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Load Management in a Smart House

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Resumo

O setor residencial é um dos setores com um dos maiores índices de consumo de eletricidade em todo o mundo. Desde há alguns anos, que têm sido realizados estudos para minimizar o consumo de energia ao nível residêncial. Nesse contexto, a ideia dos estudos que se têm vindo a desenvolver é que o cliente residencial é a parte interessada do seu próprio consumo. Com isso em mente, os algoritmos que têm vindo a ser desenvolvidos para prever e gerir o consumo da energia ao nível residêncial, analisam também o comportamento das cargas com o objetivo de minimizar os custos de energia garantindo os níveis de segurança, robustez e conforto.

No contexto das casas inteligentes, um dos objetivos das redes inteligentes é o de permitir que os clientes dotados de sistemas *Home Energy Management* (HEM) participem ativamente, o que permitirá uma maior eficiência em diferentes níveis. A ideia por detrás do HEM é a gestão e coordenação do comportamento do cliente com a produção e armazenamento de eletricidade, onde o cliente desempenha um papel vital nos mecanismos de transação de eletricidade, "adaptando" o consumo efetuado, e tomando as decisões sobre o comportamento dos próprios dispositivos de geração, consumo, e armazenamento, a fim de reduzir os custos do consumo elétrico.

Nesta dissertação, o objetivo passa pelo desenvolvimento de um algortimo que simule o comportamento de uma casa inteligente, considerando as principais cargas existentesm, como sejam os dispositivos de climatização e de aquecimento das águas sanitárias. Para o efeito, o modelo considera os parâmetros físicos da casa para obter uma melhor aproximação da realidade.

Embora a redução dos custo do consumo elétrico sejam importantes, o modelo desenvolvido considera ainda o nível de conforto do cliente, de forma a mitigar o desinteresse que o cliente possa suscitar ao utilizar o modelo proposto. Com efeito, o modelo desenvolvido considera a integração do veículo elétrico, de um sistema de armazenamento de energia baseado em baterias, e uma duma unidade de micro produção de eletricidade.

Com efeito, através da análise realizada, e considerando os diversos tipos de tarifas que o cliente pode escolher, o melhor tarifário a adotar para o problema em análise foi o do tempo de utilização, ou *time of use* (ToU), onde o cliente terá o beneficio máximo, e ainda poderá, em determinados momentos, deslocar as cargas temporalmente de forma a minimizar os custos.

Palavras-Chave

Carga, Casa inteligente, Cliente elétrico, Decisão, Home energy management, Rede inteligente.

Abstract

The residential sector is one of the sectors with one of the highest rates of electricity consumption in the world. For some years, studies have been carried out to minimize energy consumption at the residential level. In this context, the idea of the studies that have been developed is that the residential customer is the interested party of its own consumption. With this in mind, the algorithms that have been developed to predict and manage the energy consumption at the residential level, also analyze the behavior of the loads with the objective of minimizing energy costs, guaranteeing levels of safety, robustness, and comfort.

In the context of smart homes, one of the objectives of smart grids is to enable customers with home energy management (HEM) systems to actively participate, which will allow greater efficiency at different levels. The idea behind HEM is the management and coordination of customer behavior with the production and storage of electricity, where the customer plays a vital role in the electricity transaction mechanisms, adapting his consumption, and making the decisions about the behavior of the generation, consumption, and storage devices himself, in order to reduce the costs of electric consumption.

In this dissertation, the objective is to develop an algorithm that simulates the behavior of a smart house, considering the main loads that exist, such as the air conditioning and heating devices in the sanitary waters. For this purpose, the model considers the physical parameters of the house to obtain a better approximation of the reality.

Although the reduction of the electric cost consumption is important, the developed model also considers the customer's comfort, in order to mitigate the disinterest that the customer can raise when using the proposed/strategy. In fact, the model developed considers the integration of the electric vehicle (EV), a battery-based energy storage system (ESS), and a micro electricity production unit.

Moreover, through the analysis performed, and considering the different types of tariffs that the customer can choose, the best tariff to adopt for the problem under analysis was the time of use (TOU), where the customer will have the maximum benefit, and can still, in certain moments, temporarily shift loads in order to minimize the costs.

Keywords

Decision, Electrical client, Home energy management, Loads, Smart grid, Smart house.

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Gonçalo Carvalho

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Abbreviations

A/S	Ancillary Service
CAP	Capacity Market Program
DEMS	Domestic Energy Management System
DLC	Direct Load Control
DR	Demand Response
EDRP	Emergency Demand Response Program
EC	Expected Cost
EP	Expected Profit
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
HEM	Home Energy Management
HVAC	Heating, Ventilation, Air Conditioning
IBDR	Incentive-Base Demand Response
ISO	Independent System Operator
IOT	Internet of Things
LM	Local Market
MRS	Must-Run Services
PBDR	Price-Based Demand Response
PHEV	Plug-in Hybrid Electric Vehicle
RTP	Real-Time Pricing
TSO	Transmission System Operator
TOU	Time of Use

Chapter 1

Introduction

1.1 Contextualization

Society is heavily dependent on electricity. The development of control systems has enabled the energy supply service to which increases the expectation of consumers regarding prices, quality and efficiency.

One of the sectors that has been developing in mass is the exploration of the renewable energies. The main reason for the particular attention for this type of energy was the political pressure to reduce emissions of polluting gases and dependence on fossil fuels.

The European Union has set goals for the year 2020 and following years which aims to promote the use of renewable energies in order to reach 20% of total energy consumption [1], thereby reducing the consumption of polluting systems.

Thus, in order to improve efficiency, the concept of smart grid emerges. Smart grids is referred to an electrical energy system that uses information technology to make the system more efficient, reliable and sustainable. This automatization brings important benefits, like efficiency which allows the user with less energy to have the same level of quality. Another important issue solved is the reduction of pollutant gases.

