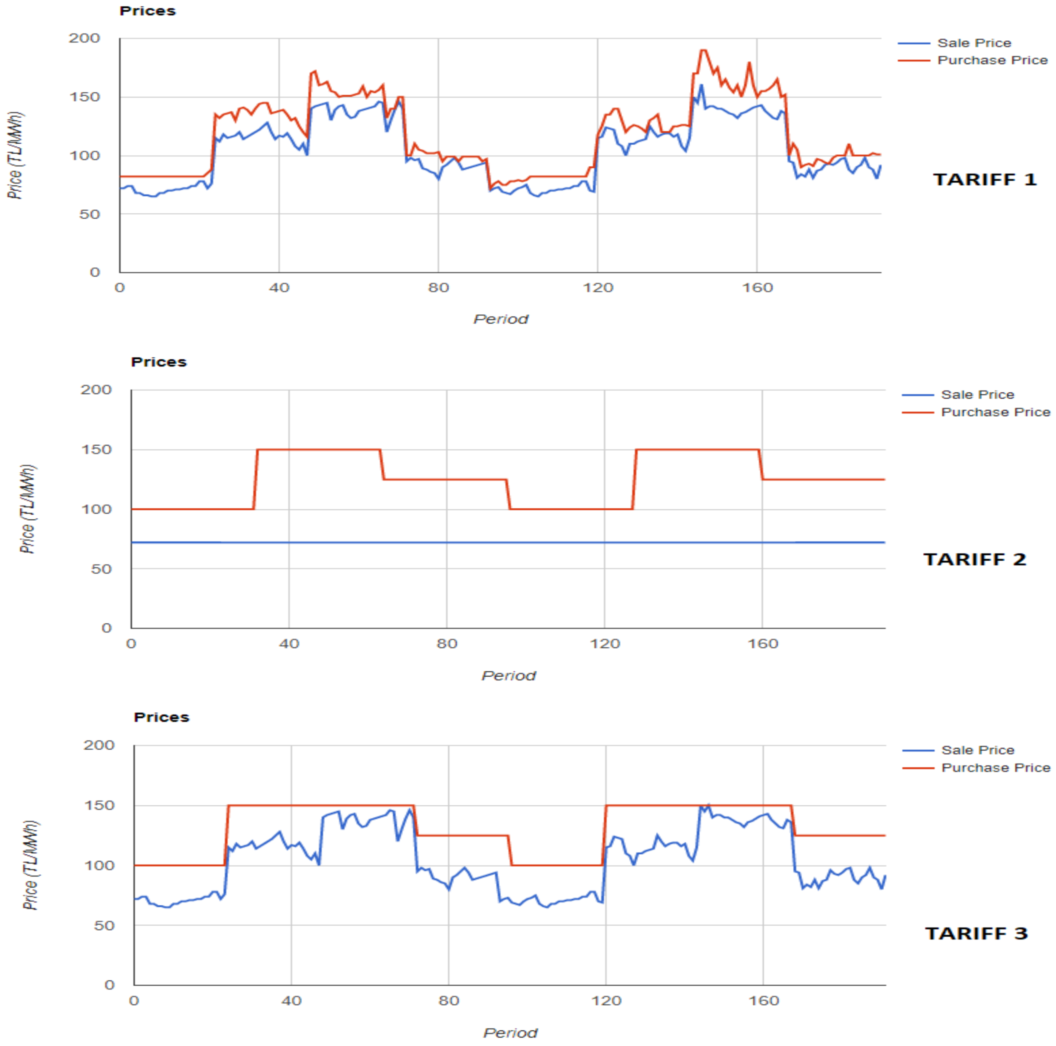


Figure 5.1: Mean Purchase and Sale Prices in Tariffs

The samples we utilize in the numerical experiments have the 2-day scheduling decision horizon consisting of 15-minute periods. Therefore, the planning horizon is 192 periods. For each price tariff, we solve the scheduling problem using the ILOG CPLEX (version 12.6.1) five times, starting with only one scenario and increasing scenario number up to 100, while limiting each run- time with a five-hour period.

When the schedules are obtained via optimization, then we simulate the 192 period decision horizon in JAVA using the same distribution parameters (for purchase and sale prices, wind and solar energy, solar radiation, external temperature, appliance usages) which are incorporated in the scenarios of the mathematical model. Since the decisions within the simulation are taken according to the optimal schedule, this simulation reflects the case of the green house supported by home energy management system.

Decisions taken from the optimal schedule and used in the simulation includes the usage periods of the air conditioner and controllable appliances, charge and discharge periods of the storage device and the electric vehicle. Since we assume that the user is absolutely free to use uncontrollable appliances any time within the given usage time intervals; the usage of an uncontrolled appliance is depending on the customer’s behavior in each scenario. Therefore, in simulation runs usage periods of those appliances are randomly determined using the same uniform distribution applied while creating the scenarios for the CPLEX model. Also the beginning periods of operation for controllable and uncontrollable appliances are randomly determined to such an extent that each work is completed without any interruption and within its corresponding ‘time interval’ as assumed in the green house model, with home energy management system support.

Since there is no decision support system in order to simulate the house without home energy management system, we need some additional assumptions and employ a series of rules about the energy storage/usage, purchase and sales. We assume that the wind turbine turns on whenever there is wind and the solar panel operates from morning to evening (when the sun is above the line of horizon). In case of energy surplus in a period, energy is stored first to storage device and then to the electric vehicle, if storage device is full. Whenever energy is needed, first stored energy is used, if this is not sufficient enough, the gap is filled by purchasing energy from the grid. Due to the general assumption of generated energy will be less than the required energy forthe house and no analysis on the future prices is considered, there is no reason for the consideration of energy sale for the house without home energy management system.

Also it is required to make some assumptions on the air conditioner's usage. Since there is an upper limit on the power for the air conditioner's consumption of the green house with home energy management system, regulating the inside temperature within the comfort level limits is managed by the home energy management system. However, it is not possible to pre-activate a decision support system for a green house. Therefore, to sustain the comfort in the green house without home energy management system, we remove the power limitation on the air conditioner. Each period; the expected inside temperature for the next period is checked to determine the role (heating or cooling) and the power is supplied by the air conditioner in the relevant period. The usage assumptions of wind turbine and solar panel is kept the same as adopted in the house with the home energy management system.

The characteristics of the controllable and uncontrollable appliances are presented in Table A.2 in the Appendix. The table is separated in two parts with respect to the type of appliances (controllable and uncontrollable). First two columns represent the appliance identity and consumption rate, while the remaining columns represent the parameters related to each usage associated with appliances. The time intervals where the operation of the appliances should take place are given in brackets in period numbers.

Each of the wind turbine and the solar panel needs two parameters; efficiency and depreciation costs as defined in the explanation of the mathematical model. Respectively, they are set to 30% and 0.01 TL/kWh for both of the generators. Parameters related to the storage device and the electric vehicle are presented in Table A.3 in the Appendix. We assume that the electric vehicle has three trips, having lengths of 4, 5 and 4 periods. The time intervals (in periods) that the electric vehicle may be out are [28-66], [80-94] and [144-160], respectively.

Model parameters that define the thermal characteristic of the building and air conditioner parameters are presented in Table A.4 in the Appendix. Daily thermal capacity coefficient which determines the heat capacity of the building is set to 80.000

$\mathrm{WsK}^{-1}\mathrm{m}^{2}$. We assume that the comfort level about the air temperature inside the home is between 18 and 22 degrees Celcius.

The parameters of the uniform distributions used to create the forecasted values for energy prices are presented in Table A.5 in the Appendix. The data used for the wind and solar energy generations in the single scenario model, forecasted outside temperature and fixed consumptions by continual appliances are provided in Table A.6 in the Appendix.

5.2. Results

5.2.1 The Comparison of the Systems “with” and “without” a HEMS

We simulate two days of two identical green houses “with” and “without” home energy management system, under the same experimental conditions. All of the simulations are carried out for 100,000 runs where each run can be considered to correspond to a scenario used in the mathematical model. Since the importance is not on the magnitude comparison, we do not assume a specific monetary measures.

First, we are focused on the green houses that are equipped with a HEMS. In such an equipped house, the schedules for the appliances, storage devices and the air conditioner are decided by the mathematical model via a certain number of scenarios. Due to the fact that as the scenario number used in the mathematical model increases, the required time to reach the optimal schedule increases exponentially, we consider up to 100 scenarios at most. At first glance, we observe from Figure 5.2 that, the average cost increases until we have 10 scenarios in the model. Increasing the number of scenarios employed in the mathematical model more does not effect the average cost significantly. In other words, if the experiment is run more than 10 scenarios, the average cost of the green house which uses home energy management system keeps the average cost within a certain range and does not follow an increasing or decreasing pattern with the increase in scenario numbers considered in the mathematical model. In Figure 5.2, value of point in the blue line is the average cost of all experiments that have same number of scenarios and price tariffs, and the label above the point shows the standart deviation of these experiment costs. The value of standart deviation decreases when the number of scenarios increases, in all price tariffs. The result of the experiment shows that, costs get closer to each other as the number of scenario increases.

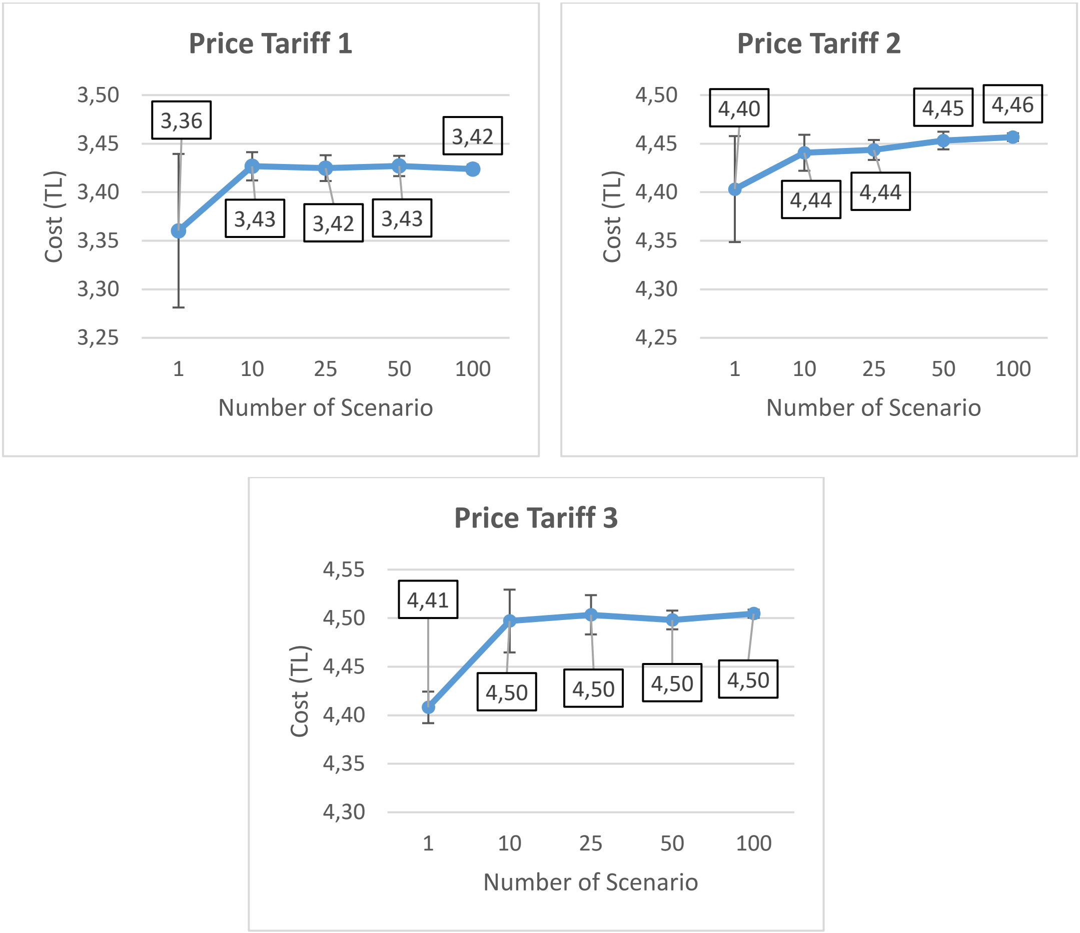


Figure 5.2: The Result of Optimization Model

We limit the runtime of the optimization model to five hours. With respect to the price tariff, we note that the runtime grows exponentially with the size of the number of scenarios in Figure 5.3. The optimization run time hit the time limitation, two times in price tariff 2 with 100 scenarios and three times in price tariff 3 with 100 scenarios . The optimality gap for the optimal solutions obtained at the time limitation are; %0.015, %0,023 for price 2, %0.049, %0.019, %0015 for price 3 in those cases.

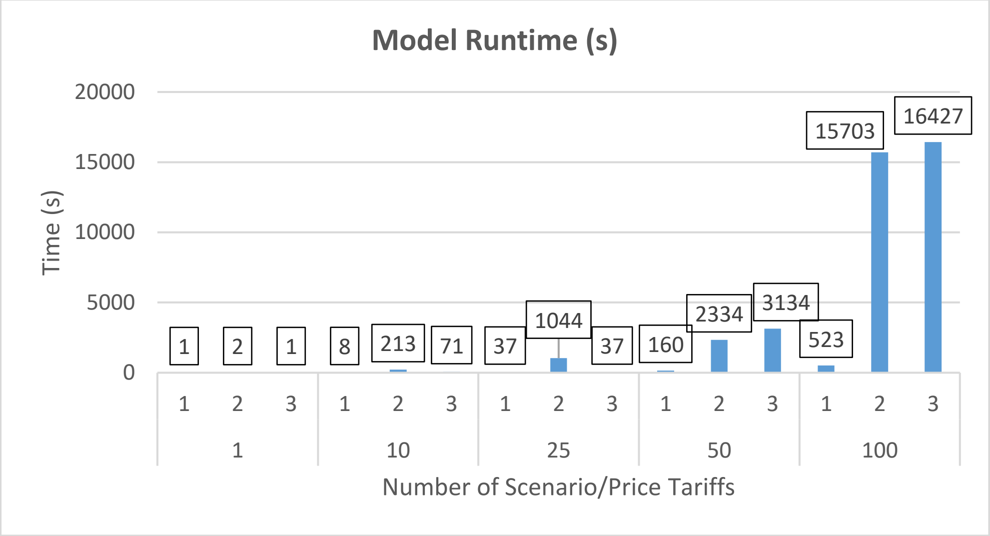


Figure 5.3: Optimization Model Runtime

As observed from the graphs given in Figure 5.4, according to the simulation runs, average costs of a green house with HEMS are roughly 3.58 for Price Tariff 1, 4.54 for Price Tariff 2 and 4.60 for Price Tariff 3 after 10 number of scenarios. In the graph, mean value and standart deviation of the simulation results can be displayed.

Figure 5.4: The Results of the Simulation

From the simulation of the other green house, which has no decision support mechanism, we obtained the corresponding costs as 5.50, 5.94 and 6.23, respectively for three price tariffs in the given order. The house without HEMS does not store energy to keep or sell later. Even if storage occurs in a period because of surplus, it is consumed primarily whenever energy is needed. Therefore, if we disregard the effect of randomness in the parameters related to wind turbine, solar panel and usage patterns of appliances; the purchase price of energy determines the cost incurred by the house without HEMS.

Therefore, a consumer can decrease the energy bill -at least- by one fourth with the usage of a HEMS. In Figure 5.5, The house “with” or “without” a model can be compared easily. %35, %24, %26 cost reduction can be achieved by the optimization model in the given order.

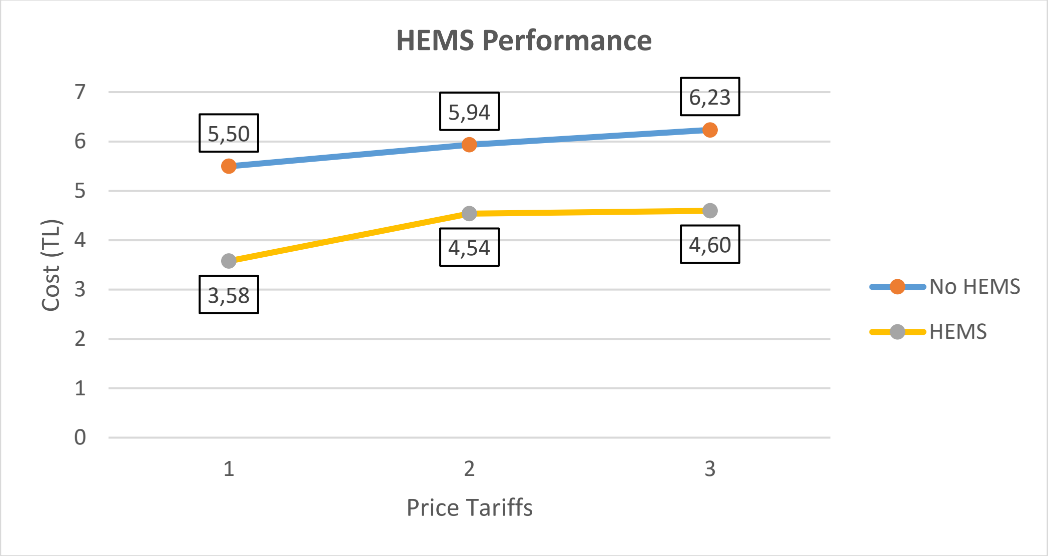


Figure 5.5: The Comparison of Simulation with HEMS and No HEMS

5.2.2 The Deterministic Method Results

We run deterministic scenarios for each price tariff to validate the system and compare results with stochastic scenarios. First, we solved three deterministic models which has taken one second by the optimization model. To validate the consistency between the optimization model and the simulation, we compare the cost of the optimization model and the simulation in equal deterministic conditions. Then, we put decision variables on the simulation to evaluate the solution before continuing with the stochastic experiments. Two options are considered in the simulation: the first is the one where the uncontrollable appliance’s starting periods are determined by the optimization model, the second is the one where the uncontrollable devices run randomly between the earliest and latest time period. The summary of results is shown in Table 5.1.

The result of the optimization model is too close to the result of the simulation without randomness, in all price tariffs. Therefore, the main factor of the difference between the optimization model and the simulation seems to be the randomness in use of the uncontrollable appliances.

The stochastic model is more compotent than the deterministic model in handling variations in the uncontrollable devices’ usages. This capability depends on the difference between the purchase and the sale prices. In price tariff 1, the deterministic model results are very close to the best stochastic result, because price difference is so small. In price tariff 2, the stochastic model gives better solutions than the deterministic model, since price diffence is larger than the other tariffs. In price tariff 3, the stochastic model is a little less cheaper than the deterministic model.

We use uniform distribution for incorporating the stochasticity in our experiments. However, in a real life case, stochasticity should be represented by more complex scenario and distributions which take into account dependence between multiple parameters.

Table 5.1: Deterministic Scenarios’ Results

Price Tariffs	**Optimization Model**	**Simulation with determined uncontrollable appliances parameter**	**Simulation with random uncontrollable appliances parameter**
1	3,4797	3,4799	3,5756
2	4,4790	4,4812	4,5620
3	4,5543	4,5552	4,6089

5.2.3 The Analysis of Experiment Results

When we compare the optimal schedules for all three of the price tariffs, we see that the energy generation is not affected with respect to the price tariffs as expected, while energy storage, purchase and sale patterns change. In Figure 5.6, it is observed that the energy generation lines are fluctuant when the scenario numbers are smaller. The same conditions can be observed at Figure 5.7. We consider that the reason of this fact is due to the plots that are approaching to the median value as the number of scenarios increases.

In this section, we also analyze the cost components, the purchase/sale amounts from grid, the energy levels of storage and PHEV, the air conditioner's consumption and the usage of the appliances. In order to analyse effect of air conditioner and storage which are critical components in terms of their consumption rate and arbitrage capabilities respectively, we experiment the scenarios only with those components.