And finally, the smart grid can detect malfunctioning devices that allow the utility to solve the problem quickly [2].

With this approach, it is necessary to create communication systems that are capable of efficient communication between systems in the smart grid. The communication infrastructure is essential for a operation of the smart grid. The type of communication used in the smart grids are Zigbee, WLAN, cellular communication, WiMAX, Power Line Communication(PLC) [3].

It was only a matter of time until the concept of smart houses emerged, making possible the whole connection with appliances at home, in order to make possible a better use of the energy in the house. The goal is to have all the devices in the house connected to the network. The number as we see on Figure 2.1 [4] will grow a lot.

However, with the creation of the communications of devices in smart house via the Internet, there are vulnerabilities of the system and security risks.

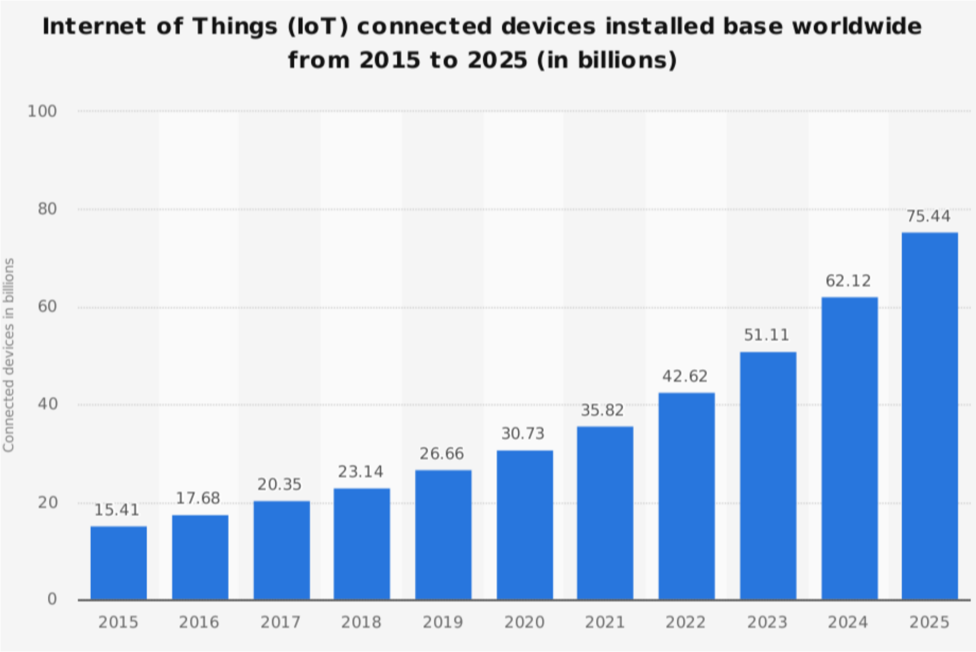

Figure 1.1: Number of connected devices in billions (with prediction).

Smart houses will have a tremendous importance ensuring the efficiency of the smart house, but also in terms of connections with the smart grid. This type of house has a huge potential but needs coordination with its user in order to obtain an optimal solution, both in terms of comfort and in terms of energy.

In order to establish the control of energy consumed in an automated house, there are electronic devices, smart meters, whose objective is to monitor in real time the energy or gas usage, and sent the information directly to the utility company. Some utilities will show what equipment's consume more energy.

Finally, once there is a connection between the smart grid and the smart house, the objective is to have real-time monitoring and adjustments of the energy consumed, in order to reduce the electric bill.

1.2 Objectives

The present work aims at the study of the functioning of a smart house, with limited resources, and equipped with a wind micro turbine, EV energy-exchange possibility, and a battery-base energy storage system (ESS). The possibility of selling back to the grid, within the line limit parameters. The objectives are:

- Evaluate the load distribution of the electric water heater for each tariff;
- Evaluate the load distribution of the heating, ventilation and air-conditioning (HVAC) system, in cooling mode, for each tariff.

- Evaluate the cost/profit associated for each tariff (flat price, time-of-use (TOU), real-time pricing (RTP) and critical price piking (CPP) schemes.

1.3 Structure of the Dissertation

This dissertation is divided into five chapters. Chapter 1 corresponds to a brief framework of the theme under analysis, the proposed objectives, motivation and the tools used, as well as the organization of the text.

In Chapter 2, a bibliographic review on the topic of smart houses is carried out. First, a little introduction about the theme, and some of its features. Then the smart house theme is presented further, with the different range of applications. Also in Chapter 2, both the theme of the different charges in a Smart House and the Internet of Things (IoT) are presented in detail and explained some of their problems and also the benefits and associated risks. Also explained are the different of Demand Response, and lastly, the associated multi objective problem and technological advances.

In Chapter 3, the mathematical formulation of the problem is presented, in which the objective function is the minimization of the cost or increase of the profit of the house. Also presented are the first and second stage restrictions, day-ahead market and real-time market, respectively.

In Chapter 4 presents the different case studies and the numerical results obtained. The impacts of the Demand Response programs for the different loads (EWH and SH) and the cost / profit associated for each tariff were analyzed. Finally, Chapter 5 presents the conclusions obtained from the studies carried out and describes the possible approaches for future work.

1.4 Organization of the Text

The present dissertation uses similar notations to those used in the scientific community, harmonizing the common aspects in all the sections. Figures, Tables and the mathematical formulation are indicated relatively to the chapter in which they are inserted, and their numbering are restarted when a new chapter is initialized.

The references that support the different chapters that compose the present dissertation will be structured and identified by [XX] and the mathematical formulation by (X.X). The abbreviations used are structured for the synthesis of names and technical information from the English language, accepted in the technical and scientific community.

Chapter 2

Literature Review

In this chapter the concepts of smart houses, considering the benefits, risks, different types of smart houses and others aspects are described. Moreover, the topics of loads and the internet-of-things (IoT) are introduced as well. Hence, the different demand response (DR) programs, and the topics of multi-objective problem and technological advances are presented.

2.1 Introduction

Nowadays, there is a need to optimize the energy consumption of houses in order to minimize the prices of the energy and reduce the greenhouse gases emissions. For that purpose, the European Union (EU) members are increasing the renewable energy production which leads with more variable power generation [5].

At this point, a new concept emerges - the concept of Smart Houses. According to [6], a Smart House is a technology where everything can be controlled and monitored in different areas such as home appliances, energy-consuming devices like heating, ventilation, air-conditioning (HVAC), dishwashers, washers and dryers, through networks. The consumers have access to in-house devices controllers which results in a better quality of life and cost saving.

Since the last decade, a competitive energy market was established. During the day there is a variation of the energy prices which makes interesting the idea of buying electricity when is cheaper. Based on that, smart homes are being integrated into a smart grid eco-system in terms of households' energy consumption and management [7]. Therefore, it is necessary to create a scheme where it is possible to change the power consumption of an electric utility customer to better match the demand with the supply. According to [8], smart house has to accomplish five important basic aspects, summarized in Figure 2.2 [8], such as:

- Automation: the ability to be connected with automatic devices to perform automatic functions;
- Multi-functionality: the capability to create different states and different outcomes;
- Adaptability: the capacity to meet user criteria;

- Interactivity: the ability to allow interaction among users;
- Efficiency: the capability to perform functions in time and cost-saving in the right manner.

2.2 Smart Houses

A smart house provides to costumers a sophisticated monitoring and control over the house equipment's through advanced automation systems. A smart house should have integrated prediction mechanism and algorithm, decision making, human-machine interface, wireless networking etc [9]. In Figure 2.3 [10], it is represented the equipment of a smart home according with reference [10].

Any device in a costumer home that uses electricity can be put on the costumer home network and at costumers' command. Whether the costumer give that command by voice, remote control, tablet or smart phone, the home reacts. Most applications relate to lighting, home security, home theater and entertainment, and thermostat regulation. Smart houses also includes security, medical treatment, data processing, entertainment and business at home [11].

Smart homes are able to record the consumption of electricity of appliances in the Smart Meter. However customers are reluctant to have Smart Meters mainly because of the costs involved [12]. Along with the electrical installation, smart houses include network setups like wireless and ZigBee[1] for example, being later discussed on Section 2.2.2. However, there are several meanings of smart house that are presented in Figure 2.1.

Smart houses, as we see in [13], can be divided into three categories of meanings, whose categories all have development both in terms of automation and consumption reduction. The first group is considered the group whose devices are controlled remotely and the equipment connected to each other.

The second group are the programmable houses whose purpose is to adapt according to different types of input sensors and to recognize certain situations. Finally, the third group are the intelligent houses, which aim to recognize the patterns and react to the inputs.

All of this developments and automation on this field will help costumers and other electrical players to reduce their internet bill and optimize the electricity bidding by doing a load management through the smart house. Next sub-chapter will be discussed the different type of loads in the house and how to take advantage of them in terms of electricity consumption.

2.2.1 Loads

With the help of a smart phone or a laptop, loads can be managed remotely to help user control and manage the energy and equipment and as a consequence reduce the energy bill. Every load has different types of operation, so it became a need to separate the different type of loads. Loads can be divided in two groups: the critical loads and controllable loads [14].

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[1] ZigBee is a network technology as a wireless communication standard.