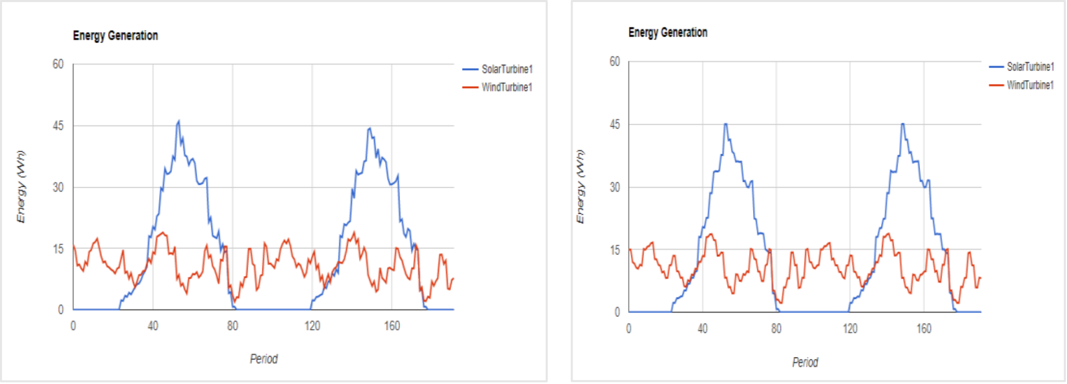


Figure 5.6: Energy Generation (1-50 Scenario)

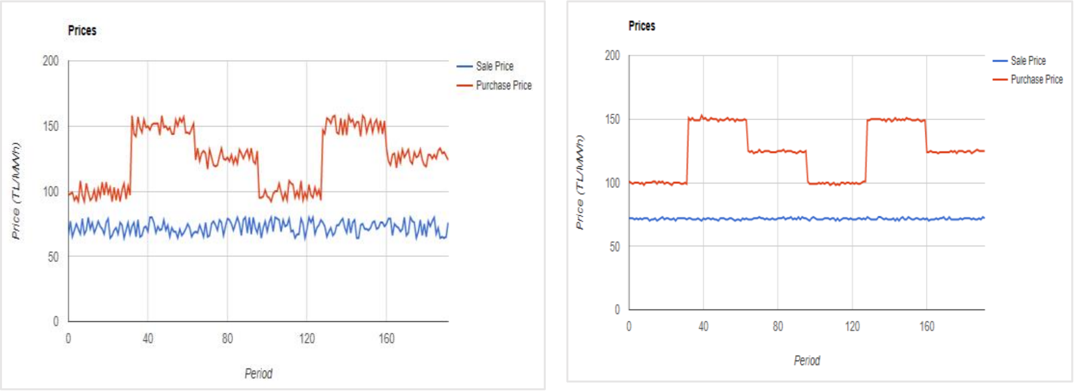


Figure 5.7: Purchase and Sale Prices in Tariff 2 (1-50 Scenario)

The result of the experiments, conducted for each price tariff, are shown at Table E.1 in the Appendix where (*) stands for the best and the worst experiments based on simulation cost.

5.2.3.1 Analysis on The Cost of Energy

Figures 5.8-10 show the energy cost observed in the simulation results, each figure has three charts: purchase cost, sale revenue and depreciation cost versus the number of scenarios for one price tariff.

At Figure 5.8 , which shows the results for the price tariff 1, the purchase cost and the sale revenue numbers decrease until 25 scenarios and then start to take a stable position.

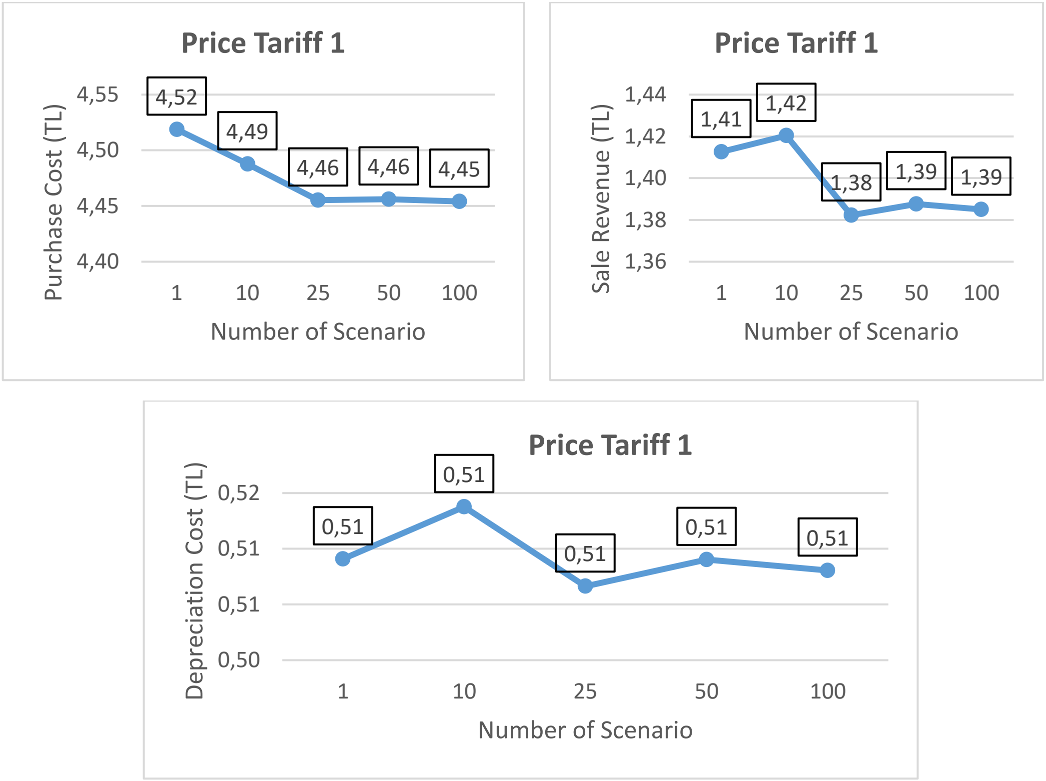


Figure 5.8: The Cost Components of Price Tariff 1

At Figure 5.9, which shows the results for price tariff 2, all the purchase cost, sale revenue and depreciation cost numbers are decreased until 10 scenarios and then becoming stable .

At Figure 5.10, which shows the results for price tariff 3, both the purchase cost and the sale revenue decreases with the increase in the number of scenarios. When we observe the depreciation cost, it also decreases until scenario 25, then becomes stable.

It can be observed that, the most expensive purchase cost occurs for tariff 3 while the cheapest one is seen in the results for tariff 2. Purchased energy amount and the purschasing price are two determining factors in this result. Even though the purchased energy amount at price tariff 1 is higher than that of price tarif 3; the median/average purchasing price is lower at tariff 1.

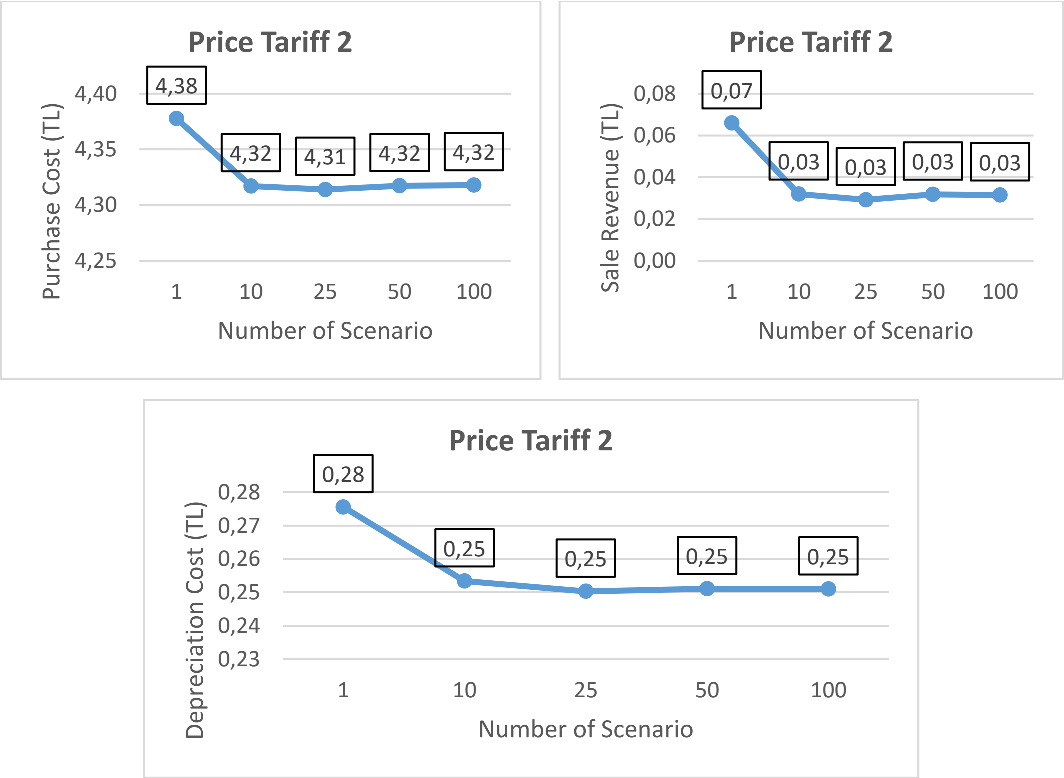


Figure 5.9: The Cost Components of Price Tariff 2

When sale revenue is considered; the highest price occurs at price tariff 1, followed by tariff 3 and tariff 2. As verified by the result, since the sales price is low and the difference between the purchase price and sales price is high at price tariff 2, it seems that it is more useful to consume the energy at domestic consumption. On the other hand, due to lower price difference and fluctations at price tariff 1, selling energy is more profitable. Price tariff 3 is between these two points.

Depreciation cost is specified by energy generation and storage charge/discharge amount. While the energy generation part is considered as fixed, the rest is directly proportional to the usage of the storage. The depreciation cost values from high to low are observed in the results for price tariff 1, price tariff 3 and price tariff 2, respectively.

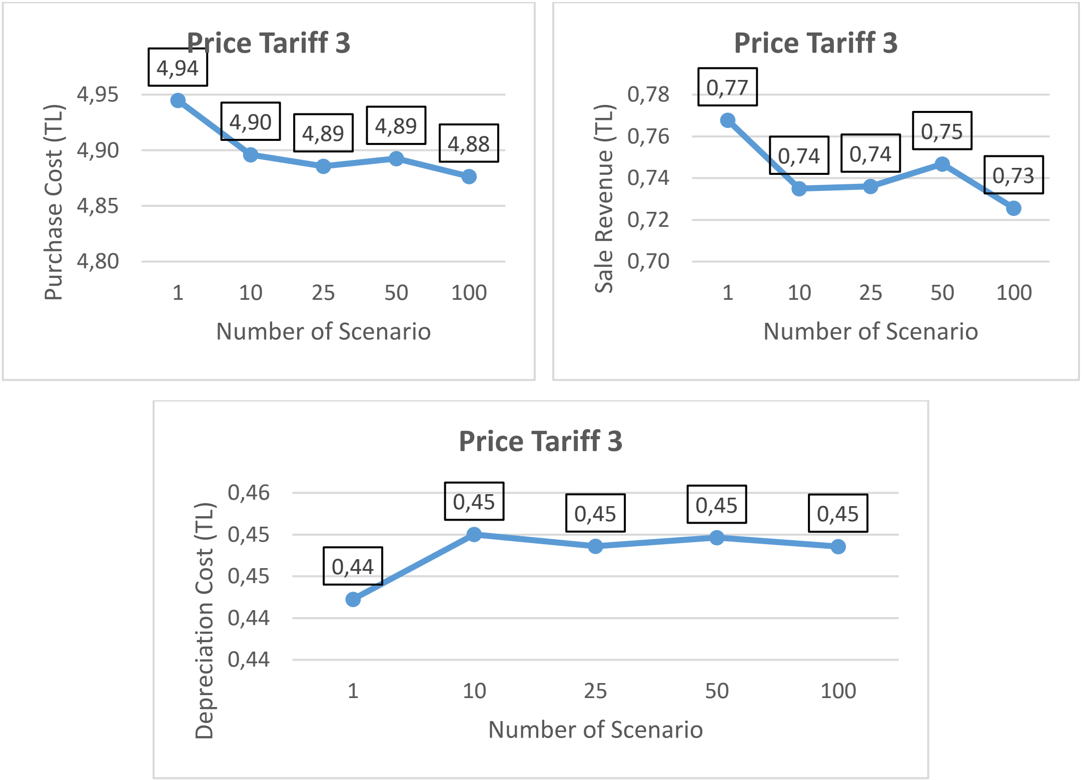


Figure 5.10: The Cost Components of Price Tariff 3

5.2.3.2 Analysis on the Amount of Energy Sold/Purchased

Figures 5.11, 5.12 and 5.13 show the grid sale/purchase amounts of the optimization model results, according to price tariffs 1, 2 and 3, respectively. The charts, beginning with the top left and in the clockwise direction, show (1) the avarage amount of energy purchased from the grid, (2) the average amount of energy sold to the grid, (3) the grid sale/purchase amount observed in the results of the best experiments (4) the grid sale/purchase amount observed in the results of the worst experiments.

As observed in Figure 5.11, corresponding to price tariff 1, both the purchase amount and the sale amount decreases until 25 scenarios, and then it becomes stable. It is observed that the system purchases and stores energy at the time intervals when purchasing price is low [0-25,80-120] and sell the stored energy at the time intervals when purchasing price is high [50-70, 144-170]. This pattern also validates the developed mathematical model's accuracy.

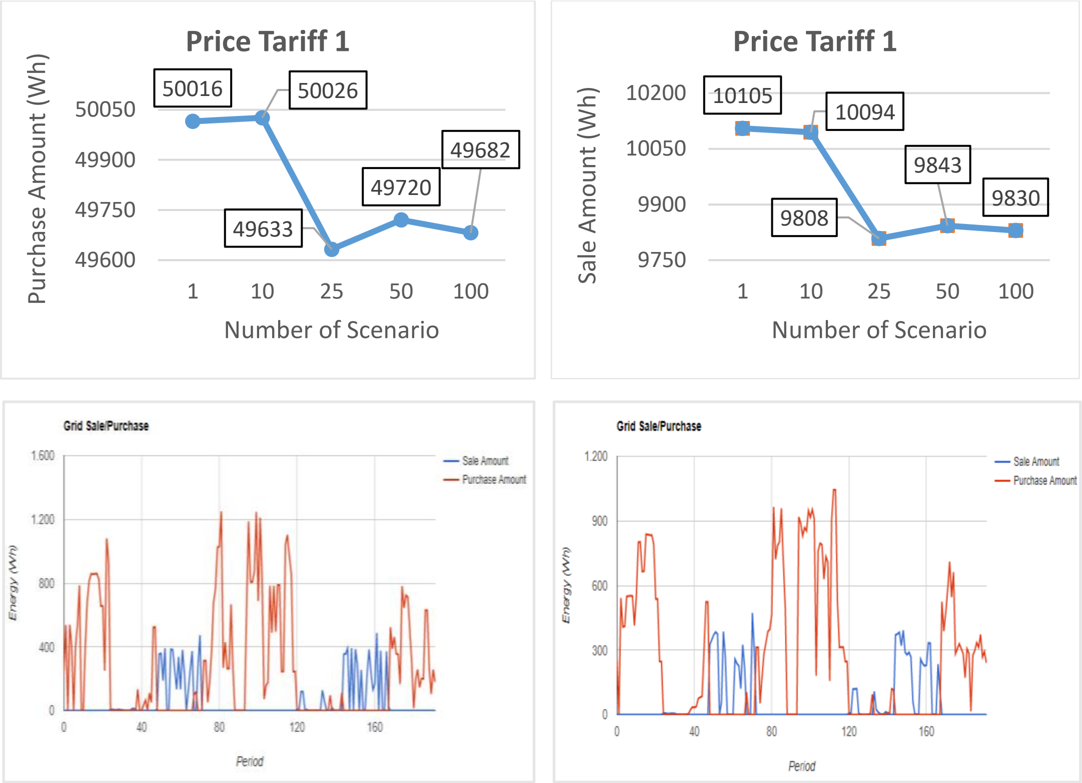


Figure 5.11: Price Tariff 1 Sale/Purchase Amount

As observed in Figure 5.12, corresponding to price tariff 2, both the purchase amount and the sale amount decreases until 10 scenarios, and then it becomes stable. The energy sale is not observed much under price tariff 2 due to the low sale prices in the market.

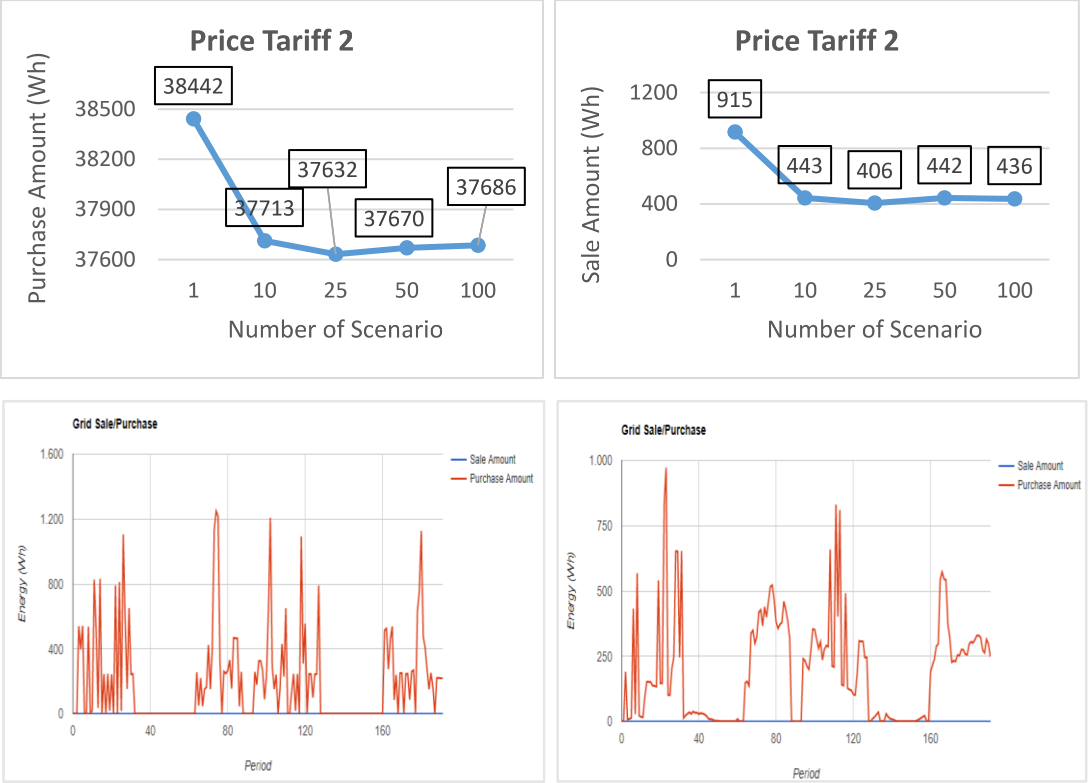


Figure 5.12: Price Tariff 2 Sale/Purchase Amount

As observed in Figure 5.13, corresponding to price tariff 3, purchase amount and sale amount slightly decreases as the number of scenario increases. Two highest energy cost intervals are observed within the intervals 24 to 71 and 120 to 167. In these periods, a very small amount energy is purchased from the grid.

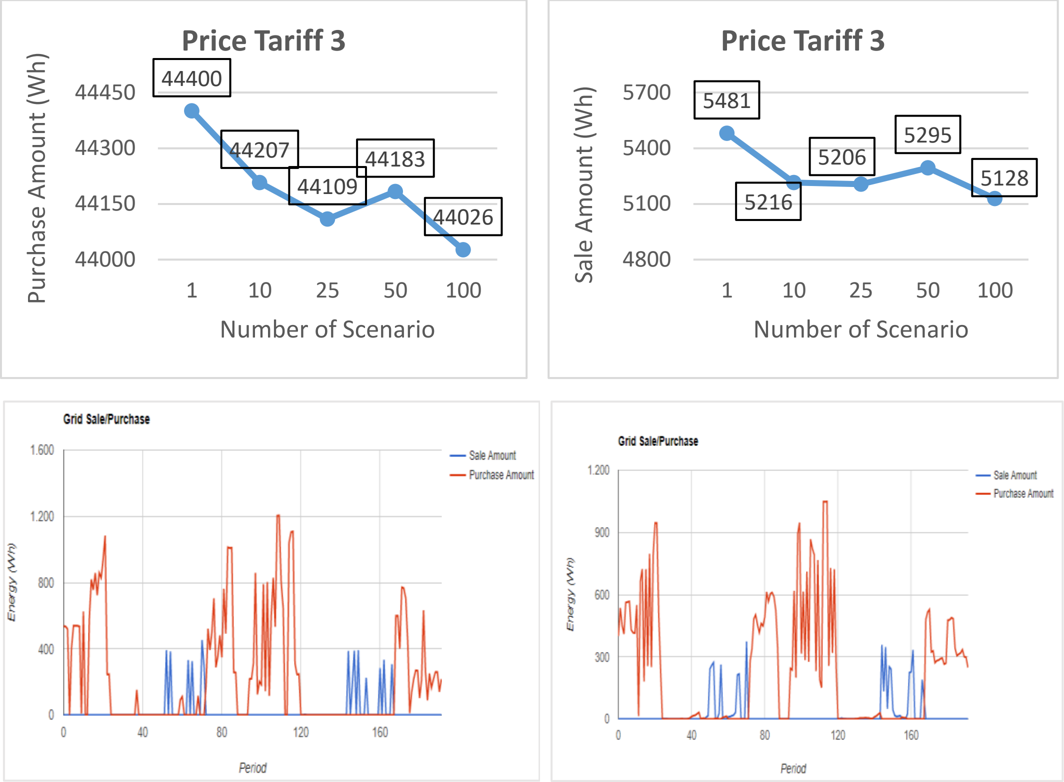


Figure 5.13: Price Tariff 3 Sale/Purchase Amount

We have seen that the most purchasing and sale is experienced at expensive price tariff 1, followed by tariff 3 and tariff 2.

5.2.3.3 Analysis on The Charged/Discarged Energy Amount by Storage Device and PHEV

Figures 5.14, 5.15 and 5.16 show the charged amount of energy by storage device and PHEV according to the optimization model results. The charts, beginning with the top left and in the clockwise direction, show (1) the energy amount that is charged by the storage, (2) the energy amount that is charged by PHEV, (3) the storage/PHEV energy level amount observed in the results of the best experiments, (4) the storage/PHEV energy level amount observed in the results of the worst experiments.