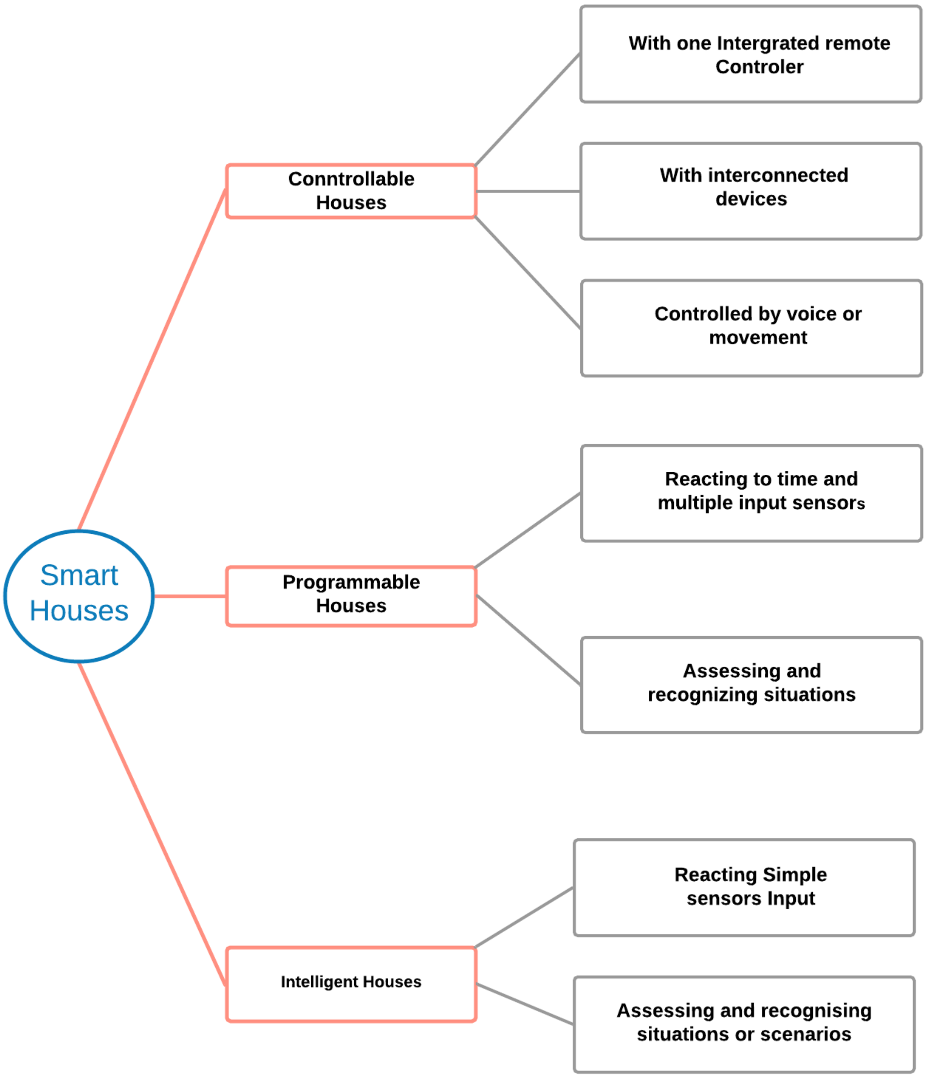

Figure 2.1: Different meanings of Smart Houses

The critical loads are lightning, refrigeration and freezing. The controllable loads, can be divided in thermostatically controlled and non-Thermostatically controlled. In the first group has HVACs and water heating. For this two different type of loads a set-point of temperature needs to be chosen whether it is the costumer or the program [15]. The non-thermostatically controlled are dishwashers, washers, dryers, plug-in hybrid electric vehicle (EV) and other equipment that does not need to have a set-point of temperature.

The market of the EVs is growing and is becoming more and more common [16]. One of the EV utility in a smart house is the flexibility trend by considering the charging/discharging schedule. This means that the charging/discharging of the EV can be scheduled in specific times in order to reduce the energy peak [17] and with some costumers' benefits.

The EV linked to a smart house has the ability of stop the charging and continue when it is convenient. Another great thing about the EV is the capability of not only, the operation of the grid to Vehicle (G2V) but also Vehicle to grid (V2G) [18]. This means that when the grid needs, the EV can also work as a battery that sells energy to the grid, a bidirectional power flow. This type of systems helps controlling the power peak.

The EV works like a battery which can absorb or consume energy. Moreover, there are different forms of achieving the goal of lowering the energy price and lower the peak which can be done adopting several types of load management. One of them is the load shifting, the most common one. In this case, loads that are independent of the time and causes minimal inconvenience, are shifted from peak time to another period of time where the grid loads are lower.

This will cause that certain equipment will work when the price is lower. Another type of load management is through the conservation, where the overall goal is to reduce the energy consumption. This type of management will maintain the shape of the daily consumption, reducing the power every hour or at least most of them. The last one is the peak clipping where the system will limit a power consumption to a superior limit, turning off the equipment when the power reaches that level of power [19].

Load shifting, one of the types of load management, can be divided in without shifting, power shifting and time shifting. The power shifting is related to the change of the loading pattern. For example, charging the EV which will be divided in different periods through a day.

The time shifting will change the start and end time to allow a better allocation of the loads [20]. However, the time shifting is limited and it can be applied on the dishwashers, dryers, and washing machines. In order to control and monitoring the equipment's behaviour, a connection between the loads and the user is crucial. To achieve that purpose, it is crucial the implementation of an efficient system of communication: - the Internet of Things (IOT).

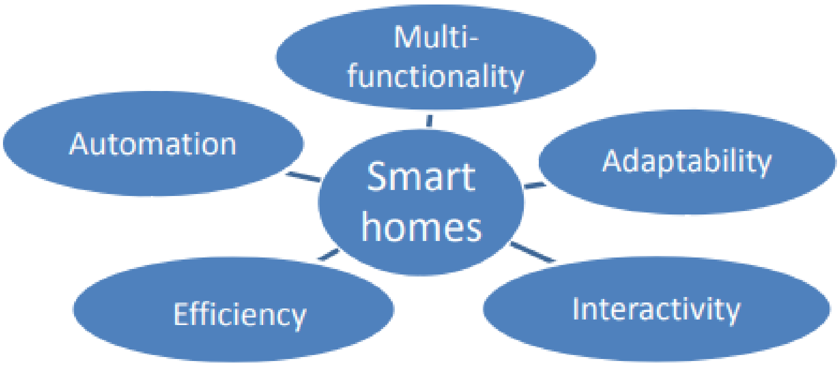

Figure 2.2: A smart house basic aspects architecture.

Figure 2.3: Equipment used in a smart house (schematic diagram).

2.2.2 Internet of Things

IoT has a variety of application domains including in smart houses concepts. The IOT is the concept that everything is connected at anytime [21]. IOT can also be defined as a vast network of smart equipment which work ‘together’ in collecting and analyzing the data and performing the necessary actions.

When IoT technology was introduced to the smart home implementation, IOT improved and changed a lot the smart houses’ concept. In a smart house, IoT technology is one of the vital applications because it supports the access, facilitates the transmission and reception of data that is necessary to control and monitoring, allowing the smart house communication [22]. In terms of layering, i.e., the architecture model, the IoT includes four fundamental blocks that make communication possible [23]:

- Discovery - supports multiple methods for devices’ communication;
- Data transmission - communication based on messaging and streaming model;
- Data management - data storage and computation;
- Device management - devices’ configuration.

For a smart house, the best way to communicate is by using wireless technology due to being easy to use, with a low cost trend, and also it reduces the cable restriction problem. The use of wireless in smart houses are currently being held by four technologies: Bluetooth, ZigBee, UWB, and Wifi [24].

However, in the smart houses' business, ZigBee is the most popular technology. ZigBee is a network technology as a wireless communication standard that has the advantage of being cheap, lower and wider coverage, and therefore, it suits the development and utilization in a smart house [25]. The concepts is also smart; ZigBee devices receive information from the home gateway, by ZigBee module, and then generates corresponding signals to manipulate the appliances that are connected.

With the development in this area of smart houses which is becoming a reality, the number of smarter equipment will grow exponentially. The reason behind this grow is the fact that every object like a freezer, or a cooler, or even a dishwasher will now become part of the network, and will be addressed too. Before the smart house 'revolution' none of these devices were addressed to the network. So it became necessary to create a protocol with higher number of addresses for the equipment's consideration [26].

In future, every equipment will need to be IPv6-capable. IPv6 is an Internet protocol which allows a higher number of addresses and has a lot of benefits compared with the IPv4 the protocol that was implemented before [27]. All of this automation is great and helps the customers life, however it has some risks that needs to be minimized/contained that will be explored on the next section.

2.3 Benefits and Risks of a Smart Home

Smart homes guarantees benefits to the electricity suppliers and for costumers [28]. In the reference [29] the study shown the multiple benefits of a smart home, compared to a non-smart home with real experimental values. It was proven that costumer with smart house have an accurate billing information helping to reduce the energy costs [28], helping the costumer to regulate his behavior while using this technology. The communication between the energy supplier and the costumer is essential due to the knowledge of the energy market mechanisms and the different energy rates [28].

Moreover, in [30] the authors described the numerous benefits of a smart home which can improve the customer's lifestyle. A smart home can save energy, make the things with lesser efforts, saving time and money, providing the comfort, and improving the quality of life and leisure [30]. Hence, smart houses also can provide healthcare for all the individuals, especially for the older people, being possible to measure the vital signs of the people in their own home [31]. However, there are some associated risks, like the increased dependence on the technology, the increased dependence on the electricity networks, the possibility of privacy invasion, among others [30]. In addition, the biggest problem is achieving the necessary security. This has been the major problem for a smart-home implementation. Integrating security-enhancing methods is difficult because the design is not linear and it requires substantial investigation.

For instance, in [32], a risk analysis in a smart home automation system was performed, and the results shown that with the implementation of standard measures, the risks can be minimized to acceptable levels. The security needs to be achieved in different points:

- Confidentiality - the guarantee that the data will be disclosed only with authorized entities or systems. This means that only authorized people are allowed to access a certain information;
- Integrity - the guarantee, accuracy and consistency of data will be maintained. No unauthorized modifications, destruction or losses of data will go undetected;
- Availability - the assurance that any network resource (data/bandwidth/equipment) will always be available for any authorized entity. Such resources are also protected against any incident that threatens their availability;
- Authenticity and Authorization - the validation that communicating parties are who they claim they are, and that messages supposedly sent by them are indeed sent by them. Also, the access rights of every entity in the system are defined for the purposes of access control;
- Non repudiation - undeniable proof will exist to verify the truthfulness of any claim of an entity [33].

Together with the risks associated with smart houses' security, there is another setback linked with energy costs, that was already mentioned. In order to minimize the energy costs, the smart houses have programs that helps users to reduce the expenses. This programs are called demand response (DR) programs.

2.4 Demand Response Programs

DR, as explained in Figure 2.4 [34], can be divided in two groups: DR-based on prices (PBDR) and DR-based on incentives (IBDR) programs.The IBDR programs are classified in three groups: voluntary, required and market clearing programs and the price based only in voluntary programs. A DR program introduces the load flexibility, where different entities will benefit starting with costumers and electricity supplier [35]. The main goal of these DR programs is to regulate the operational and economical parameters of the power system [36].

In [37] the authors discovered the optimum performance for two types of DR, incentive and price-based, by studying the customers satisfaction. As described, every house has different optimal type of DR. In this sense, the tariffs will need to get a difference between permanent or transient price signal.

Permanent signals reflect the variation of price by time, location and size [38]. For instance, in certain locals which has several congestion or prices variations, it is used the permanent signals with different prices by hourly blocks, which is the cause of the TOU pricing. Additionally, in some cases, signal needs to be transient, which is the case of situations that only will happen in specific times of the year, for example in extreme weather conditions.

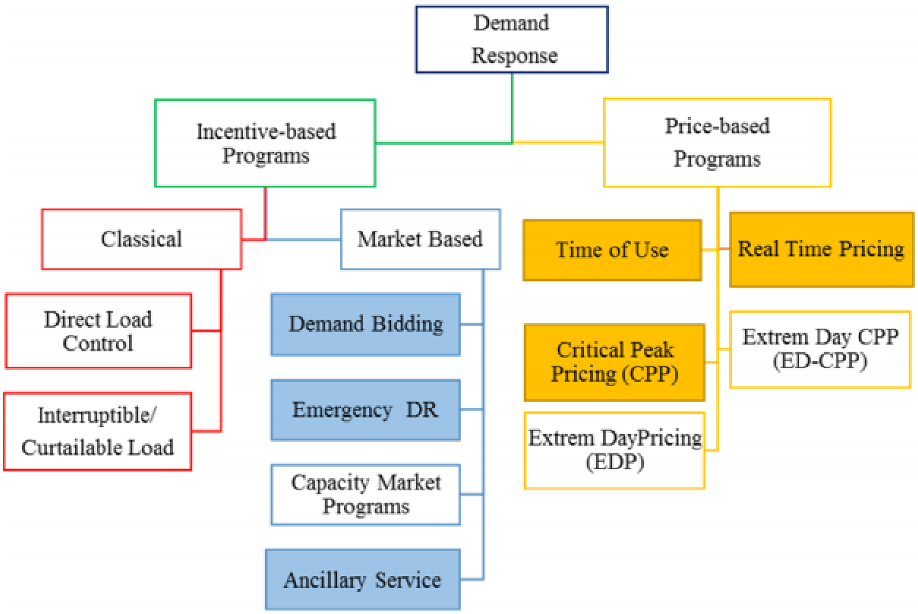

Figure 2.4: Classification of DR.