As observed in Figure 5.14, corresponding to price tariff 1, amount of the charged energy by storage device decreases until 25 scenarios, and then it becomes stable, while amount of the charged energy by PHEV increases until 10 scenarios. It is observed that the storage device charges and stores energy at the time intervals when purchasing price is low [0-25,80-120] and discharges the stored energy at the time intervals when purchasing price is high [50-70, 144-170].

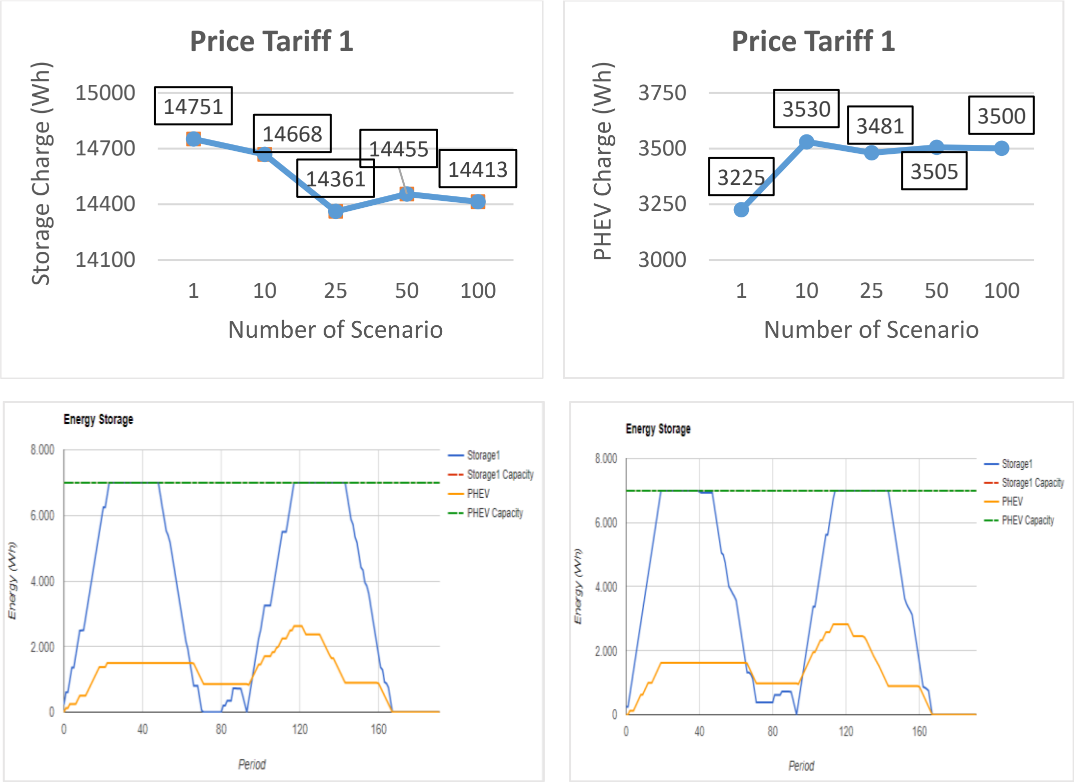


Figure 5.14: Price Tariff 1 Storage Amount

As observed in Figure 5.15, corresponding to price tariff 2, amount of the charged energy both by storage device and PHEV decrease until 25 scenarios, and then it becomes stable. It is observed that the storage device charges and stores energy at the time intervals when purchasing price is low [0-31,96-127] and discharges the stored energy at the time intervals when purchasing price is high [34-63, 128-160].

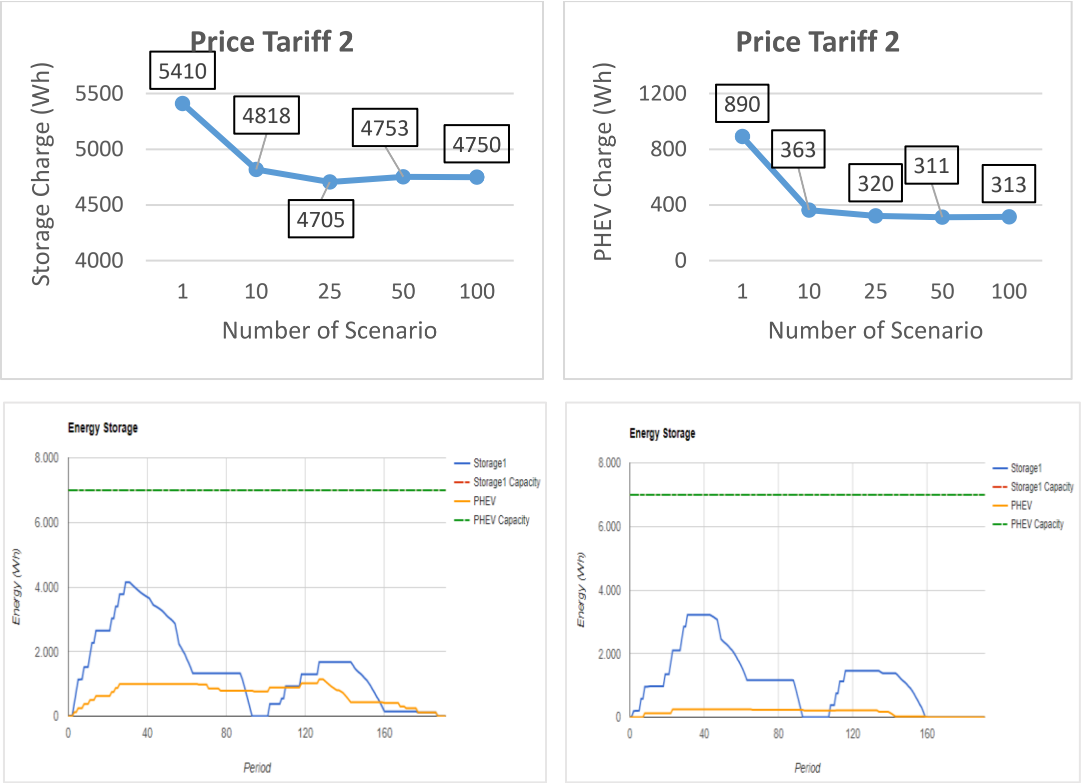


Figure 5.15: Price Tariff 2 Storage Amount

As observed in Figure 5.16, corresponding to price tariff 3, amount of the charged energy by storage device increases until 50 scenarios, and then it becomes stable, while amount of the charged energy by PHEV increases until 25 scenarios. It is observed that the stored energy is used at the time intervals when purchasing price is high like periods [24-71, 120-167].

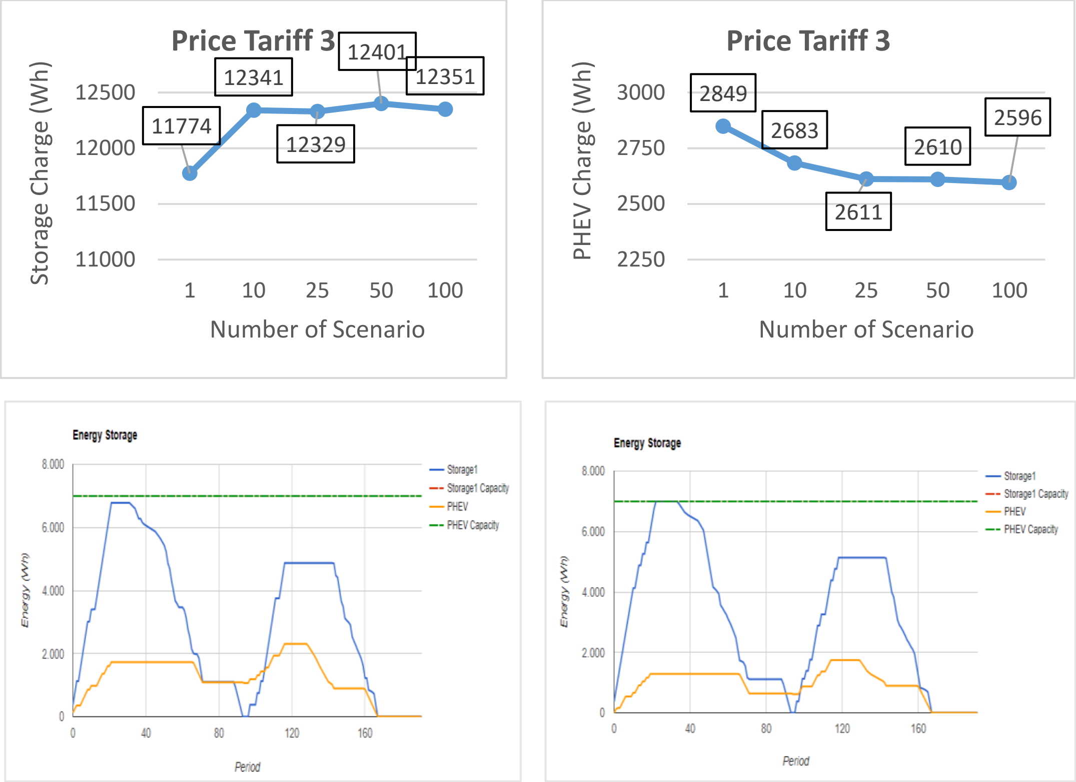


Figure 5.16: Price Tariff 3 Storage Amount

When looked up to the top three figures; we see that the most storage and PHEV usage is realized at price tariff 1 then comes tariff 3 and at the end tariff 2 comes. The storage's charge and discharge periods are cohorent with the buying and selling prices.

We have seen that the storage device and PHEV usage is experienced mostly at price tariff 1, followed by tariff 3 and tariff 2. The periods of charge and discharge are cohorent with buying and selling prices.

5.2.3.4 Analysis on The Air Conditioner Consumption

Figures 5.17, 5.18 and 5.19 show the air conditioner's energy consumption according to the optimization model. The chart on the top shows the consumption as the number of scenarios increases, while the charts on the lower left and right show the consumption observed in the results of the best experiments and the worst experiments respectively.

As observed in Figure 5.17, corresponding to price tariff 1, amount of the consumed energy by air conditioner decreases until 25 scenarios, and then it becomes stable. When we compare the consumptions in the best and worst experiments, it is observed that the consumption graph for the best experiments is more regular.

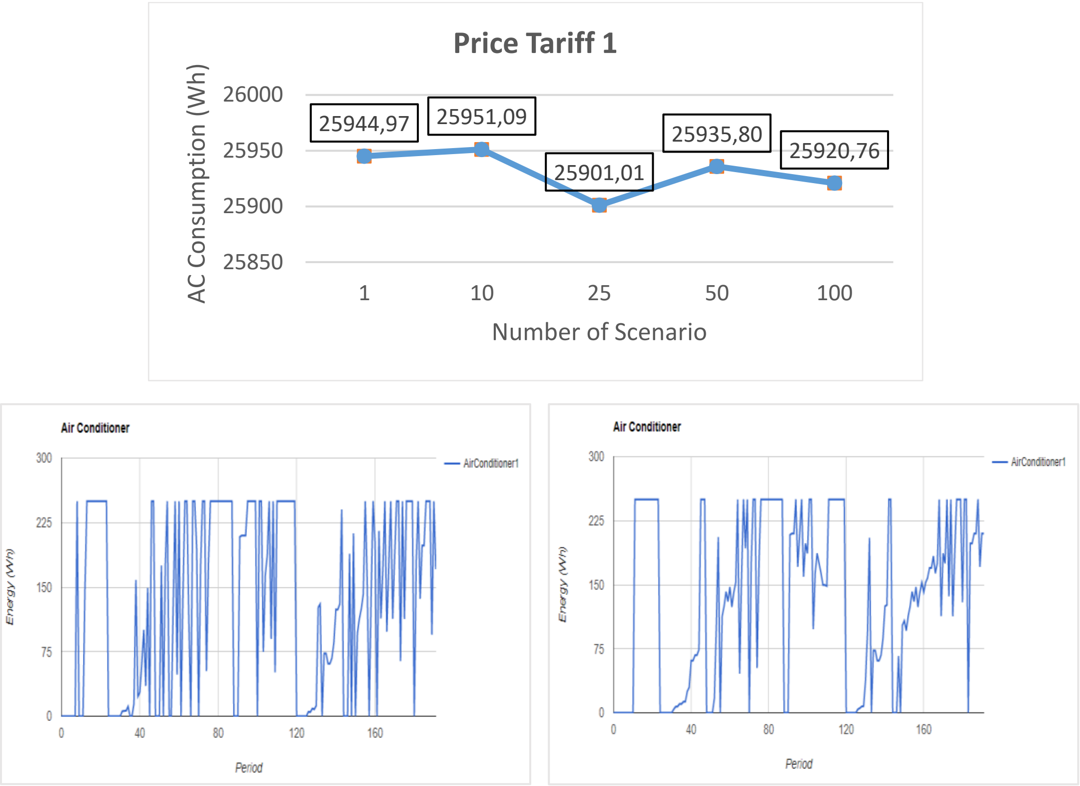


Figure 5.17: Price Tariff 1 Air Conditioner Consumption

As observed in Figure 5.18, corresponding to price tariff 2, amount of the consumed energy by air conditioner decreases slightly as the number of scenarios increases. When we compare the consumptions in the best and worst experiments, it is observed that the consumption graph for the best experiments is more regular.

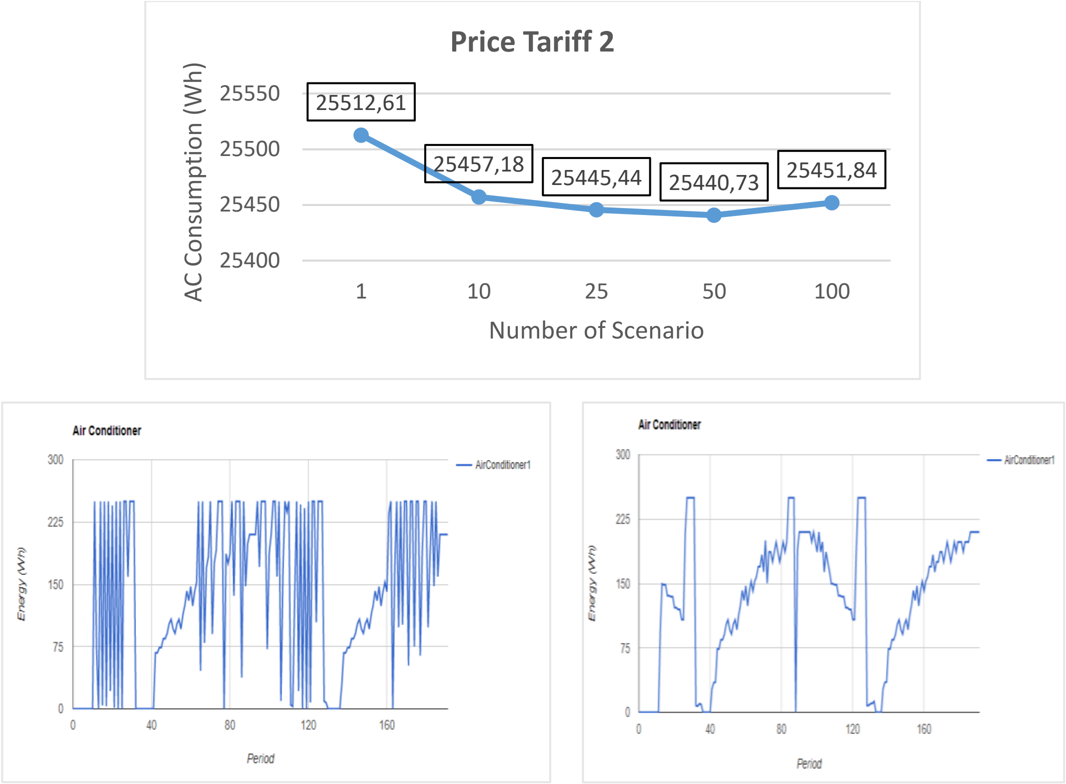


Figure 5.18: Price Tariff 2 Air Conditioner Consumption

As observed in Figure 5.19, corresponding to price tariff 3, amount of the consumed energy by air conditioner decreases slightly as the number of scenarios increases up to 50 scenarios. When we compare the consumptions in the best and worst experiments, it is observed that the consumption graph for the best experiments is more regular.

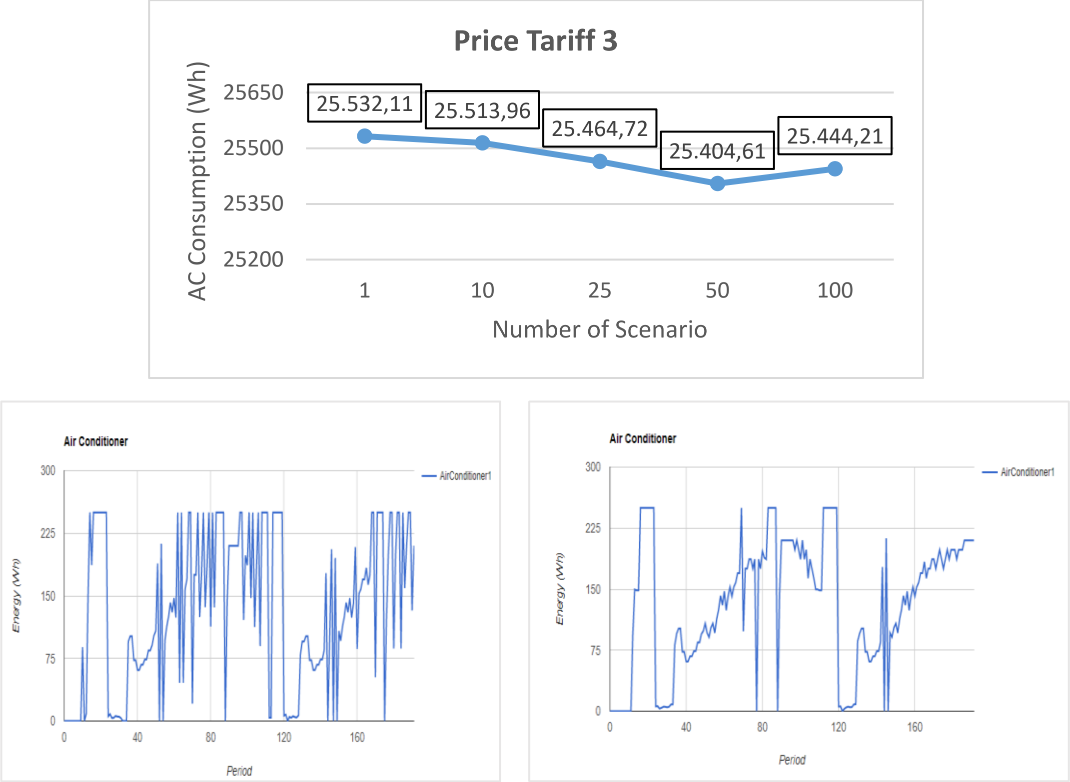


Figure 5.19: Price Tariff 3 Air Conditioner Consumption

5.2.3.5 Analysis on Usage Periods of Controllable/Uncontrollable/Continuous Appliances

Figures 5.20-22 show the scheduling of the appliances by optimization model. The Gantt Chart on the top shows the scheduling of the appliances that is observed in the result of the worst experiments, while the chart at the bottom shows the scheduling of the appliances that is observed in the result of the the best experiments. In these charts, the controllable appliances are given in the first order, and they are followed by uncontrollable and continuous appliances. Earliest and latest periods for the usages of controllable and uncontrollable appliances are shown in gray color. The recommended working periods are marked with blue and light blue for controllable and uncontrollable appliances, respectively.

As observed in Figure 5.20, corresponding to price tariff 1, for both of the worst and best experiment, it is observed that the appliances are forced to operate at the times when the purchasing price is low .We have seen that there are minor differences in the schedules between the best and worst experiments.