A different approach was done in [39], where it was studied a DR management, with multiple utility companies, with interaction between the utility companies and residential costumers, as a two-level game strategy. The authors in [40] developed an algorithm based on a Stackelberg game [2] between the utility companies and costumers in order to maximize the revenue of the utility companies and the payoff of each costumer.

2.4.1 Incentive Based Demand Response Programs

IBDR programs include Direct Load Control (DLC), interruptible/curtail-able services, Bidding/Buy Back (DB), Emergency DR Program (EDRP), Capacity Market Program (CAP) and Ancillary Service Markets (A/S) [42]. IBDR programs gives incentives in addition to their electricity rate on retail. The values of the incentives can be fixed or it fluctuate over time with the load [43]. The DLC is the turning ON/OFF of the electrical appliances or devices of customers which is controlled directed by the power supply in order to control the peak-load hours [44].

DLC devices allows utilities to remotely manage the demand for electricity by directly modifying the operation of costumer's devices – typically air conditioners, pool pumps and electric hot water systems. This technology involves an utility, or system operator, which installing equipment that allows costumers to switch some appliances during peak hours, and when there is a critical event [45].

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[2] Stackelberg game - in a Stackelberg game, one player is the leader and the rest are followers. The problem is to obtain an optimal strategy for the leader assuming that the followers react in a way to optimize their objective functions with the leader actions [41].

Customers using DLC programs are paid as a one-off sign-up payment, recurring annual payment, ongoing electricity bill discounts, or by free hardware installation [45].

A different type of incentive program is the EDRP, tested in the United States of America, which is based on the historical demand, price data, and the short-term load forecasting. The Independent System Operator (ISO) usually uses this program in order to prevent the spike prices effect. ISO usually pay to consumers a considerable amount of money as an incentive to consumers to reduce the consumption [46].

Hence, on the capacity market, the users bid in the reduction capacity in the same way as producers bid in the generation market [47]. The CAP participants get paid to avoid the utilization of energy during peak events. Also there are the A/S, which are acquired by the Transmission System Operator (TSO), with the goal of keeping the balance between the demand and the supply in order to stabilize the transmission system, and maintaining the power quality on an economical basis in any electricity market [48].

2.4.2 Price Based Demand Response Programs

PBDR programs are capable of offering a scheme based on the price variation. As example, real time pricing (RTP) scheme is able to “transport” the wholesale market principles into the retail market.

Costumers can benefit from the electricity bill reduction if he adjusts his demand accordingly to the prices. Costumers are informed about the tariffs an hour-ahead in order to adjust their loads [49]. Another price-based DR, the Time of Use (TOU) pricing, is an electricity model that changes with the time of the day. This tariff is low in off-peak, moderate in mid-peak and higher in peak-periods.

TOU also includes the seasonal variation of the energy consumption [50]. TOU pricing is more practical than RTP for most of the consumers, and reduces the efficiency of the single pricing [51]. Moreover, the objective of the CPP program is to reduce drastically the load during few intervals where the price is very high [52]. However, as stated before, due to the difference between costumers, the optimization of the energy in a smart house is not linear. Costumers may have different set-points of temperature or different comfort ‘settings’ levels which could result in a cheaper or expensive energy bill.
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2.4.3 Multi-Objective Problem

The energy consumption optimization in smart houses is essential as the costumer comfort. The costumer comfort can be regulated through a simple remote control. Although, increasing the costumer comfort will increase the energy bill [53].

With this in mind, it is necessary to do a optimization between the costumer comfort and the energy reduction. In reference [54], it is shown a Table showing the difference of energy prices while setting different costumer’s comfort levels.

Table 2.1 [54], it is possible to observe that in the case 4, the costumer comfort is the highest, which will result in highest net cost too. Hence, in the case 1 and case 2, costumer is able to sell energy to the grid, resulting in a revenue, without having waste of power.

2.4.4 Technological Advances

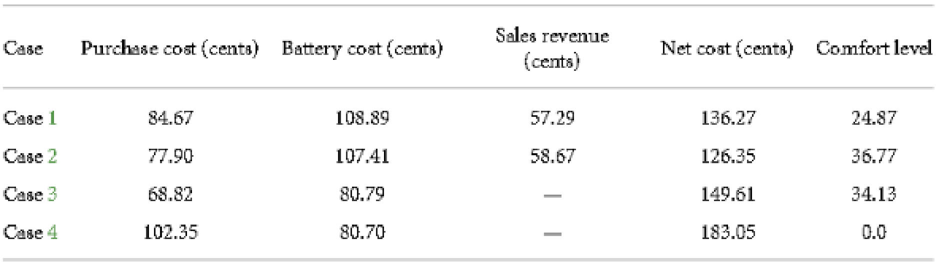
In [55], it was developed an algorithm which finds the costumer's normal usage trend and provides some recommendations based on that trend made by a multi-objective search algorithm. In other words, the proposed algorithm regulates the optimization based on the costumer settings, allowing a better user comfort.

In [56], the authors described an algorithm that scheduled the consumption of the energy, of different equipment, in a dynamic pricing environment, benefiting the costumer by minimizing the electricity cost. The proposed algorithm was based on binary particle swarm optimization, for residential electricity consumers.

The proposed model optimally scheduled the electricity consumption of different household appliances in a dynamic pricing environment in order to minimize the costumer's electricity cost. the results have shown that the proposed method efficiently shifts the appliances operation time from high-peak to low-peak hours and leads to significant electricity bill saving.

Another example is provided in [57], where it was proposed a multi-objective optimization which found the best solution based on different battery capacities. Since a battery with high capacity is very expensive, the proposed study analyzed the viability of different battery technologies economically.

Table 2.1: Different prices of the energy-based on different comfort levels.



Case	Purchase cost (cents)	Battery cost (cents)	Sales revenue (cents)	Net cost (cents)	Comfort level
Case 1	84.67	108.89	57.29	136.27	24.87
Case 2	77.90	107.41	58.67	126.35	36.77
Case 3	68.82	80.79	—	149.61	34.13
Case 4	102.35	80.70	—	183.05	0.0

Chapter 3

Methodology

In this chapter, it will be presented the mathematical formulation which defines the cost or revenue for the residential costumer. Moreover, it is presented the described mathematical formulation necessary to correlate the relation between the smart house consumption and the exchanges with the network. The different constraints of both, smart home and the network are also formulated.

3.1 Introduction

The model used in this works runs under a stochastic programming and it is divided in two different stages: the first stage is the day-ahead market, where the price of the trade is set for the next-day, and the second stage, or the real-time price, where the energy can be traded in real-time, having different prices from the day-ahead model.

On this proposed model, it was considered some stochastic parameters, which corresponds to wind generation, due to the natural uncertainty from the wind behaviour. One of the primarily goals is to obtain the physical-based model of the house, in a way that t it is possible to understand in which way the energy usage increases for the electric water heater and the heating, ventilation and air-conditioning (HVAC) system.

In this sense, the objective of this work is to implement an algorithm which allow a physical-based model of the electric water Heating and the model that considers the HVAC system, and its use, in order to minimize the power consumption/energy cost, considering as well the costumer comfort in a right manner.

3.2 Objective Function Modelling

The objective function is the minimization of the total expected cost (EC), or increase the expected profit (EP) by selling/purchasing energy to/from the day-ahead and real-time market. The objective function will consider the first and second stages, the day-ahead and the real-time stages, respectively. The first Equation 3.1, EP or (EC) consists in two parts. The first part is the EP due to the trade energy with the day-ahead local Market (LM).

The second part of the Equation represents the profit of the exchanged energy in the real-time market. This is related with the energy revenue, the energy cost, the wind spillage cost, and the load shedding costs of the space and water heater. Notice that in this formulation the cost of the battery-based energy storage system (ESS) and the EV are equal to zero, because it is a domestic energy management problem analysis only.

For the first stage, it was considered the day-ahead market where the considered variables are only related to the 'day ahead' market , and they are not considering the different wind scenarios. For the second stage, 10 different wind scenarios were considered, and every scenario has a 10 % rate of appearance.

The wind micro-turbine, ESS, and EV are the energy resources in the house. The HVAC system is considered as a thermostat programmable controllable load, the electric water heater tank is considered as thermostat controllable and shiftable load, and the must-run services as non-dispatchable loads, without considering the uncertainty of this type of loads.

$$EP = \sum_{t} \lambda_t^{da} P_t^{net,da} + \sum_{t} \pi_w \sum_{t} (\lambda_t^{sold,rt} P_{tw}^{sold,rt} - \lambda_t^{pur,rt} P_{tw}^{pur,rt} - V^S S_{tw}) \tag{3.1}$$

where:

- EP - Expected profit.
- λ_t^{da} - Energy price with the day-ahead market.
- $P_t^{net,da}$ - Energy traded with the day-ahead market.
- π_w - probability of scenarios.
- $\lambda_t^{sold,rt}$ - Sold price, in real-time market.
- $P_{tw}^{sold,rt}$ - Sold Energy in real-time market.
- $\lambda_t^{pur,rt}$ - Energy price (buy) in real-time market.
- $P_{tw}^{pur,rt}$ - Energy consumed in real-time market.
- V^S - Spillage cost of the wind system.
- S_{tw} - Wind Energy.

3.2.1 Day-Ahead Stage

$$P_t^{wind,da} + \gamma_b P_t^{b,dis,da} + \gamma_{ev} P_t^{ev,dis,da} = L_t^{sh,pred,da} + L_t^{swh,pred,da} + L_t^{mrs,pred,da} + \gamma_b P_{tw}^{b,ch,da} + \gamma_{ev} P_t^{ev,ch,da} + P_t^{net,da} \tag{3.2}$$

$$-fmax <= P_t^{net,da} <= fmax \tag{3.3}$$

$$P_t^{net,da} = P_t^{wind,pred} \tag{3.4}$$

where:

- $P_t^{wind,da}$ - Wind point forecast.
- γ_b - Coefficient.
- $P_t^{b,dis,da}$ - Energy of the battery charging.
- γ_{ev} Coefficient.
- $P_t^{ev,dis,da}$ - Energy of the EV discharging.
- $L_t^{sh,pred,da}$ - Predicted values of the HVAC system.
- $L_t^{swh,pred,da}$ - Predicted values of the electric water heater.
- $L_t^{mrs,pred,da}$ - Predicted values for must run services.
- $P_{tw}^{b,ch,da}$ - Energy of the battery charging.
- $P_t^{ev,ch,da}$ - Energy of the EV discharging.
- $P_t^{net,da}$ - Energy traded with the day-ahead market.

Equation 3.2 represents the power balance equation due to the power output of the wind micro-turbine, the discharged power of the ESS, the discharged power of the EV, the charge power of the ESS, the charged power of the EV, the traded energy with the LM, the predicted values of the water heater, the HVAC system, and the must-run services.