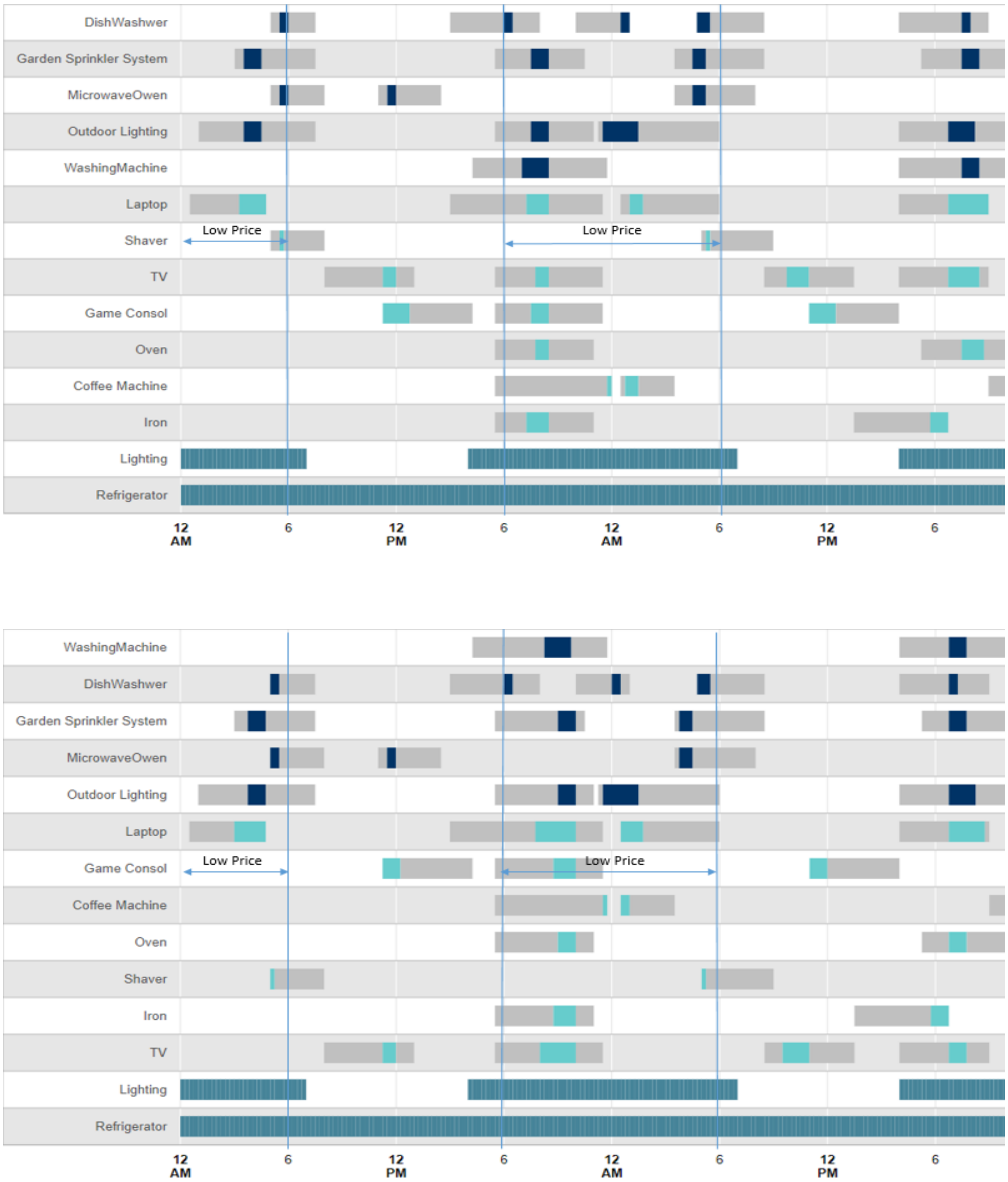


Figure 5.20: Price Tariff 1 Gantt Chart

As observed in Figure 5.21, corresponding to price tariff 2, for both of the worst and best experiment, it is observed that the appliance usages are forced to operate at the times when the purchasing price is low. We have seen that there are slightly more differences in the schedules between the best and worst experiments, if we compare the changes in this figure with those of the previous one.

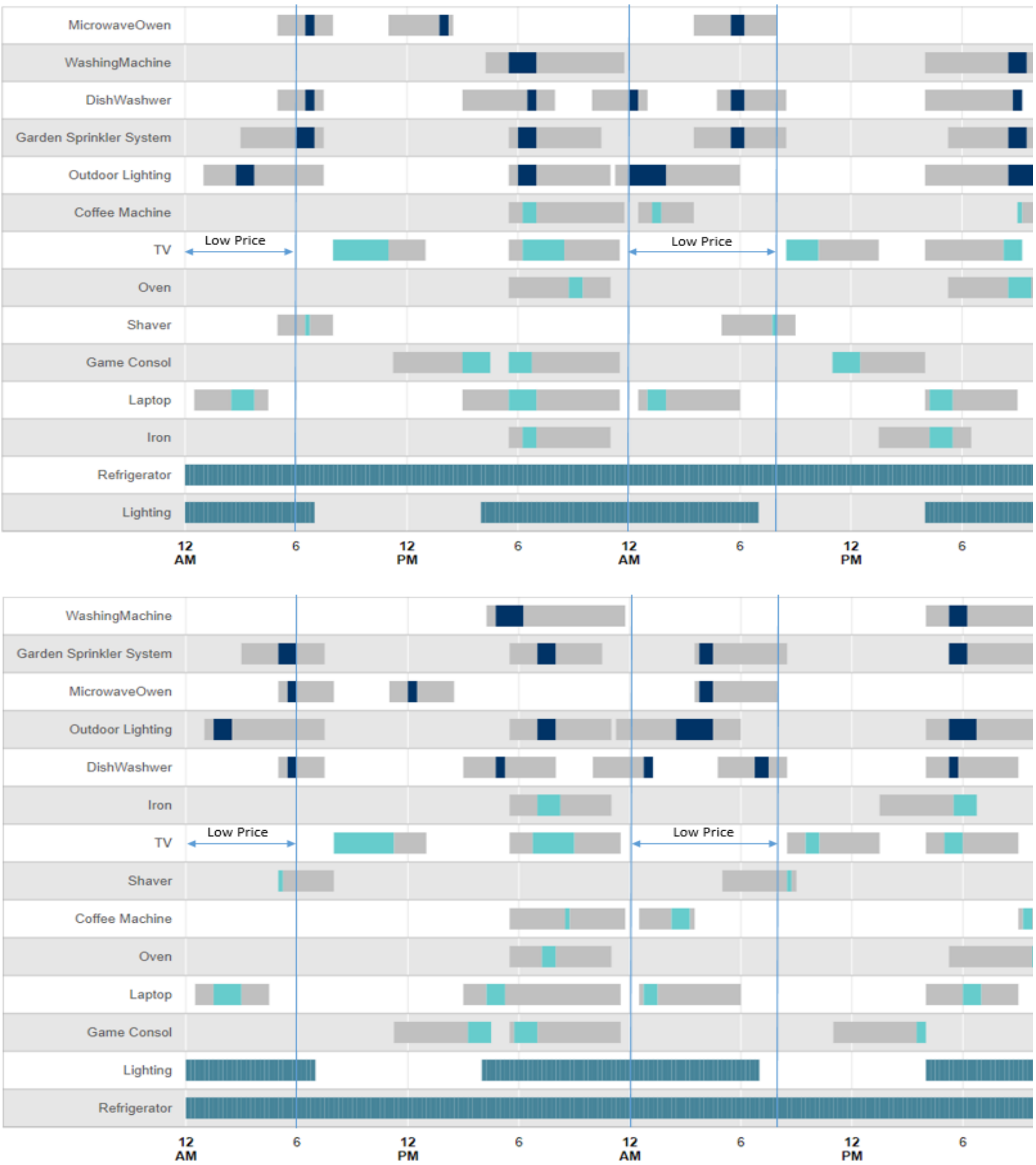


Figure 5.21: Price Tariff 2 Gantt Chart

As observed in Figure 5.22, corresponding to price tariff 3, for both of the worst and best experiment, it is observed that the appliance usages are forced to operate at the times when the purchasing price is low .We have seen here again that there are slightly more differences in the schedules between the best and worst experiments, if we compare the changes in this figure with those of the Figure 20.

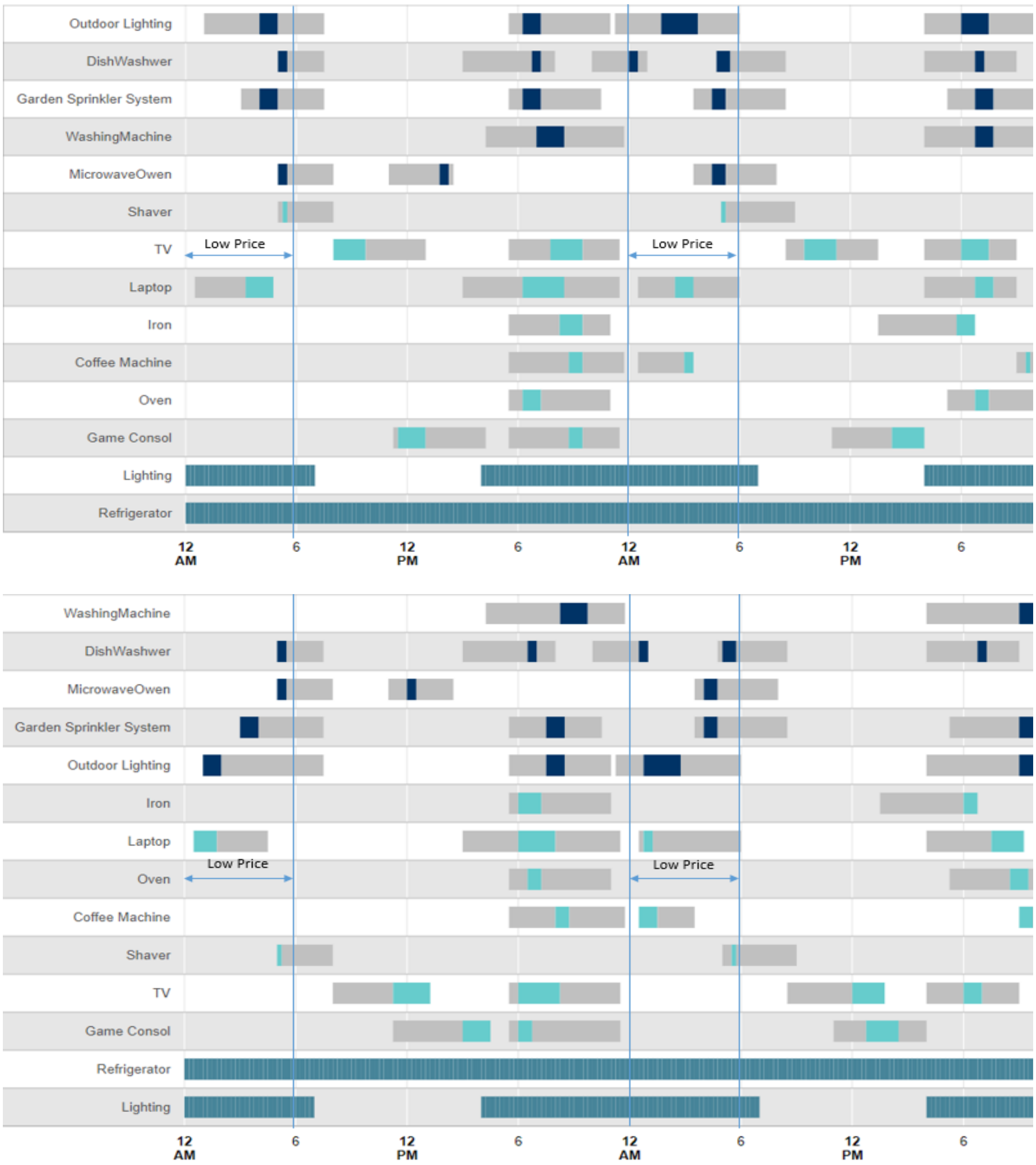


Figure 5.22: Price Tariff 3 Gantt Chart

5.2.3.6 When There is Only the Air Conditioner

For each price tariff, all the appliances -except the air conditioner- are excluded and experiments with 100 scenarios is run. Figures 5.23, 5.24 and 5.25 show the air conditioner's consumption, its effects on the inner and outer temperature of the house according to optimization model results. In each figure, the chart on the left side shows the air conditioner's consumption and the chart on the right side shows the temperature.

Unlike the other experiments, the air conditioner consumption cost is high at all price tariffs as outlined in Appendix E. In an environment where no storage is available, the air conditioner works to keep the temperature in the comfort range, inevitably using the energy sold by the grid.

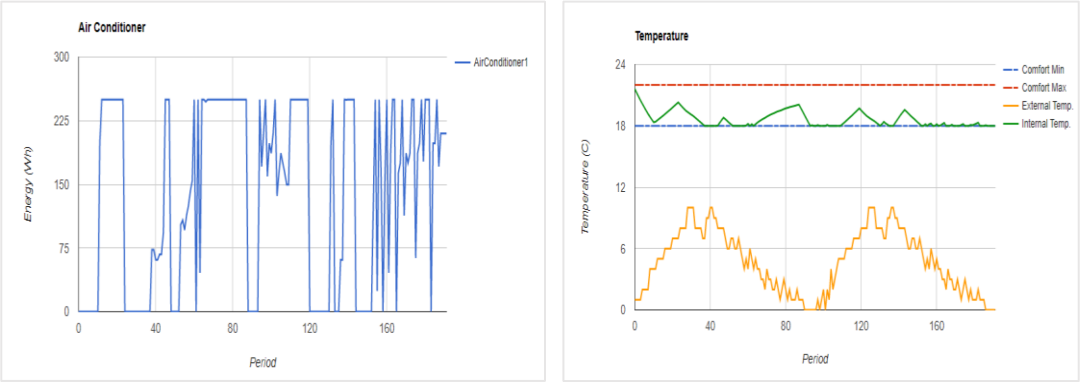


Figure 5.23: Price Tariff 1 (Only Air Conditioner)

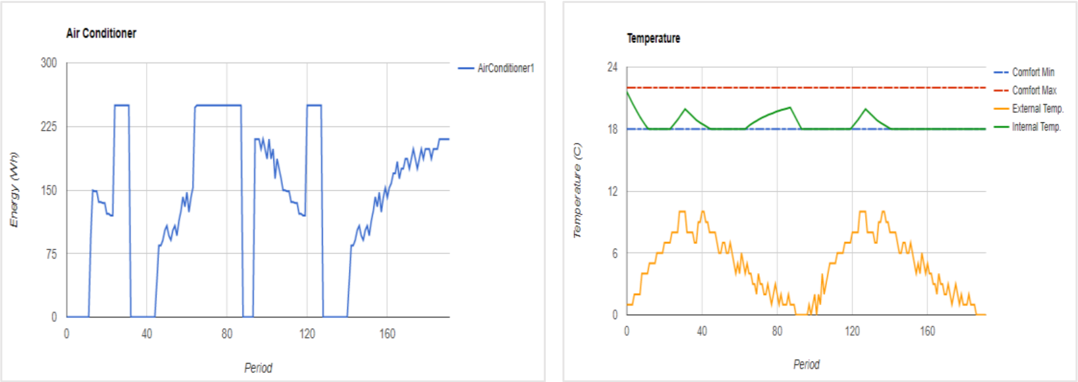


Figure 5.24: Price Tariff 2 (Only Air Conditioner)

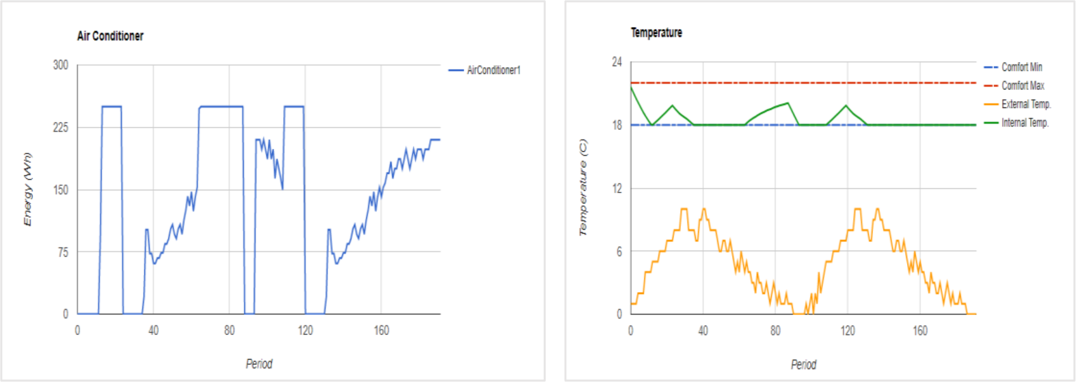


Figure 5.25: Price Tariff 3 (Only Air Conditoner)

5.2.3.7 When There is Only the Storage Device

For each price tariff, all the appliances -except the storage device- are excluded and experiments with 100 scenarios are run. In these experiments, storage device’s efficiency value and depreciation cost are set to 1 and 0, respectively.

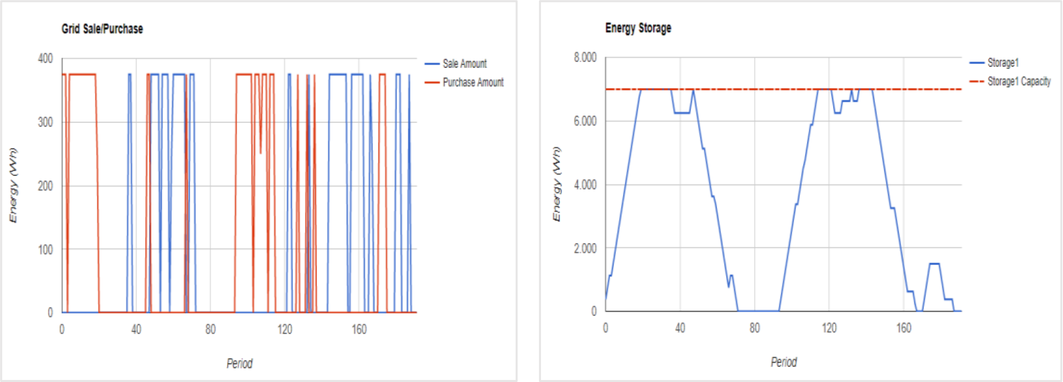


Figure 5.26: Price Tariff 1 (Only Storage Device)

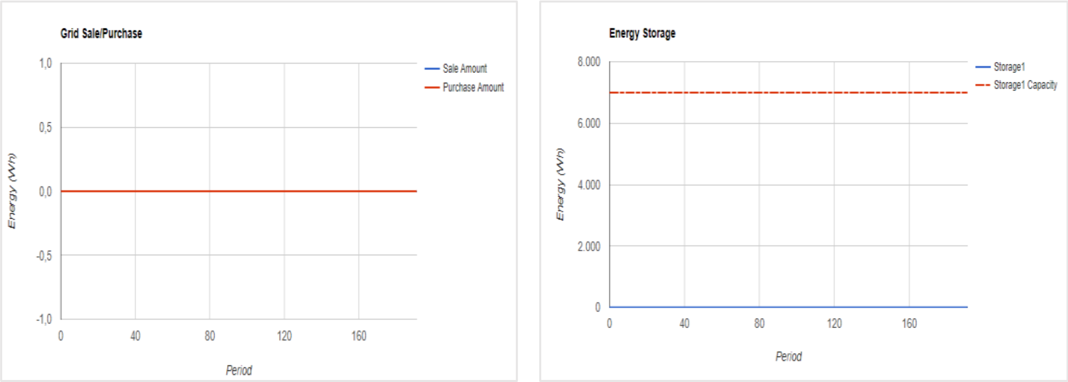


Figure 5.27: Price Tariff 2 (Only Storage Device)

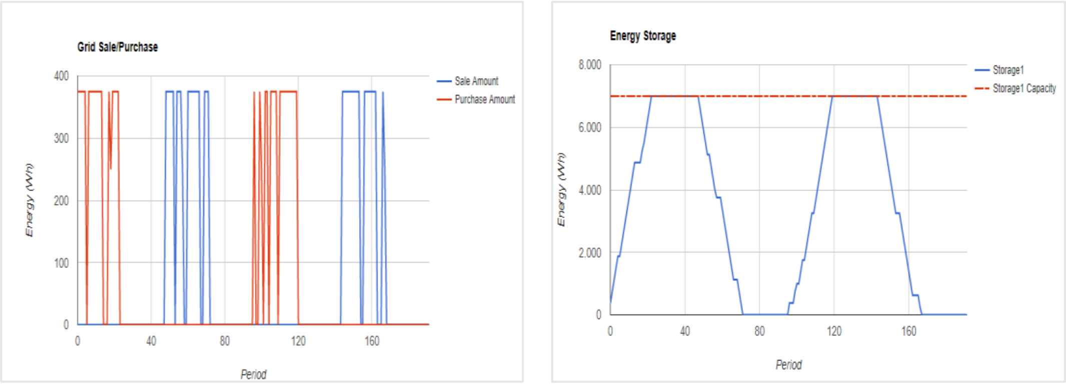


Figure 5.28: Price Tariff 3 (Only Storage Device)

It is observed that the storage device does not store at all at price tariff 2. The storage device stores well at price tarif 1 and 3. At price tariff 3, the storage device charges to full at the times when purchasing price is low and it discharges when the sales price is high, which supports profitable energy management.

CHAPTER 6

CONCLUSION

In this thesis, we develop an optimization model to schedule home appliances, energy batteries and air-conditioners under a stochastic environement. The energy management system considered in the thesis has the ability to integrate with renewable energy sources.

Optimization model objective is minimizing the total energy cost, while the model is constrained by the requirements of meeting the usage demand of appliances and ensuring the comfort of household. Air conditioner is used to keep the inner temperature level between minimum and maximum comfort levels. Household can use electrical batteries and PHEVs to get benefit from the fluctuation in the electricity price. We have observed that the usage of the HEMS model can reduce the household's energy bill and gives better solutions at all of the experimented price tariff conditions.

We only utilize the uniform distribution in the simulation experiments which limits the benefit obtained from the HEMS. Therefore, in a future study, real world data can be used to analyze the past behavior of the household and a more realistic distribution can be utilized.

Moreover, in real life, the mathematical model could run with accurate forecast services available to the HEMS. This will further improve 25-35% cost reduction results which we observed in our numerical studies. Due to the reasons mentioned above, the cost reduction amounts reported here should be considered as a very cautious claim.

As for the future work, runtime of optimization model can be further reduced using parallel processing capabilities of CPLEX solver. The study in this thesis propose a novel approach in scheduling home energy resources in planning horizon of up to two days. The model can be further improved to get solutions for hour-ahead and real time scheduling in order to adopt to varying conditions.

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[40]] Figure 1.2 What if the smartest grid of all was your own grid?, available at

http://www.eaton.com/FTC/utilities/MicrogridEnergySystems/index.html
[Accessed 10.03.2018]

APPENDIX A

EXPERIMENT DATA

Table A.1 : Unit, Measure, Abbreviation

Unit	**Unit Measure**	**Abbreviation**
Temperature	Celcius	C
Temperature	Kelvin	K
Length	Meter	m
Power	Watt	W
Power	KiloWatt	kW
Power	MegaWatt	MW
Time	Second	s
Time	Hour	h
Energy	Watt Hour	Wh
Money	Turkish Lira	TL
Irradiance	Watt per Square Meter	W/m^2
Area	Square Meter	m^2
Transmittance	Watt per Celcius Square Meter	W/Cm^2
Heat	British Thermal Unit	BTU
Volume	Cubic meter	m^3
Energy Efficiency Ratio	BTU per Hour Watt	BTU/hW

Table A.2 : Parameters for Controllable and Uncontrollable Appliances

Controllable Appliances						
Appliance	**Consumption Rate (W)**	**Work Duration Period**				
		[Early Start-Latest Stop Period]				
		Usage 1	**Usage 2**	**Usage 3**	**Usage 4**	**Usage 5**
Diswasher	250	2	2	3	2	2
		[20-30]	[60-80]	[88-100]	[115-130]	[160-180]
Washing Machine	500	6	4			
		[65-95]	[160-190]			
Lighting	50	4	4	8	6	
		[4-30]	[70-92]	[93-120]	[160-190]	
Oven	900	2	2	3		
		[20-32]	[44-58]	[110-128]		
Sprinkler	100	4	4	3	4	
		[12-30]	[70-90]	[110-130]	[165-190]	
Electric Vehicle	20	4	5	4		
		[28-66]	[80-94]	[144-160]		
Uncontrollable Appliances						
Appliance	**Consumption Rate (W)**	**Work Duration Period Mean, Std. Deviation**				
		[Early Start-Latest Stop Period]				
		Usage 1	**Usage 2**	**Usage 3**	**Usage 4**	**Usage 5**
Stove	800	4,1	4,1			
		[70-92]	[165-190]			
TV	250	8,4	6,2	6,2	4,2	
		[32-52]	[70-94]	[130-150]	[160-180]	
Laptop	125	6,1	6,2	5,2	6,2	
		[2-18]	[60-94]	[98-120]	[160-180]	
Coffee Machine	1500	2,1	3,1	2,1		
		[70-95]	[98-110]	[180-191]		
Iron	1100	4,1	4,1			
		[70-92]	[150-170]			
Shaver	15	1,0.1	1,0.1			
		[20-32]	[116-132]			
Game Consol	125	5,1	4,1	5,2		
		[45-65]	[70-94]	[140-160]		

Table A.3: Storage Device and Electric Vehicle Parameters

Parameter	**Storage Device**	**Electric Vehicle**
Initial Storage Level (Wh)	0	0
Maximum Storage Level (Wh)	7000	7000
Charge Rate (W)	1500	500
Charge Efficiency	0.92	0.92
Charge Cost (TL/kWh)	0.01	0.01
Discharge Rate (W)	1500	500
Discharge Efficiency	0.92	0.92
Discharge Cost (TL/kWh)	0.01	0.01

Table A.4: The Building and Air Conditioner Parameters

Parameter	**Unit**	**Value**
Initial Temperature	C	22
Surface Exposed to Sun	m^2	15
Horizontal Surface	m^2	100
Wall Surface	m^2	27
Window Surface	m^2	6
Volume of Building	m^3	30
Wall Transmittance	W/Cm^2	0.4
Roof Transmittance	W/Cm^2	0.2
Floor Transmittance	W/Cm^2	0.6
Window Transmittance	W/Cm^2	2.1
Circulation of Fresh Air into Building	W/Cm^3	0.2
Air Conditioner Efficiency Ratio for Cooling	BTU/hW	8
Air Conditioner Efficiency Ratio for Heating	BTU/hW	8
Air Conditioner Cooling Maximum Power	W	500
Air Conditioner Heating Maximum Power	W	500

Table A.5: Purchase and Sale Prices

Period	Price Tariff 1				Price Tariff 2				Price Tariff 3			
	Purchase Price		**Sale Price**		**Purchase Price**		**Sale Price**		**Purchase Price**		**Sale Price**	
	Mean	**Std D.**	**Mean**	**Std D.**	**Mean**	**Std D.**	**Mean**	**Std D.**	**Mean**	**Std D.**	**Mean**	**Std D.**
1	82	5	72	5	100	5	72	5	100	5	72	5
2	82	5	72	5	100	5	72	5	100	5	72	5
3	82	5	74	5	100	5	72	5	100	5	74	5
4	82	5	74	5	100	5	72	5	100	5	74	5
5	82	5	68	5	100	5	72	5	100	5	68	5
6	82	5	68	5	100	5	72	5	100	5	68	5
7	82	5	66	5	100	5	72	5	100	5	66	5
8	82	5	66	5	100	5	72	5	100	5	66	5
9	82	5	65	5	100	5	72	5	100	5	65	5
10	82	5	65	5	100	5	72	5	100	5	65	5
11	82	5	68	5	100	5	72	5	100	5	68	5
12	82	5	68	5	100	5	72	5	100	5	68	5
13	82	5	70	5	100	5	72	5	100	5	70	5
14	82	5	70	5	100	5	72	5	100	5	70	5
15	82	5	71	5	100	5	72	5	100	5	71	5
16	82	5	71	5	100	5	72	5	100	5	71	5
17	82	5	72	5	100	5	72	5	100	5	72	5
18	82	5	72	5	100	5	72	5	100	5	72	5
19	82	5	74	5	100	5	72	5	100	5	74	5
20	82	5	74	5	100	5	72	5	100	5	74	5
21	82	5	78	5	100	5	72	5	100	5	78	5
22	82	5	78	5	100	5	72	5	100	5	78	5
23	85	5	72	5	100	5	72	5	100	5	72	5
24	88	5	76	5	100	5	72	5	100	5	76	5
25	135	5	115	5	100	5	72	5	150	5	115	5
26	132	5	112	5	100	5	72	5	150	5	112	5
27	135	5	118	5	100	5	72	5	150	5	118	5
28	136	5	115	5	100	5	72	5	150	5	115	5
29	137	5	116	5	100	5	72	5	150	5	116	5
30	130	5	117	5	100	5	72	5	150	5	117	5
31	140	5	120	5	100	5	72	5	150	5	120	5
32	141	5	114	5	100	5	72	5	150	5	114	5
33	139	5	116	5	150	5	72	5	150	5	116	5
34	135	5	118	5	150	5	72	5	150	5	118	5
35	140	5	120	5	150	5	72	5	150	5	120	5
36	144	5	122	5	150	5	72	5	150	5	122	5
37	145	5	125	5	150	5	72	5	150	5	125	5
38	145	5	128	5	150	5	72	5	150	5	128	5

Table A.5 continued

39	136	5	120	5	150	5	72	5	150	5	120	5
40	137	5	114	5	150	5	72	5	150	5	114	5
41	138	5	117	5	150	5	72	5	150	5	117	5
42	139	5	116	5	150	5	72	5	150	5	116	5
43	135	5	119	5	150	5	72	5	150	5	119	5
44	130	5	114	5	150	5	72	5	150	5	114	5
45	132	5	108	5	150	5	72	5	150	5	108	5
46	125	5	105	5	150	5	72	5	150	5	105	5
47	120	5	110	5	150	5	72	5	150	5	110	5
48	116	5	100	5	150	5	72	5	150	5	100	5
49	170	5	140	5	150	5	72	5	150	5	140	5
50	172	5	142	5	150	5	72	5	150	5	142	5
51	160	5	143	5	150	5	72	5	150	5	143	5
52	161	5	144	5	150	5	72	5	150	5	144	5
53	163	5	145	5	150	5	72	5	150	5	145	5
54	155	5	130	5	150	5	72	5	150	5	130	5
55	154	5	139	5	150	5	72	5	150	5	139	5
56	150	5	142	5	150	5	72	5	150	5	142	5
57	151	5	143	5	150	5	72	5	150	5	143	5
58	151	5	135	5	150	5	72	5	150	5	135	5
59	151	5	132	5	150	5	72	5	150	5	132	5
60	152	5	133	5	150	5	72	5	150	5	133	5
61	153	5	138	5	150	5	72	5	150	5	138	5
62	159	5	139	5	150	5	72	5	150	5	139	5
63	150	5	140	5	150	5	72	5	150	5	140	5
64	155	5	141	5	150	5	72	5	150	5	141	5
65	154	5	142	5	125	5	72	5	150	5	142	5
66	156	5	146	5	125	5	72	5	150	5	146	5
67	160	5	145	5	125	5	72	5	150	5	145	5
68	132	5	120	5	125	5	72	5	150	5	120	5
69	140	5	130	5	125	5	72	5	150	5	130	5
70	140	5	139	5	125	5	72	5	150	5	139	5
71	150	5	146	5	125	5	72	5	150	5	146	5
72	150	5	140	5	125	5	72	5	150	5	140	5
73	100	5	95	5	125	5	72	5	125	5	95	5
74	100	5	98	5	125	5	72	5	125	5	98	5
75	110	5	96	5	125	5	72	5	125	5	96	5
76	105	5	97	5	125	5	72	5	125	5	97	5
77	104	5	89	5	125	5	72	5	125	5	89	5
78	102	5	88	5	125	5	72	5	125	5	88	5
79	102	5	86	5	125	5	72	5	125	5	86	5
80	102	5	85	5	125	5	72	5	125	5	85	5
81	103	5	80	5	125	5	72	5	125	5	80	5

Table A.5 continued

82	95	5	90	5	125	5	72	5	125	5	90	5
83	99	5	92	5	125	5	72	5	125	5	92	5
84	99	5	95	5	125	5	72	5	125	5	95	5
85	99	5	98	5	125	5	72	5	125	5	98	5
86	95	5	94	5	125	5	72	5	125	5	94	5
87	99	5	88	5	125	5	72	5	125	5	88	5
88	99	5	89	5	125	5	72	5	125	5	89	5
89	99	5	90	5	125	5	72	5	125	5	90	5
90	99	5	91	5	125	5	72	5	125	5	91	5
91	99	5	92	5	125	5	72	5	125	5	92	5
92	95	5	93	5	125	5	72	5	125	5	93	5
93	97	5	94	5	125	5	72	5	125	5	94	5
94	72	5	70	5	125	5	72	5	125	5	70	5
95	76	5	72	5	125	5	72	5	125	5	72	5
96	78	5	73	5	125	5	72	5	125	5	73	5
97	75	5	69	5	100	5	72	5	100	5	69	5
98	75	5	68	5	100	5	72	5	100	5	68	5
99	78	5	67	5	100	5	72	5	100	5	67	5
100	78	5	70	5	100	5	72	5	100	5	70	5
101	79	5	72	5	100	5	72	5	100	5	72	5
102	78	5	73	5	100	5	72	5	100	5	73	5
103	79	5	75	5	100	5	72	5	100	5	75	5
104	82	5	68	5	100	5	72	5	100	5	68	5
105	82	5	66	5	100	5	72	5	100	5	66	5
106	82	5	65	5	100	5	72	5	100	5	65	5
107	82	5	68	5	100	5	72	5	100	5	68	5
108	82	5	68	5	100	5	72	5	100	5	68	5
109	82	5	70	5	100	5	72	5	100	5	70	5
110	82	5	70	5	100	5	72	5	100	5	70	5
111	82	5	71	5	100	5	72	5	100	5	71	5
112	82	5	71	5	100	5	72	5	100	5	71	5
113	82	5	72	5	100	5	72	5	100	5	72	5
114	82	5	72	5	100	5	72	5	100	5	72	5
115	82	5	74	5	100	5	72	5	100	5	74	5
116	82	5	74	5	100	5	72	5	100	5	74	5
117	82	5	78	5	100	5	72	5	100	5	78	5
118	82	5	78	5	100	5	72	5	100	5	78	5
119	90	5	70	5	100	5	72	5	100	5	70	5
120	90	5	69	5	100	5	72	5	100	5	69	5
121	118	5	115	5	100	5	72	5	150	5	115	5
122	125	5	116	5	100	5	72	5	150	5	116	5
123	135	5	124	5	100	5	72	5	150	5	124	5
124	135	5	123	5	100	5	72	5	150	5	123	5

Table A.5 continued

125	140	5	122	5	100	5	72	5	150	5	122	5
126	140	5	110	5	100	5	72	5	150	5	110	5
127	130	5	108	5	100	5	72	5	150	5	108	5
128	120	5	100	5	100	5	72	5	150	5	100	5
129	124	5	110	5	150	5	72	5	150	5	110	5
130	126	5	110	5	150	5	72	5	150	5	110	5
131	125	5	112	5	150	5	72	5	150	5	112	5
132	123	5	113	5	150	5	72	5	150	5	113	5
133	120	5	114	5	150	5	72	5	150	5	114	5
134	130	5	125	5	150	5	72	5	150	5	125	5
135	132	5	120	5	150	5	72	5	150	5	120	5
136	135	5	116	5	150	5	72	5	150	5	116	5
137	120	5	118	5	150	5	72	5	150	5	118	5
138	120	5	119	5	150	5	72	5	150	5	119	5
139	120	5	119	5	150	5	72	5	150	5	119	5
140	125	5	116	5	150	5	72	5	150	5	116	5
141	125	5	118	5	150	5	72	5	150	5	118	5
142	126	5	108	5	150	5	72	5	150	5	108	5
143	126	5	104	5	150	5	72	5	150	5	104	5
144	125	5	115	5	150	5	72	5	150	5	115	5
145	170	5	150	5	150	5	72	5	150	5	150	5
146	170	5	145	5	150	5	72	5	150	5	145	5
147	190	5	161	5	150	5	72	5	150	5	150	5
148	190	5	140	5	150	5	72	5	150	5	140	5
149	180	5	142	5	150	5	72	5	150	5	142	5
150	170	5	142	5	150	5	72	5	150	5	142	5
151	175	5	140	5	150	5	72	5	150	5	140	5
152	160	5	140	5	150	5	72	5	150	5	140	5
153	165	5	138	5	150	5	72	5	150	5	138	5
154	158	5	136	5	150	5	72	5	150	5	136	5
155	154	5	135	5	150	5	72	5	150	5	135	5
156	160	5	132	5	150	5	72	5	150	5	132	5
157	150	5	136	5	150	5	72	5	150	5	136	5
158	160	5	137	5	150	5	72	5	150	5	137	5
159	180	5	139	5	150	5	72	5	150	5	139	5
160	160	5	141	5	150	5	72	5	150	5	141	5
161	150	5	142	5	125	5	72	5	150	5	142	5
162	155	5	143	5	125	5	72	5	150	5	143	5
163	155	5	138	5	125	5	72	5	150	5	138	5
164	157	5	135	5	125	5	72	5	150	5	135	5
165	160	5	132	5	125	5	72	5	150	5	132	5
166	165	5	131	5	125	5	72	5	150	5	131	5
167	150	5	138	5	125	5	72	5	150	5	138	5

Table A.5 continued

168	152	5	136	5	125	5	72	5	150	5	136	5
169	100	5	95	5	125	5	72	5	125	5	95	5
170	110	5	94	5	125	5	72	5	125	5	94	5
171	105	5	81	5	125	5	72	5	125	5	81	5
172	90	5	84	5	125	5	72	5	125	5	84	5
173	92	5	82	5	125	5	72	5	125	5	82	5
174	93	5	88	5	125	5	72	5	125	5	88	5
175	91	5	81	5	125	5	72	5	125	5	81	5
176	97	5	87	5	125	5	72	5	125	5	87	5
177	96	5	88	5	125	5	72	5	125	5	88	5
178	94	5	92	5	125	5	72	5	125	5	96	5
179	93	5	93	5	125	5	72	5	125	5	93	5
180	98	5	92	5	125	5	72	5	125	5	92	5
181	100	5	94	5	125	5	72	5	125	5	94	5
182	100	5	97	5	125	5	72	5	125	5	97	5
183	100	5	98	5	125	5	72	5	125	5	98	5
184	110	5	88	5	125	5	72	5	125	5	88	5
185	100	5	85	5	125	5	72	5	125	5	85	5
186	100	5	90	5	125	5	72	5	125	5	90	5
187	100	5	92	5	125	5	72	5	125	5	92	5
188	100	5	98	5	125	5	72	5	125	5	98	5
189	100	5	90	5	125	5	72	5	125	5	90	5
190	102	5	88	5	125	5	72	5	125	5	88	5
191	101	5	80	5	125	5	72	5	125	5	80	5
192	101	5	92	5	125	5	72	5	125	5	92	5

Table A.6: Energy Generation,Weather and Continuous Appliance

Period	**Solar Energy**		**Wind Energy**		**Weather**		**Continuous App.**	
	Mean	**Std D.**	**Mean**	**Std D.**	**Radiation**	**Temperature**	**Refrigerator**	**Lighting**
1	0	0	200	10	0	1	25	5
2	0	0	200	10	0	1	25	5
3	0	0	160	10	0	1	25	5
4	0	0	160	10	0	1	25	5
5	0	0	140	10	0	2	25	5
6	0	0	140	10	0	2	25	5
7	0	0	150	10	0	2	25	5
8	0	0	150	10	0	2	25	5
9	0	0	200	10	0	4	25	5
10	0	0	200	10	0	4	25	5
11	0	0	210	10	0	4	25	5
12	0	0	210	10	0	4	25	5
13	0	0	220	10	2	5	25	5
14	0	0	220	10	2	5	25	5
15	0	0	170	10	3	5	25	5
16	0	0	170	10	3	5	25	5
17	0	0	150	10	4	6	25	5
18	0	0	150	10	4	6	25	5
19	0	0	130	10	5	6	25	5
20	0	0	130	10	5	6	25	5
21	0	0	110	10	6	7	25	5
22	0	0	110	10	6	7	25	5
23	0	0	150	10	8	7	25	5
24	0	0	150	10	8	7	25	5
25	30	1	180	10	8	8	25	10
26	30	1	180	10	8	8	25	10
27	45	2	130	10	15	8	25	10
28	45	2	130	10	15	8	25	10
29	50	5	110	10	20	10	25	0
30	50	5	110	10	20	10	25	0
31	70	5	80	10	25	10	25	0
32	70	5	80	10	25	10	25	0
33	90	5	100	10	25	8	25	0
34	90	5	100	10	25	8	25	0
35	110	10	120	10	20	8	25	0
36	110	10	120	10	20	8	25	0
37	130	10	140	10	25	7	25	0
38	130	10	140	10	25	7	25	0
39	240	10	160	10	30	9	25	0

Table A.6 continued

40	240	10	160	10	30	9	25	0
41	270	10	180	10	30	10	25	0
42	270	10	180	10	30	10	25	0
43	300	10	240	10	35	9	25	0
44	300	10	240	10	35	9	25	0
45	380	10	250	10	40	8	25	0
46	380	10	250	10	40	8	25	0
47	450	10	230	10	30	8	25	0
48	450	10	230	10	30	8	25	0
49	450	10	180	10	35	7	25	0
50	450	10	180	10	35	6	25	0
51	500	10	190	10	30	6	25	0
52	500	10	190	10	30	7	25	0
53	600	10	110	10	35	7	25	0
54	600	10	110	10	35	6	25	0
55	550	10	80	10	30	6	25	0
56	550	10	80	10	30	7	25	0
57	510	10	60	10	25	6	25	0
58	510	10	60	10	25	5	25	0
59	480	10	120	10	20	4	25	0
60	480	10	120	10	20	5	25	0
61	480	10	100	10	15	4	25	0
62	480	10	100	10	15	6	25	0
63	420	10	120	10	10	5	25	0
64	420	10	120	10	10	4	25	0
65	400	10	130	10	10	5	25	30
66	400	10	130	10	10	4	25	30
67	420	10	200	10	5	4	25	40
68	420	10	200	10	5	3	25	40
69	300	10	170	10	5	3	25	40
70	300	10	170	10	3	2	25	40
71	250	10	130	10	0	4	25	40
72	250	10	130	10	0	3	25	40
73	250	10	100	10	0	3	25	80
74	250	10	100	10	0	2	25	80
75	200	10	150	10	0	2	25	80
76	200	10	150	10	0	3	25	80
77	190	10	200	10	0	2	25	80
78	190	10	200	10	0	1	25	80
79	60	10	70	10	0	2	25	60
80	60	10	70	10	0	3	25	60
81	10	0	40	10	0	2	25	60
82	10	0	40	10	0	1	25	60

Table A.6 continued

83	0	0	30	10	0	2	25	60
84	0	0	30	10	0	1	25	60
85	0	0	80	10	0	1	25	60
86	0	0	80	10	0	1	25	60
87	0	0	110	10	0	2	25	40
88	0	0	110	10	0	1	25	40
89	0	0	190	10	0	1	25	40
90	0	0	190	10	0	1	25	40
91	0	0	150	10	0	0	25	40
92	0	0	150	10	0	0	25	40
93	0	0	80	10	0	0	25	40
94	0	0	80	10	0	0	25	40
95	0	0	110	10	0	0	25	40
96	0	0	110	10	0	0	25	40
97	0	0	200	10	0	0	25	40
98	0	0	200	10	0	1	25	40
99	0	0	160	10	0	0	25	40
100	0	0	160	10	0	1	25	40
101	0	0	140	10	0	2	25	5
102	0	0	140	10	0	0	25	5
103	0	0	150	10	0	2	25	5
104	0	0	150	10	0	1	25	5
105	0	0	200	10	0	4	25	5
106	0	0	200	10	0	2	25	5
107	0	0	210	10	0	3	25	5
108	0	0	210	10	0	4	25	5
109	0	0	220	10	2	5	25	5
110	0	0	220	10	2	5	25	5
111	0	0	170	10	3	5	25	5
112	0	0	170	10	3	5	25	5
113	0	0	150	10	4	6	25	5
114	0	0	150	10	4	6	25	5
115	0	0	130	10	5	6	25	5
116	0	0	130	10	5	6	25	5
117	0	0	110	10	6	7	25	5
118	0	0	110	10	6	7	25	5
119	0	0	150	10	8	7	25	5
120	0	0	150	10	8	7	25	5
121	30	1	180	10	8	8	25	10
122	30	1	180	10	8	8	25	10
123	45	2	130	10	15	8	25	10
124	45	2	130	10	15	8	25	10
125	50	5	110	10	20	10	25	0

Table A.6 continued

126	50	5	110	10	20	10	25	0
127	70	5	80	10	25	10	25	0
128	70	5	80	10	25	10	25	0
129	90	5	100	10	25	8	25	0
130	90	5	100	10	25	8	25	0
131	110	10	120	10	20	8	25	0
132	110	10	120	10	20	8	25	0
133	130	10	140	10	25	7	25	0
134	130	10	140	10	25	7	25	0
135	240	10	160	10	30	9	25	0
136	240	10	160	10	30	9	25	0
137	270	10	180	10	30	10	25	0
138	270	10	180	10	30	10	25	0
139	300	10	240	10	35	9	25	0
140	300	10	240	10	35	9	25	0
141	380	10	250	10	40	8	25	0
142	380	10	250	10	40	8	25	0
143	450	10	230	10	30	8	25	0
144	450	10	230	10	30	8	25	0
145	450	10	180	10	35	7	25	0
146	450	10	180	10	35	6	25	0
147	500	10	190	10	30	6	25	0
148	500	10	190	10	30	7	25	0
149	600	10	110	10	35	7	25	0
150	600	10	110	10	35	6	25	0
151	550	10	80	10	30	6	25	0
152	550	10	80	10	30	7	25	0
153	510	10	60	10	25	6	25	0
154	510	10	60	10	25	5	25	0
155	480	10	120	10	20	4	25	0
156	480	10	120	10	20	5	25	0
157	480	10	100	10	15	4	25	0
158	480	10	100	10	15	6	25	0
159	420	10	120	10	10	5	25	0
160	420	10	120	10	10	4	25	0
161	400	10	130	10	10	5	25	30
162	400	10	130	10	10	4	25	30
163	420	10	200	10	5	4	25	40
164	420	10	200	10	5	3	25	40
165	300	10	170	10	5	3	25	40
166	300	10	170	10	3	2	25	40
167	250	10	130	10	0	4	25	40
168	250	10	130	10	0	3	25	40

Table A.6 continued

169	250	10	100	10	0	3	25	80
170	250	10	100	10	0	2	25	80
171	200	10	150	10	0	2	25	80
172	200	10	150	10	0	3	25	80
173	190	10	200	10	0	2	25	80
174	190	10	200	10	0	1	25	80
175	60	10	70	10	0	2	25	60
176	60	10	70	10	0	3	25	60
177	10	0	40	10	0	2	25	60
178	10	0	40	10	0	1	25	60
179	0	0	30	10	0	2	25	60
180	0	0	30	10	0	1	25	60
181	0	0	80	10	0	1	25	60
182	0	0	80	10	0	1	25	60
183	0	0	110	10	0	2	25	40
184	0	0	110	10	0	1	25	40
185	0	0	190	10	0	1	25	40
186	0	0	190	10	0	1	25	40
187	0	0	150	10	0	0	25	40
188	0	0	150	10	0	0	25	40
189	0	0	80	10	0	0	25	40
190	0	0	80	10	0	0	25	40
191	0	0	110	10	0	0	25	40
192	0	0	110	10	0	0	25	40

APPENDIX B

BUİLDİNG HEAT DEMAND AND INTERNAL TEMPERATURE

This model calculates the internal temperature of the home or another type of building considering its thermal inertia, the transmittance of its walls and the power injections given by heating/cooling systems and of solar radiation. Thermal models explanation can be found in Fraisse et al. (2002) and Kampf and Robinson (2007).

Thermal model's inputs are effective heat or cool input, external air temperature, previous internal temperature, solar radiation, inertia class, thermal trasmittance which are listed in Table B.1.

Effective heat or cool input is indicated in watts. This is calculated by the home consumption model and represents the effective heat injected or absorbed from the home by the heater, heat pump or the air conditioning if existed. It is different from their consumption since it takes into consideration each device's performance factor.

External air temperature is expressed in degrees Celsius. It comes from the meteorological model and represents the temperature outside the building. Previous internal temperature is also expressed in degrees Celsius. It is calculated by this same module and is relative to the previous time step.

Solar radiation is demonstrated in watts per square meters. It comes from the meteorological model.

Inertia class is a static parameter which can take five possible values from 'very heavy' to 'very light', as described in Table B.2. A heavier inertia class corresponds to a more massive building which keeps the heat better.

Thermal transmittance is a static parameter and can be calculated as described in the building's heating demand model.

Table B.1: Thermal Model's Inputs

Parameter Name	**Unit**	**Symbol**	**Default Value**	**Range**
Effective heating or cooling	W	P	0	-3000,3000
External air temperature	C	T_{ext}	15	-50,50
Previous internal temperature	C	T_{int}	20	-50,50
Solar radiation	W/m^2	E	0	0,1400
Inertia class	string	I	Medium	Very Light...Very Heavy

Table B.2: Thermal Capacity Coefficient

Inertia Class	**Per Unit Daily Thermal Capacity**
Very Light	0.617×10^{-2}
Light	0.617×10^{-2}
Medium	0.617×10^{-2}
Heavy	0.617×10^{-2}
Very Heavy	0.617×10^{-2}

The variation of the internal temperature can be calculated as

$$\frac{dT_{int}}{dt} = (\frac{(T_{int} - T_{ext})}{U} - S_{sun} . E + P)$$

where,

P is the power of heating or cooling source, unit of W.

C is the heat capacity, unit of Ws/K.

U is the thermal transmittance of the building, unit of W/C.

S_{sun} is the surface exposed to sun, unit of m^2.

E is the global horizontal radiation from the meterological model, unit of W/m^2.

The heat capacity can be calculated as proposed. The method consists in estimating a general category for the thermal inertia of a building, such as very light, heavy, etc., and proposes an universal value of the thermal capacitance based for surface unit.

$C = x \cdot S_{\mathrm{horizontal}}$

where,

$S_{\mathrm{horizontal}}$ is the horizontal surface of the building, unit of m^2.

x is the the per unit daily thermal capacity coefficient.

The transmittance U (the reciprocal of the thermal resistance), is calculated as the sum of the transmittance of the different parts of the building as

$$U = U_{\mathrm{wall}} . S_{\mathrm{wall}} + U_{\mathrm{roof}} . S_{\mathrm{horizontal}} + U_{\mathrm{floor}} . S_{\mathrm{horizontal}} + U_{\mathrm{windows}} . S_{\mathrm{windows}} + A . V$$

where,

$U_{\mathrm{wall,roof,floor,windows}}$ is the transmittance of the walls, the roof, the floor and the windows, unit of W/Cm^2

$S_{\mathrm{wall,horizontal,windows}}$ is the surface of the walls, the roof and the the windows, unit of m^2.

A is a parameter taking into account the circulation of fresh air into the building, unit of W/Cm^3

V is the volume of building, unit of m^3

APPENDIX C

WEB SERVİCE REQUEST AND RESPONSE

The following is an example request Json body for “/ScheduleHomeResources”

```
{
        "Owner":"String content",
        "PlanInput":{
                "AirConditioners":[{
                        "Active":true,
                        "EnergyEfficiencyRatioCooling":1.26743233E+15,
                        "EnergyEfficiencyRatioHeating":1.26743233E+15,
                        "MaximumCoolingPower":1.26743233E+15,
                        "MaximumHeatingPower":1.26743233E+15,
                        "Name":"String content"
                }],
                "AlternativeResultCount":2147483647,
                "Building":{
                        "BuildingVolume":1.26743233E+15,
                        "CirculationOfFreshAir":1.26743233E+15,
                        "HorizontalSurface":1.26743233E+15,
                        "InertiaClass":0,
                        "InitialTemperature":1.26743233E+15,
                        "SurfaceExposedToSun":1.26743233E+15,
                        "TransmittanceOfFloor":1.26743233E+15,
                        "TransmittanceOfRoof":1.26743233E+15,
                        "TransmittanceOfWalls":1.26743233E+15,
                        "TransmittanceOfWindows":1.26743233E+15,
```

```
"WallSurface":1.26743233E+15,
"WindowsSurface":1.26743233E+15
},
    "ComfortLevelforTemperature":{
    "PeriodComfortLevelTemperatures":[{
        "Key":2147483647,
        "Value":{
            "MaximumTemperature":1.26743233E+15,
            "MinimumTemperature":1.26743233E+15
        }
    }]
},
"ContinousAppliances":[{
    "Active":true,
    "ConsumptionRates":[{
        "Key":2147483647,
        "Value":2147483647
    }],
    "Name":"String content"
}],
"ControllableAppliances":[{
    "Active":true,
    "ConsumptionRate":1.26743233E+15,
    "ControllableWorks":[{
        "EarlyStartPeriod":2147483647,
        "LateStopPeriod":2147483647,
        "WorkDuration":2147483647
    }],
    "Name":"String content"
}],
"ElectricVehicles":[{
    "Active":true,
    "ChargeCost":1.26743233E+15,
    "ChargeEfficiency":1.26743233E+15,
```

```
        "ChargeRate":2147483647,
        "ConsumptionRate":1.26743233E+15,
        "DischargeCost":1.26743233E+15,
        "DischargeEfficiency":1.26743233E+15,
        "DischargeRate":2147483647,
        "ElectricVehicleUsages":[{
            "OutPeriodEnd":2147483647,
            "OutPeriodStart":2147483647,
            "WorkDuration":2147483647
        }],
        "InitialStorageLevel":2147483647,
        "MaximumStorageLevel":2147483647,
        "Name":"String content"
    }],
    "ExternalTemperature":{
        "ExternalTemperatures":[{
            "Key":2147483647,
            "Value":1.26743233E+15
        }]
    },
    "GridConstraint":{
        "PeriodGridConstraints":[{
            "Key":2147483647,
            "Value":{
                "MaximumPurchaseAmount":2147483647,
                "MaximumSaleAmount":2147483647
            }
        }]
    },
    "PlanDate":"String content",
    "PurchasePrice":{
        "PurchasePrices":[{
            "Key":2147483647,
            "Value":{
```

```
                  "Deviation":1.26743233E+15,
                  "Distribution":0,
                  "MeanValue":2147483647
            }
      }]
},
"SalePrice":{
      "SalePrices":[{
            "Key":2147483647,
            "Value":{
                  "Deviation":1.26743233E+15,
                  "Distribution":0,
                  "MeanValue":2147483647
            }
      }]
},
"SolarForecastUsage":true,
"SolarGenerators":[{
      "Active":true,
      "DepreciationCost":1.26743233E+15,
      "Efficiency":1.26743233E+15,
      "Generations":[{
            "Key":2147483647,
            "Value":{
                  "Deviation":1.26743233E+15,
                  "Distribution":0,
                  "MeanValue":2147483647
            }
      }],
      "Name":"String content"
}],
"SolarRadiation":{
      "SolarRadiations":[{
            "Key":2147483647,
```

```
                "Value":1.26743233E+15
        }]
},
"StorageDevices":[{
        "Active":true,
        "ChargeCost":1.26743233E+15,
        "ChargeEfficiency":1.26743233E+15,
        "ChargeRate":2147483647,
        "DischargeCost":1.26743233E+15,
        "DischargeEfficiency":1.26743233E+15,
        "DischargeRate":2147483647,
        "InitialStorageLevel":2147483647,
        "MaximumStorageLevel":2147483647,
        "Name":"String content"
}],
"UncontrollableAppliances":[{
        "Active":true,
        "ConsumptionRate":1.26743233E+15,
        "Name":"String content",
        "UncontrollableWorks":[{
                "Deviation":1.26743233E+15,
                "Distribution":0,
                "EarlyStartPeriod":2147483647,
                "LateStopPeriod":2147483647,
                "MeanValue":2147483647,
                "MeanWorkDuration":2147483647
        }]
}],
"WindForecastUsage":true,
"WindGenerators":[{
        "Active":true,
        "DepreciationCost":1.26743233E+15,
        "Efficiency":1.26743233E+15,
        "Generations":[{
```

```
                "Key":2147483647,
                "Value":{
                    "Deviation":1.26743233E+15,
                    "Distribution":0,
                    "MeanValue":2147483647
                }
            }],
            "Name":"String content"
        }],
        "nDays":2147483647,
        "nPeriodsPerDay":2147483647,
        "nScenarios":2147483647
    },
    "PlanName":"String content"
}
```

The following is an example request Json body for “/GetScheduleStatus/{PlanID}”:

```
{

    "Message":"String content",

    "Status":"String content"

}
```

The following is an example request Json body for “/GetScheduleResult/{PlanID}”:

```
{

    "Message":"String content",

    "Result":{

        "AirConditionerResult":[{

            "MaximumCoolingPower":1.26743233E+15,

            "MaximumHeatingPower":1.26743233E+15,

            "Name":"String content",
```

```
        "PeriodConsumption":[{
            "Consumption":1.26743233E+15,
            "OperationType":"String content",
            "Period":2147483647
        }]
    }],
    "ComfortLevelforTemperature":{
        "PeriodTemperature":[{
            "Period":2147483647,
            "PeriodComfortLevelTemperature":{
                "MaximumTemperature":1.26743233E+15,
                "MinimumTemperature":1.26743233E+15
            }
        }]
    },
    "ContinousAppliances":[{
        "Name":"String content",
        "PeriodConsumptions":[{
            "Period":2147483647,
            "Value":1.26743233E+15
        }]
    }],
    "ControllableApplianceResult":[{
        "ControllableWorkResult":[{
```

```
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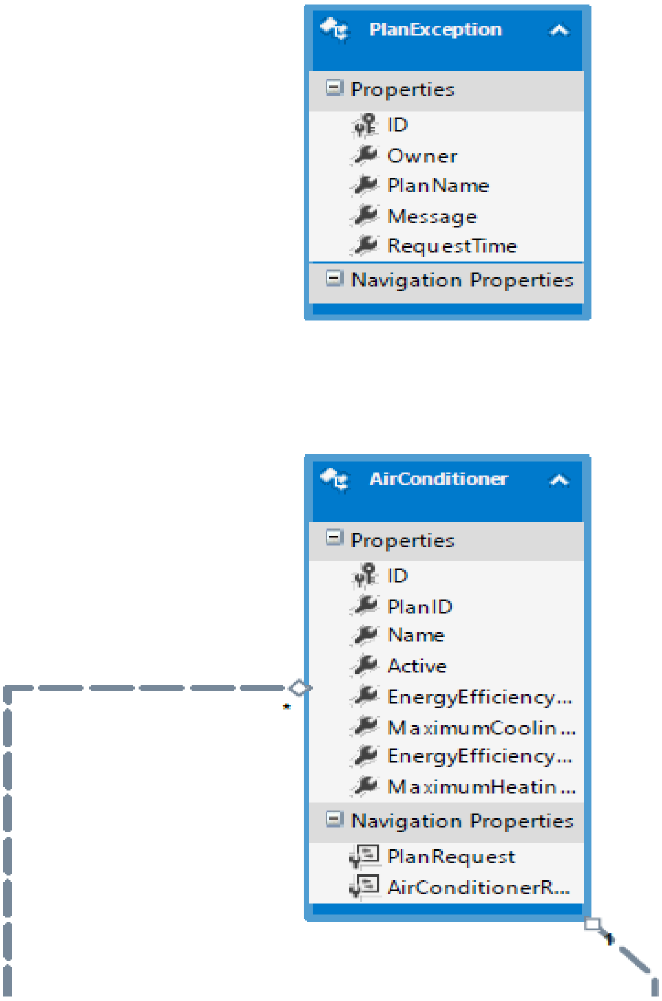
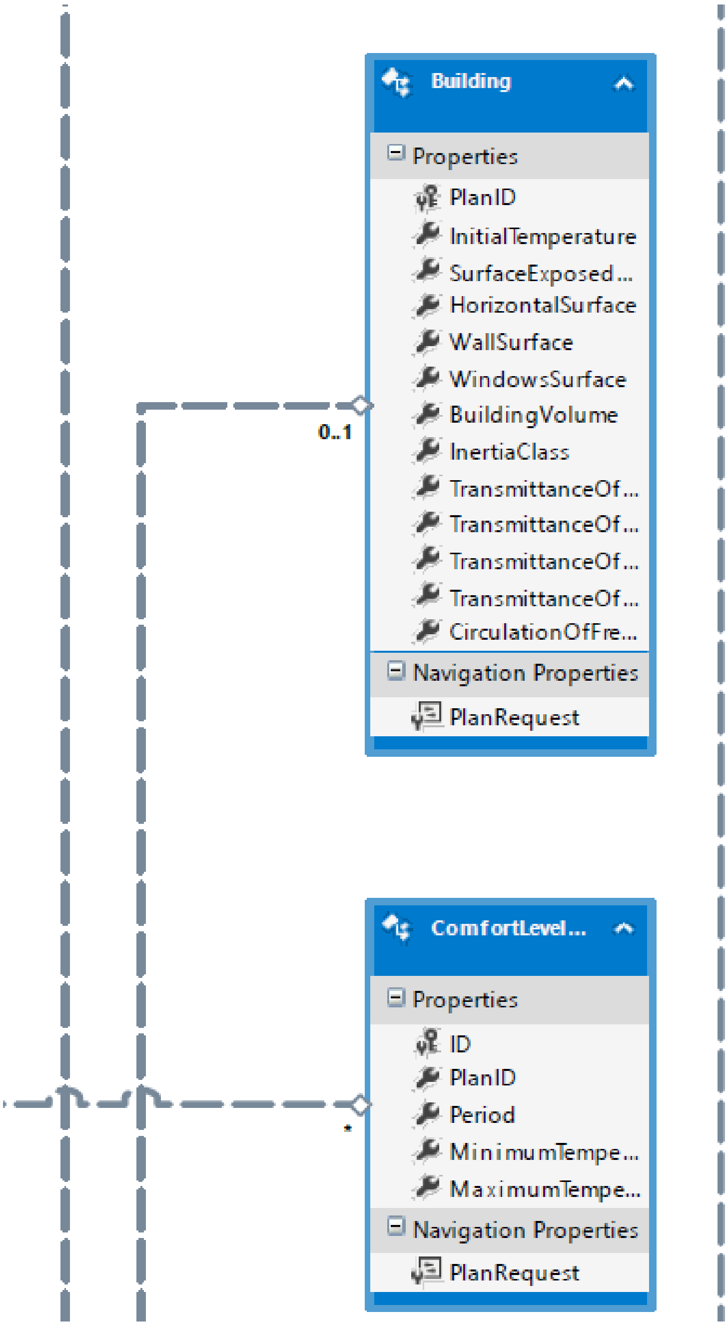
APPENDIX D

DATABASE DİAGRAM

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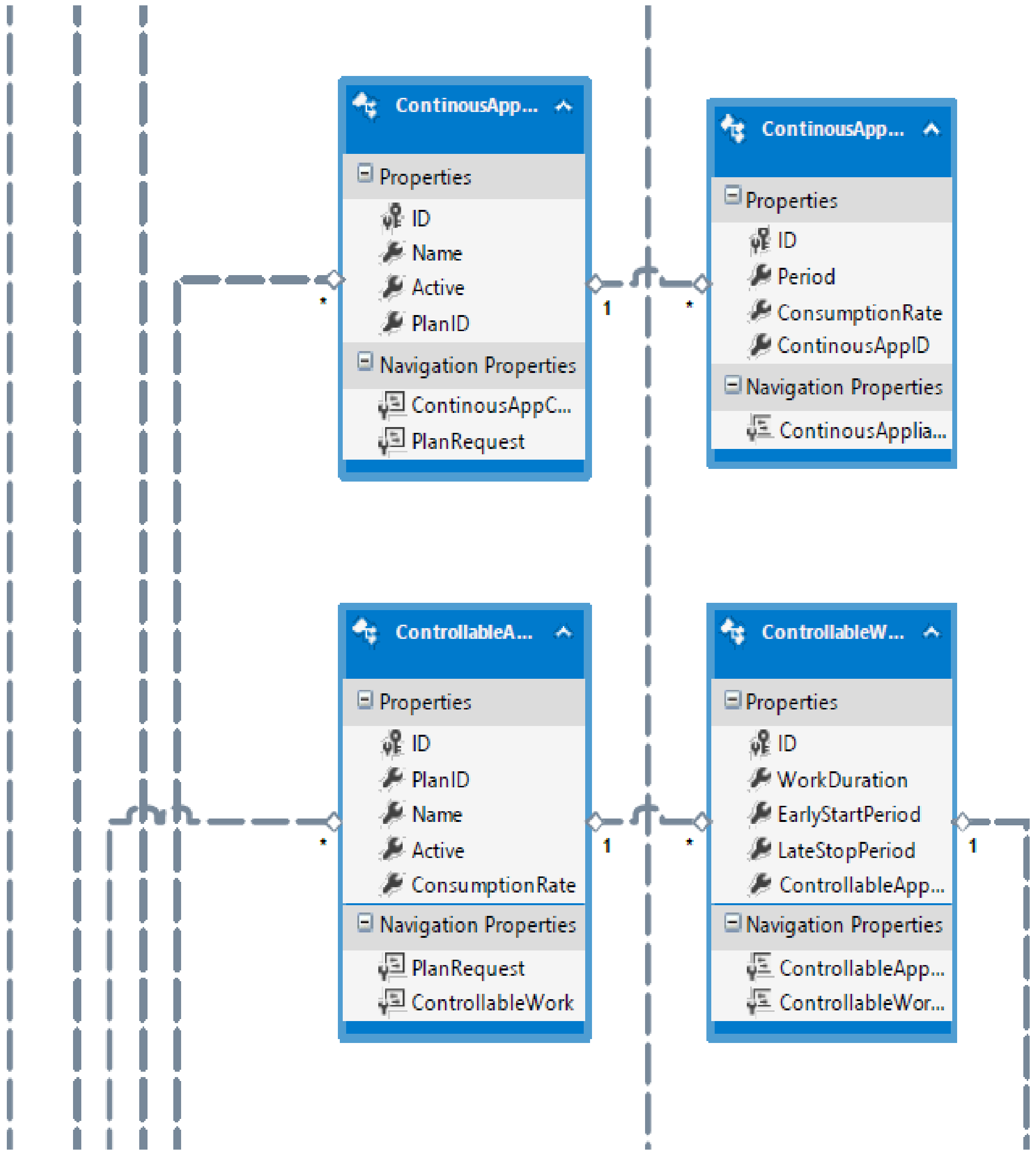
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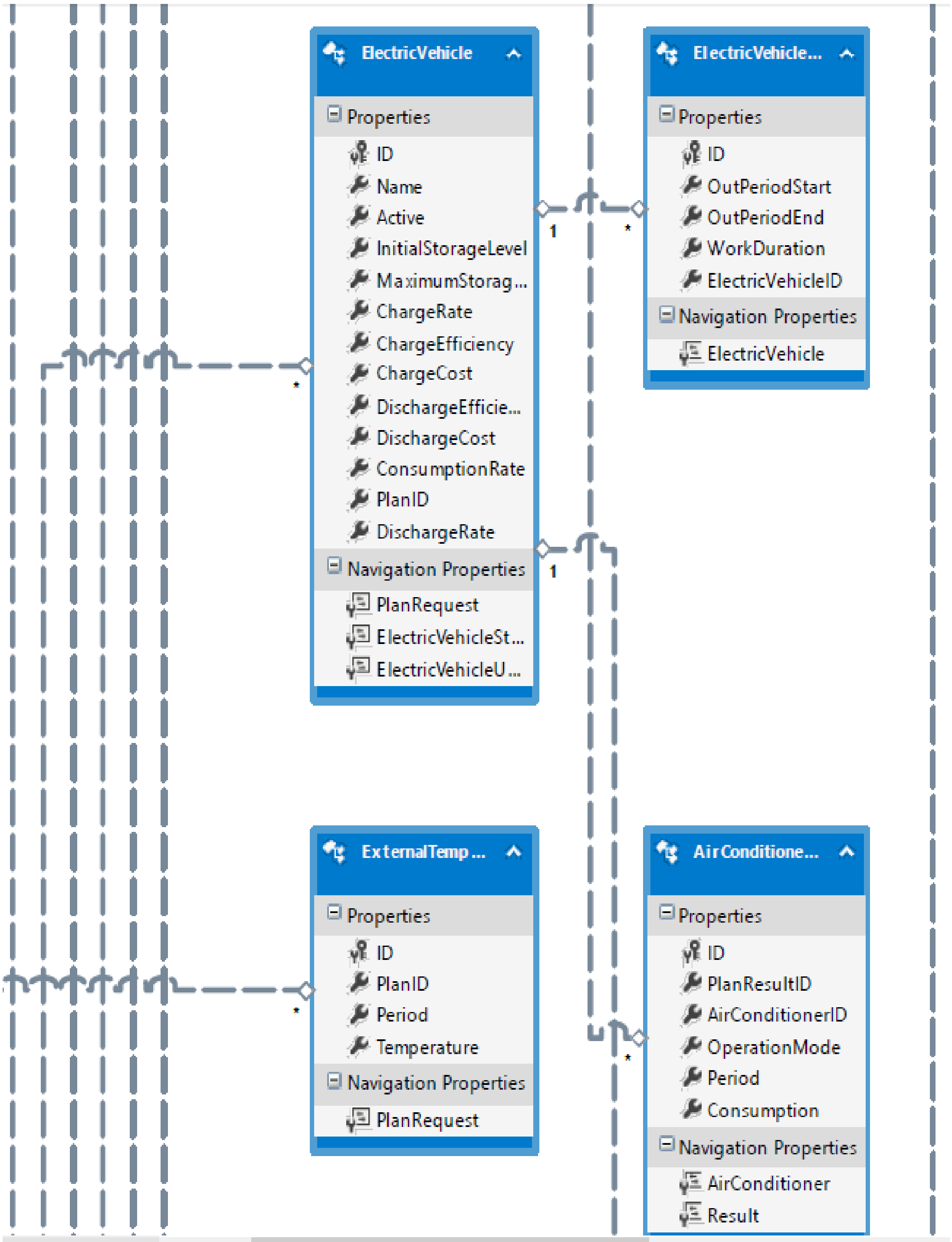
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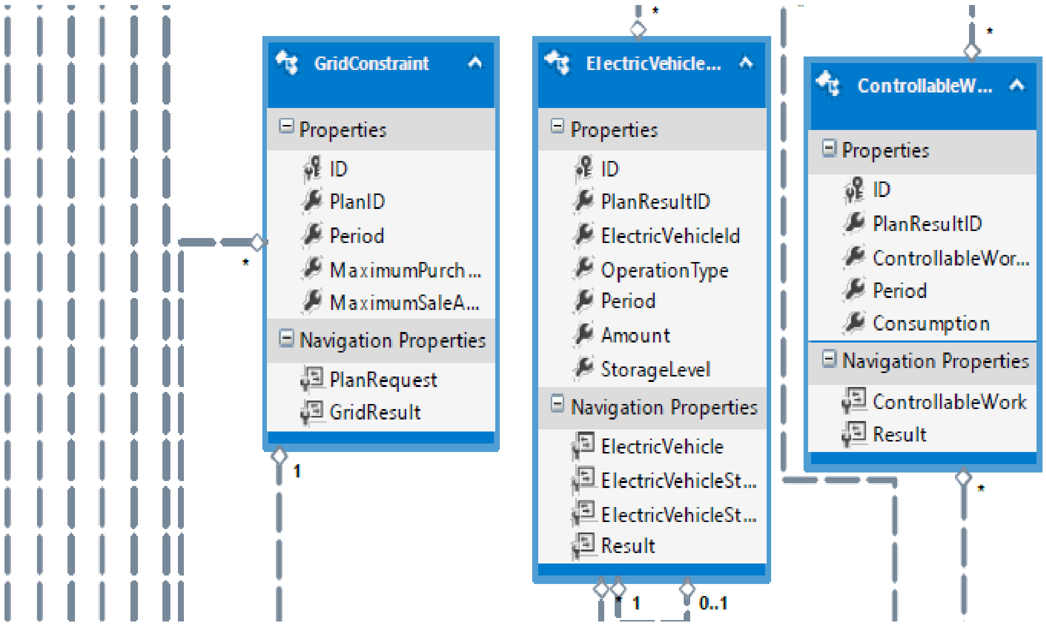
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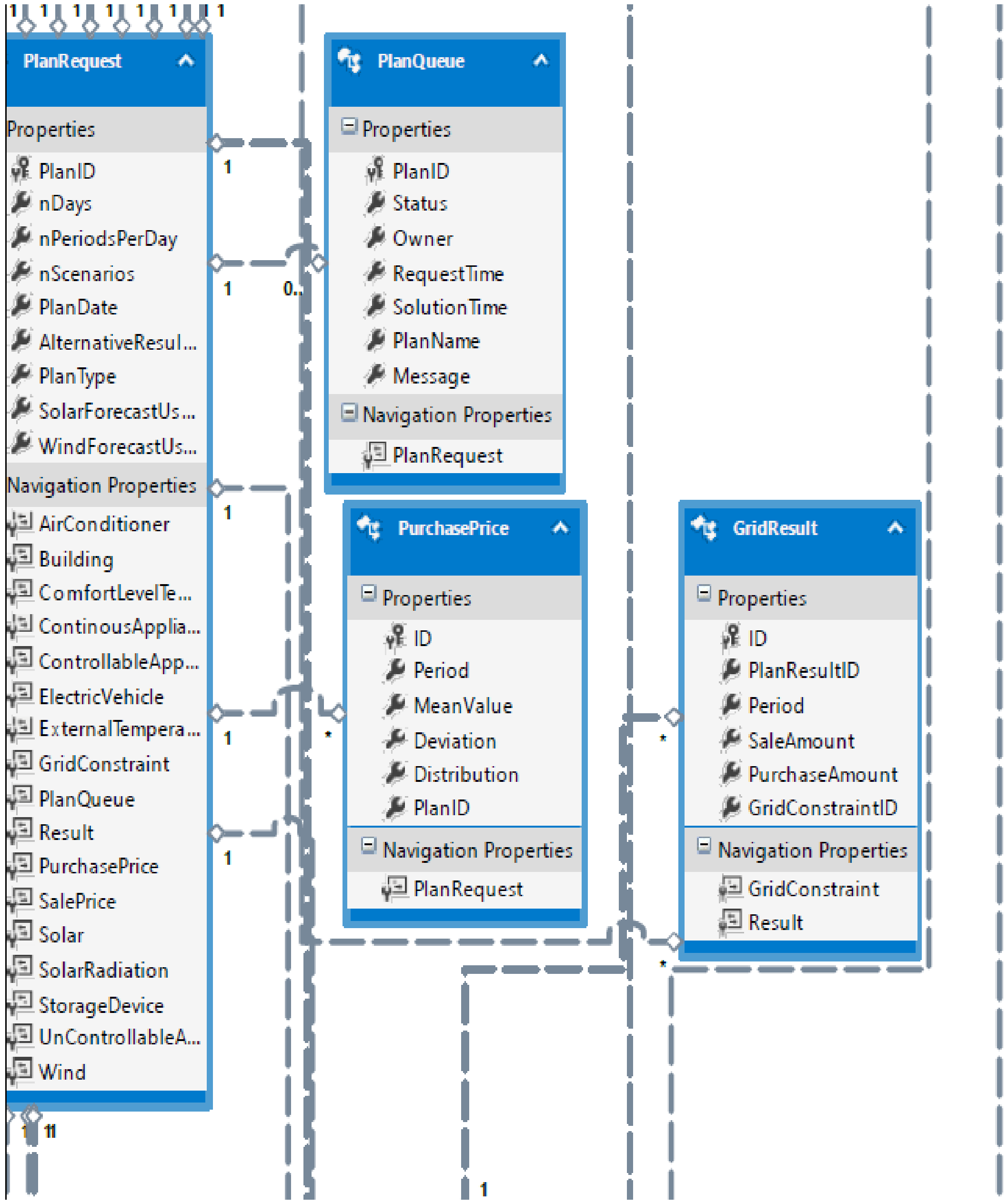
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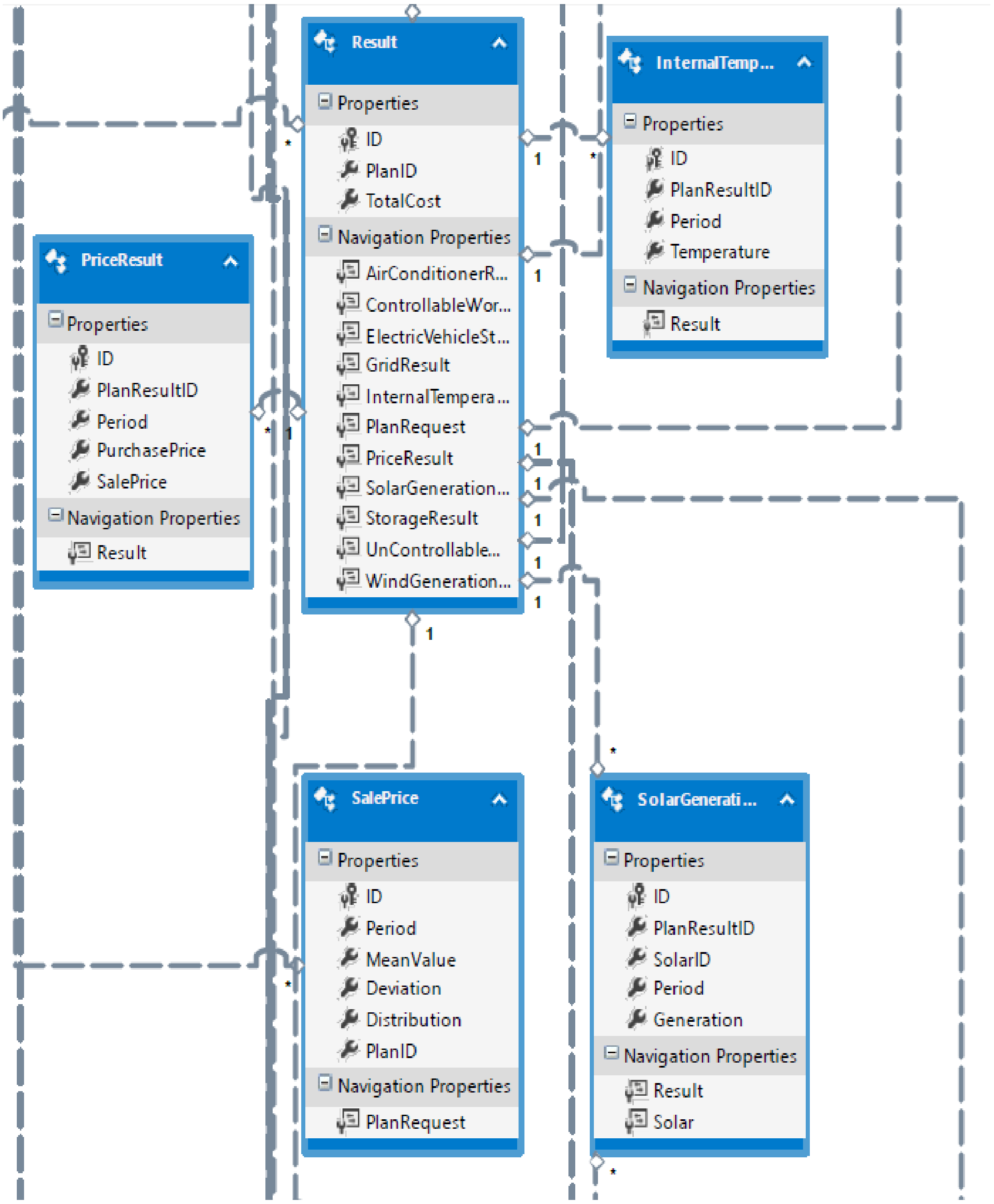
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Period
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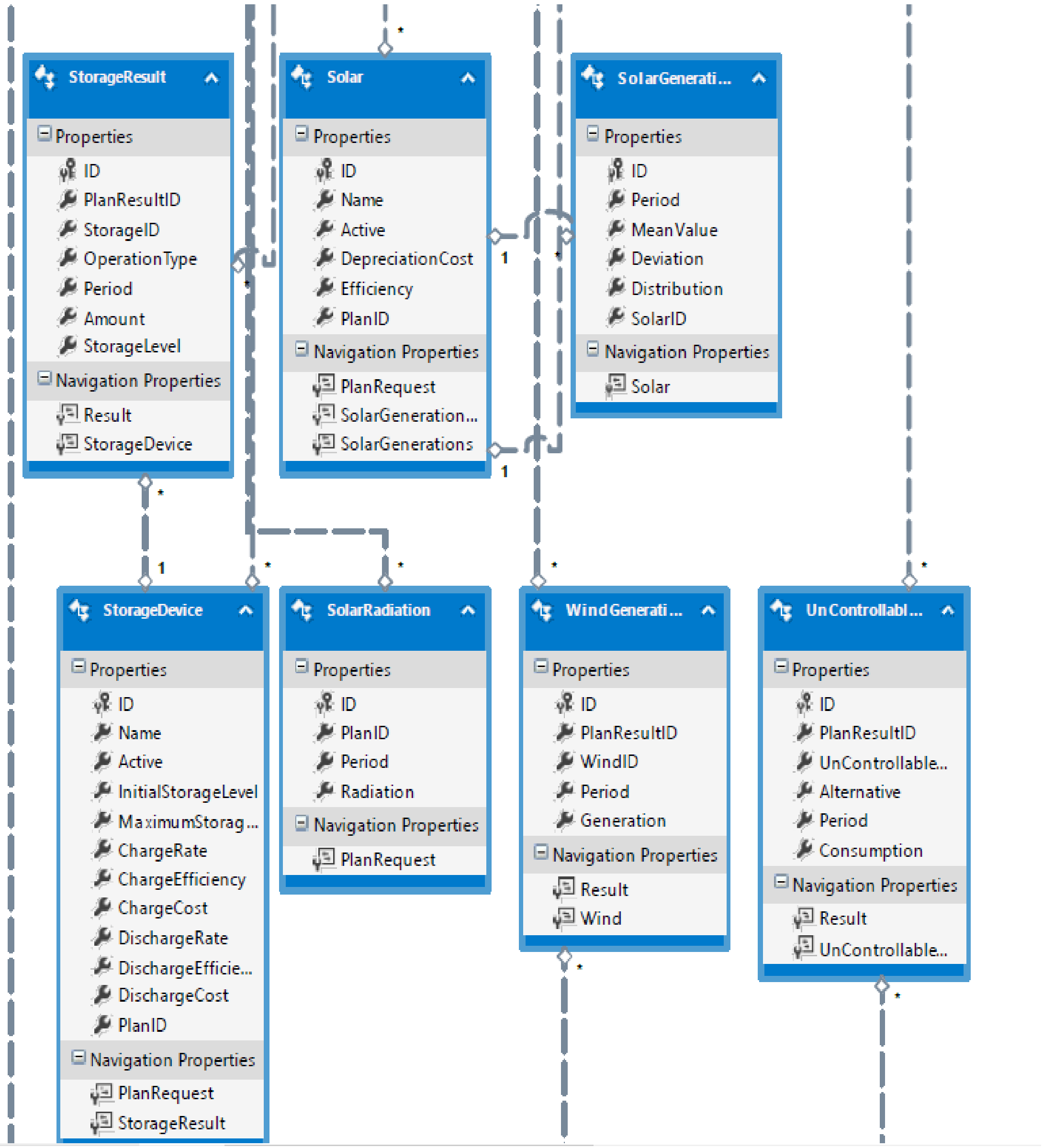
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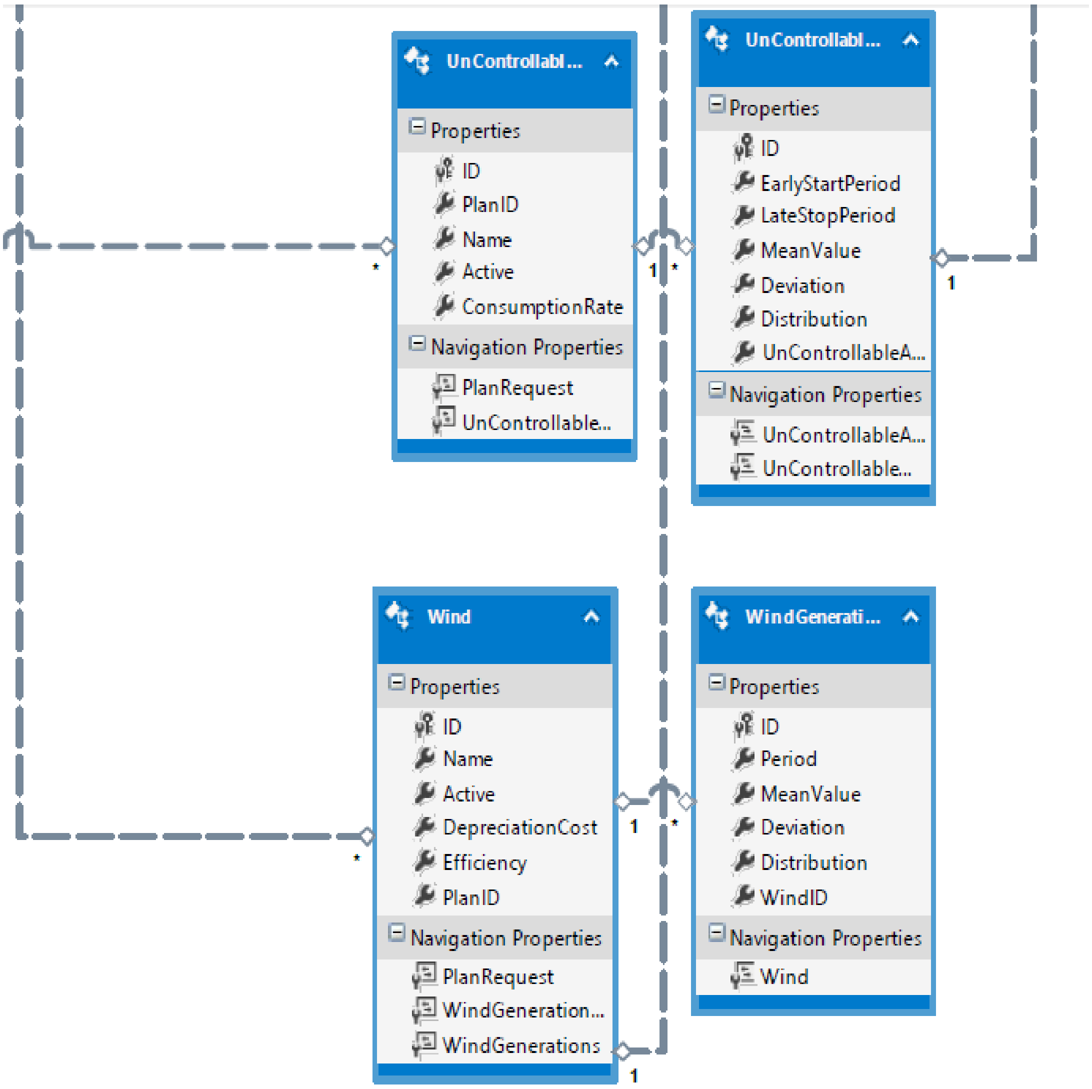

Figure D.1: Database Diagram

APPENDIX E

The Result of Optimization Model and Simulation

Table E.1: The Result of Optimization Model and Simulation

Price Tariff	Scenario	Experiment	Model			Simulation		
			Duration(s)	Gap (%)	Cost	Cost	Purchase Cost	Sale Revenue
1	1	1	1	0	3,3052	3,6173	4,5178	1,4109
		2*	1	0	3,2790	3,6290	4,5190	1,3989
		3	1	0	3,3336	3,6125	4,5484	1,4423
		4	1	0	3,4163	3,6053	4,5074	1,4181
		5	1	0	3,4677	3,6124	4,5015	1,3928
	Average		**1**	**0**	**3,3603**	**3,6153**	**4,5188**	**1,4126**
	10	1	7	0	3,4428	3,5805	4,4832	1,4138
		2	8	0	3,4285	3,5803	4,4870	1,4215
		3	6	0	3,4278	3,5824	4,4776	1,4069
		4	6	0	3,4030	3,5795	4,5126	1,4509
		5	12	0	3,4313	3,5827	4,4780	1,4087
	Average		**7,8**	**0**	**3,4267**	**3,5811**	**4,4877**	**1,4204**
	25	1	23	0	3,4202	3,5790	4,4594	1,3881
		2	40	0	3,4230	3,5796	4,4517	1,3780
		3	29	0	3,4235	3,5801	4,4305	1,3516
		4	32	0	3,4106	3,5790	4,4584	1,3870
		5	62	0	3,4467	3,5799	4,4758	1,4067
	Average		**37,2**	**0**	**3,4248**	**3,5795**	**4,4552**	**1,3823**
	50	1	305	0	3,4315	3,5775	4,4460	1,3762
		2	81	0	3,4336	3,5777	4,4602	1,3929
		3	94	0	3,4093	3,5772	4,4599	1,3918
		4	132	0	3,4347	3,5779	4,4478	1,3791
		5	187	0	3,4260	3,5769	4,4667	1,3984
	Average		**159,8**	**0**	**3,4270**	**3,5774**	**4,4561**	**1,3877**

Table E.1 continued

1	100	1	648	0	3,4189	3,5776	4,4593	1,3901
		2	638	0	3,4263	3,5777	4,4534	1,3844
		3*	273	0	3,4284	3,5765	4,4431	1,3732
		4	398	0	3,4191	3,5771	4,4524	1,3832
		5	660	0	3,4269	3,5767	4,4623	1,3942
	Average		**523,4**	**0**	**3,4239**	**3,5772**	**4,4541**	**1,3850**
	100	Only AC	3	0	2,7810	2,8492	2,8492	0,0000
	100	Only Storage	1	0	-0,9342	-0,8681	1,5425	2,4106
	1	Deterministic	1	0	3,4797	3,5756	4,4875	1,4274
2	1	1	2	0	4,4332	4,5883	4,3825	0,0679
		2*	3	0	4,4056	4,6099	4,4039	0,0878
		3	2	0	4,3763	4,5788	4,3578	0,0488
		4	2	0	4,3288	4,5714	4,3529	0,0524
		5	2	0	4,4721	4,5881	4,3913	0,0727
	Average		**2,2**	**0**	**4,4032**	**4,5873**	**4,3777**	**0,0659**
	10	1	399	0	4,4302	4,5387	4,3133	0,0308
		2	112	0	4,4190	4,5428	4,3271	0,0385
		3	98	0	4,4572	4,5434	4,3238	0,0321
		4	222	0	4,4342	4,5310	4,3058	0,0250
		5	235	0	4,4625	4,5373	4,3156	0,0329
	Average		**213,2**	**0**	**4,4406**	**4,5386**	**4,3171**	**0,0319**
	25	1	686	0	4,4477	4,5354	4,3142	0,0286
		2	2429	0	4,4317	4,5366	4,3164	0,0310
		3	700	0	4,4431	4,5361	4,3133	0,0289
		4	619	0	4,4584	4,5320	4,3102	0,0248
		5	788	0	4,4368	4,5352	4,3155	0,0327
	Average		**1044,4**	**0**	**4,4435**	**4,5351**	**4,3140**	**0,0292**
	50	1	1775	0	4,4608	4,5373	4,3172	0,0317
		2*	2723	0	4,4508	4,5294	4,3043	0,0236
		3	1913	0	4,4461	4,5355	4,3140	0,0299
		4	2907	0	4,4439	4,5398	4,3281	0,0399
		5	2350	0	4,4646	4,5405	4,3224	0,0339
	Average		**2333,6**	**0**	**4,4532**	**4,5365**	**4,3172**	**0,0318**
	100	1	13288	0	4,4566	4,5398	4,3238	0,0357
		2	18000	0,015	4,4527	4,5380	4,3197	0,0333

Table E.1 continued

2	100	3	18000	0,0232	4,4588	4,5374	4,3142	0,0259
		4	13240	0	4,4622	4,5352	4,3152	0,0304
		5	15985	0	4,4534	4,5374	4,3171	0,0318
	Average		**15702,6**	**0,0076**	**4,4568**	**4,5376**	**4,3180**	**0,0314**
	100	AC	1	0	3,1223	3,1232	3,1232	0,0000
	100	Storage	2	0	0	0,0000	0,0000	0,0000
	1	Deterministic	1	0	4,4790	4,5620	4,3633	0,0618
3	1	1	1	0	4,3910	4,6232	4,9849	0,8157
		2	1	0	4,4327	4,6197	5,0063	0,8394
		3*	1	0	4,4124	4,6289	4,9074	0,7210
		4	2	0	4,4079	4,5993	4,9208	0,7642
		5	2	0	4,3964	4,6255	4,9048	0,6987
	Average		**1,4**	**0**	**4,4081**	**4,6193**	**4,9448**	**0,7678**
	10	1	46	0	4,4871	4,6061	4,9120	0,7605
		2	34	0	4,4838	4,6099	4,8582	0,6907
		3	51	0	4,4560	4,6086	4,8798	0,7212
		4	92	0	4,5385	4,6234	4,9210	0,7473
		5	134	0	4,5197	4,6079	4,9100	0,7554
	Average		**71,4**	**0**	**4,4970**	**4,6112**	**4,8962**	**0,7350**
	25	1	23	0	4,5341	4,6040	4,8644	0,7050
		2	40	0	4,4795	4,5878	4,8779	0,7352
		3	29	0	4,4940	4,6047	4,9406	0,7974
		4	32	0	4,5088	4,5948	4,9101	0,7719
		5	62	0	4,5010	4,6006	4,8360	0,6707
	Average		**37,2**	**0**	**4,5035**	**4,5984**	**4,8858**	**0,7360**
	50	1	3128	0	4,5140	4,6033	4,8821	0,7255
		2	1339	0	4,4949	4,5899	4,8990	0,7610
		3	2274	0	4,4972	4,5994	4,8650	0,7093
		4	7192	0	4,4877	4,5924	4,9003	0,7597
		5	1739	0	4,4968	4,5917	4,9163	0,7786
	Average		**3134,4**	**0**	**4,4981**	**4,5953**	**4,8925**	**0,7468**
	100	1	13750	0	4,5000	4,6040	4,8902	0,7385
		2	14384	0	4,5028	4,6042	4,8522	0,6908
		3*	18000	0,0494	4,5109	4,5845	4,8377	0,6932
		4	18000	0,0191	4,5032	4,6017	4,9213	0,7779
		5	18000	0,0148	4,5062	4,6032	4,8816	0,7278

Table E.1 continued

	Average		**16426,8**	**0,0167**	**4,5046**	**4,5995**	**4,8766**	**0,7257**
	100	AC	1	0		3,2817	3,2817	0,0000
	100	Storage	2	0		-0,5769	1,3999	1,9768
	1	Deterministic	1	0		4,6089	4,9467	0,7953

Price Tariff	**Scenario**	**Experiment**	**Simulation**							
			Depr. Cost	**Purchase Amount**	**Sale Amount**	**AC Cons.**	**Storage Charge**	**Storage Dischar.**	**PHEV Charge**	**PHEV Dischar.**
1	1	1	0,5104	50034,81	10098,32	25984,52	14818,91	14818,91	3211,72	3146,72
		2*	0,5089	50006,43	9980,69	25964,78	14722,76	14598,05	3292,64	3227,64
		3	0,5063	50162,15	10337,76	25907,21	14576,85	14576,85	3250,00	3185,00
		4	0,5161	50104,06	10177,36	25924,71	14817,20	14817,19	3495,63	3430,63
		5	0,5037	49770,57	9931,09	25943,65	14820,62	14820,62	2875,00	2810,00
	Average		**0,5091**	**50015,61**	**10105,05**	**25944,97**	**14751,27**	**14726,33**	**3225,00**	**3160,00**
	10	1	0,5110	49970,43	10049,91	25965,82	14560,65	14560,65	3499,35	3434,35
		2	0,5149	50027,55	10099,03	25939,97	14729,49	14729,49	3526,34	3461,34
		3	0,5117	49875,95	9982,11	25924,57	14717,68	14717,68	3375,00	3310,00
		4	0,5178	50278,13	10325,15	25938,85	14726,99	14727,00	3673,61	3608,61
		5	0,5134	49978,53	10014,43	25986,23	14605,53	14605,53	3576,69	3511,69
	Average		**0,5138**	**50026,12**	**10094,13**	**25951,09**	**14668,07**	**14668,07**	**3530,20**	**3465,20**
	25	1	0,5077	49726,16	9849,33	25943,31	14395,30	14395,30	3498,51	3433,51
		2	0,5059	49609,04	9779,35	25912,58	14305,09	14305,10	3500,16	3435,16
		3	0,5012	49347,15	9582,98	25889,71	14104,30	14104,31	3466,29	3401,29
		4	0,5076	49656,95	9845,50	25879,17	14394,89	14394,89	3495,63	3430,63
		5	0,5108	49824,40	9984,32	25880,28	14604,85	14604,86	3442,99	3377,99
	Average		**0,5066**	**49632,74**	**9808,29**	**25901,01**	**14360,89**	**14360,89**	**3480,72**	**3415,72**
	50	1	0,5077	49651,94	9760,87	25958,86	14429,25	14429,25	3466,45	3401,45
		2	0,5104	49713,66	9880,00	25880,83	14497,65	14497,65	3532,95	3467,95
		3	0,5092	49763,88	9870,16	25950,19	14468,05	14468,05	3500,00	3435,00
		4	0,5091	49659,71	9785,63	25932,80	14437,21	14437,21	3528,82	3463,82
		5	0,5087	49811,47	9918,74	25956,32	14444,76	14444,76	3499,25	3434,25
	Average		**0,5090**	**49720,13**	**9843,08**	**25935,80**	**14455,38**	**14455,38**	**3505,49**	**3440,49**

Table E.1 continued

1	100	1	0,5084	49711,50	9869,12	25905,94	14433,89	14433,89	3496,75	3431,75
		2	0,5087	49690,07	9820,51	25935,63	14439,16	14439,16	3506,82	3441,82
		3*	0,5066	49598,41	9744,89	25938,64	14343,90	14343,90	3498,13	3433,13
		4	0,5079	49703,87	9818,60	25949,86	14403,12	14403,12	3501,79	3436,79
		5	0,5087	49704,57	9896,36	25873,75	14444,60	14444,60	3498,28	3433,28
	Average		**0,5081**	**49681,68**	**9829,90**	**25920,76**	**14412,93**	**14412,93**	**3500,35**	**3435,36**
	100	Only AC	0,0000	26395,92	0,00	26395,92	0,00	0,00	0,00	0,00
	100	Only Storage	0,0000	17750,00	17750,00	0,00	17750,00	17750,00	0,00	0,00
	1	Deterministic	0,5155	50043,99	10147,29	25904,76	14750,00	14750,00	3536,22	3471,22
2	1	1	0,2738	38461,79	943,53	25482,37	5227,92	5167,87	1000,00	935,00
		2*	0,2938	38893,10	1219,00	25529,25	5823,79	5823,79	1375,00	1310,00
		3	0,2698	38177,22	677,13	25501,30	5246,78	5190,55	781,66	716,66
		4	0,2710	38192,43	728,28	25513,61	5185,27	5185,27	875,00	810,00
		5	0,2695	38485,18	1009,28	25536,50	5564,57	5564,57	420,00	355,00
	Average		**0,2756**	**38441,94**	**915,45**	**25512,61**	**5409,67**	**5386,41**	**890,33**	**825,33**
	10	1	0,2561	37690,49	427,55	25433,00	4864,35	4864,35	452,86	387,86
		2	0,2542	37823,40	535,13	25475,24	5013,00	5013,00	208,92	143,92
		3	0,2518	37757,42	446,35	25477,51	4825,90	4825,90	290,95	188,89
		4	0,2502	37581,57	347,19	25460,40	4514,36	4523,05	500,85	435,85
		5	0,2545	37711,04	456,50	25439,72	4873,48	4875,82	361,41	296,41
	Average		**0,2534**	**37712,78**	**442,54**	**25457,18**	**4818,22**	**4820,42**	**363,00**	**290,58**
	25	1	0,2497	37617,06	397,03	25442,76	4651,53	4651,53	345,44	280,44
		2	0,2512	37646,62	431,07	25429,86	4675,14	4675,14	395,57	330,57
		3	0,2517	37643,12	401,40	25446,10	4797,56	4797,56	295,25	230,25
		4	0,2466	37590,40	344,91	25494,73	4537,01	4537,01	303,94	238,94
		5	0,2523	37662,47	453,55	25413,74	4865,69	4865,68	259,08	194,08
	Average		**0,2503**	**37631,93**	**405,59**	**25445,44**	**4705,39**	**4705,39**	**319,86**	**254,86**
	50	1	0,2518	37662,66	440,69	25429,45	4774,27	4774,27	323,54	258,54
		2*	0,2486	37546,30	327,96	25451,53	4683,08	4683,08	258,92	193,92
		3	0,2514	37639,40	415,18	25436,66	4819,98	4819,98	258,68	193,68
		4	0,2516	37785,03	554,68	25439,24	4749,89	4749,89	340,46	275,46
		5	0,2520	37718,12	470,89	25446,78	4736,85	4736,85	375,00	310,00
	Average		**0,2511**	**37670,30**	**441,88**	**25440,73**	**4752,81**	**4752,81**	**311,32**	**246,32**

Table E.1 continued

2	100	1	0,2516	37757,39	495,24	25469,04	4780,03	4780,03	311,77	246,77
		2	0,2515	37706,40	462,01	25450,86	4721,07	4721,07	366,11	301,11
		3	0,2492	37636,39	360,18	25452,72	4698,67	4648,40	294,76	229,76
		4	0,2504	37653,88	422,45	25449,88	4731,30	4731,30	299,90	234,90
		5	0,2520	37675,37	441,17	25436,69	4817,53	4817,53	294,68	229,68
	Average		**0,2510**	**37685,89**	**436,21**	**25451,84**	**4749,72**	**4739,67**	**313,44**	**248,44**
	100	AC	0,0000	26047,40	0,00	26047,40	0,00	0,00	0,00	0,00
	100	Storage	0,0000	0,0000	0,00	0,00	0,00	0,00	0,00	0,00
	1	Deterministic	0,2604	38204,34	858,30	25478,60	5051,09	5051,09	481,06	416,06
3	1	1	0,4540	44864,58	5823,72	25555,94	12276,40	12276,40	2933,46	2868,46
		2	0,4528	45057,87	5973,19	25615,53	12190,03	12190,03	2957,57	2892,57
		3*	0,4425	44151,91	5182,73	25575,84	11652,02	11652,02	2982,21	2917,21
		4	0,4427	44193,35	5459,37	25341,08	12013,73	12013,73	2628,97	2563,97
		5	0,4194	43733,43	4964,75	25572,15	10736,21	10736,21	2743,88	2678,88
	Average		**0,4423**	**44400,23**	**5480,75**	**25532,11**	**11773,68**	**11773,68**	**2849,22**	**2784,22**
	10	1	0,4546	44388,46	5395,67	25503,32	12625,00	12625,00	2616,20	2551,20
		2	0,4424	43829,25	4911,38	25529,25	11868,82	11868,82	2762,85	2697,85
		3	0,4500	44074,13	5119,95	25503,51	12250,00	12250,00	2759,05	2694,05
		4	0,4497	44368,48	5288,85	25502,92	12335,82	12198,61	2726,34	2661,35
		5	0,4534	44376,15	5362,31	25530,81	12625,00	12625,00	2552,71	2487,71
	Average		**0,4500**	**44207,29**	**5215,63**	**25513,96**	**12340,93**	**12313,49**	**2683,43**	**2618,43**
	25	1	0,4446	43877,14	4982,25	25488,37	12117,79	12117,79	2621,97	2556,97
		2	0,4451	44011,36	5180,11	25422,13	12211,26	12211,26	2554,89	2489,89
		3	0,4615	44721,39	5656,71	25518,95	12954,56	12954,56	2628,04	2563,04
		4	0,4567	44389,67	5496,89	25383,70	12515,69	12515,70	2828,83	2763,83
		5	0,4352	43547,29	4713,38	25510,44	11845,11	11845,12	2422,85	2357,85
	Average		**0,4486**	**44109,37**	**5205,87**	**25464,72**	**12328,88**	**12328,88**	**2611,32**	**2546,32**
	50	1	0,4467	44061,39	5138,34	25503,40	12283,24	12283,24	2560,35	2495,35
		2	0,4519	44270,50	5388,60	25412,09	12477,34	12477,34	2628,94	2563,94
		3	0,4438	43900,56	5022,61	25293,00	12171,48	12171,48	2621,44	2370,75
		4	0,4518	44258,70	5394,79	25397,01	12478,64	12478,64	2620,24	2555,24
		5	0,4541	44426,29	5528,53	25417,57	12595,09	12595,09	2617,72	2552,72
	Average		**0,4496**	**44183,49**	**5294,58**	**25404,61**	**12401,16**	**12401,16**	**2609,74**	**2507,60**

Table E.1 continued

3	100	1	0,4524	44189,77	5230,47	25486,88	12511,80	12511,79	2616,25	2551,25
		2	0,4428	43762,51	4889,66	25484,70	12100,57	12100,56	2550,73	2485,73
		3*	0,4401	43598,10	4863,34	25288,66	12136,33	12060,41	2414,36	2349,36
		4	0,4583	44502,52	5502,31	25482,44	12660,66	12660,66	2763,26	2698,26
		5	0,4494	44078,15	5155,14	25478,40	12344,49	12344,49	2635,32	2570,32
	Average		**0,4486**	**44026,21**	**5128,18**	**25444,21**	**12350,77**	**12335,58**	**2595,98**	**2530,98**
	100	AC	0,0000	26071,93	0,00	26071,93	0,00	0,00	0,00	0,00
	100	Storage	0,0000	14000,00	14000,00	0,00	14000,00	14000,00	0,00	0,00
	1	Deterministic	0,4575	44704,99	5664,80	25526,87	13887,43	13887,43	1500,00	1435,00