Equation 3.3 represents the limit of power in the lines, in both directions. On the day-ahead market, as opposite of the RTP scheme, only the forecasted values are considered.

3.2.2 Real-Time Pricing

$$P_{tw}^{wind,rt} + P_{tw}^{b,dis,rt} + P_{tw}^{ev,dis,rt} + P_{tw}^{pur,rt} = L_{tw}^{shd,rt} + L_{tw}^{swd,rt} + L_{tw}^{mrs,rt} + P_{tw}^{b,ch,rt} + P_{tw}^{ev,ch,rt} + P_{tw}^{net,da} + P_{tw}^{sold,rt} \tag{3.5}$$

$$-f_{max} \leq P_{tw}^{net,da} + P_{tw}^{sold,rt} + P_{tw}^{pur,rt} \leq f_{max}, \forall t, \forall w \tag{3.6}$$

$$P_{tw}^{sold,rt}, P_{tw}^{pur,rt} \geq f_{max}, \forall t, \forall w \tag{3.7}$$

where:

- $P_{tw}^{wind,rt}$ - Energy of the wind spillage in real-time.
- $P_{tw}^{b,dis,rt}$ - Energy of the battery discharging in real-time.

- $P_{tw}^{ev,dis,rt}$ - Energy of the EV in real-time.
- $P_{tw}^{pur,rt}$ - Energy bought with the market in real-time.
- $L_{tw}^{shd,rt}$ - Energy consumed by the space heater in real time.
- $L_{tw}^{swd,rt}$ - Energy consumed by the electric water heater in real-time.
- $L_{tw}^{mrs,rt}$ - Energy consumed by must run services in real-time.
- $P_{tw}^{b,ch,rt}$ - Energy used by the battery while charging.
- $P_{tw}^{ev,ch,rt}$- Energy used by the EV while charging.
- $P_{tw}^{net,da}$ - Energy traded with the grid.
- $P_{tw}^{sold,rt}$ - Energy sold in real-time.

Equation 3.5 represents the power Equation of the house, in real-time. The values of energy consumption by the HVAC system and the electric water heater tank were calculated based on the algorithms presented below.

The energy balance was performed every 5 minutes in order to incorporate the values obtained for the HVAC system and the electric water heater tank models. These models need to calculate values every 5 minutes, or every 10 minutes in order to model accurately these loads.

Equation 3.6 express the load balances on the smart house exchange lines with the smart grid. In this way, the sum of the values of the energy exchanges with the network must obey the constraints of the maximum limits of the line.

3.2.3 Model of the Water Heating Load

The following equations represent the Water Heating model [58].

$$T_{t+1}^{h,w} = T_t^a + Q.R.u_t^{EWH} - (T_t^a - T_t^{h,w}).e^{-\frac{\Delta T}{R.C}}, \forall t < T^{max}, m_t = 0 \tag{3.8}$$

$$T_{t+1}^{h,w} = \frac{T_t^{h,w}.(0,26417 \times M - m_t) + T_t^{c,w}.m_t}{M \times 0,26417}, \forall t < T^{max}, m_t > 0 \tag{3.9}$$

$$T^{h,w,min} \leq T_t^{h,w} \leq T^{h,w,max}, \forall t \tag{3.10}$$

$$T_t^{minws} < T_t^{h,w} < T^{h,w,max}, m_t > 0, \forall t \tag{3.11}$$

$$P_t^{EWH} = Q.u_t^{EWH}, \forall t \tag{3.12}$$

where:

- $T_{t+1}^{h,w}$ - Temperature of the water in the tank;
- T_t^a - Outdoor temperature;
- Q - Electric Water Heater Power (kWh);
- R - Electric water heater resistivity (°C/kWh);
- C - Electric Water Heater capacitance (kWh/°C)
- Δt - Duration of time interval (h);
- u_t^{EWH} - Binary variable - 1-ON, 0-OFF;
- $T_t^{c,w}$ - Inlet Hot water temperature;
- M - Tank volume in liters;
- m_t - Hot water usage;
- $T^{h,w,min}$ - Minimum permanent hot water temperature;
- $T^{h,w,max}$ - Maximum permanent hot water temperature;
- T_t^{minws} -Minimum hot water temperature while showering;
- P_t^{EWH} - Power for each time slot;

Equation 3.8 is related when the hot water is not being used,that means no one is using the shower at that moment, for instance, and the temperature is decreasing slowly overtime. However, if the temperature is not appropriate, the system will run automatically to elevate the temperature within the desired range.

Equation 3.9 is related when hot water is being used, assuming 3 daily periods, which maybe related with 3 baths at different times. During these 10-minute time periods, the electric heater water tank is programmed not to warm up for safety reasons.

Equation 3.10 models the limits of the temperature for each time slot. The temperature should be between 20°C and 60°C. Equation 3.11 shows the temperature limits during the bath of the costumer, and should not be lower than 40°C, for comfort reasons.

Equation 3.12 is related to the power consumed while the electric water heater tank is working. The parameter P_t^{EWH}, (the demand for electricity of the electric water heater tank), shows the energy consumed for each time slot.

3.2.4 Modelling of the HVAC system

The following equations represent the HVAC model [58].

For the HVAC system first it is calculated the temperature in the room:

$$T_t^r = \left(1 - \frac{\Delta T}{1000.M_a c_a R^{eq}}\right) T_{t-1}^r + \frac{\Delta T}{1000.M_a c_a R^{eq}}.T_{t-1}^a - u_{t-1}^{AC}.\frac{COP.P_{AC}.\Delta T}{1000.M_a c_a R^{eq}}, \forall t > 1 \tag{3.13}$$

$$SP_t - S_t^d \leq T_t^r \leq SP_t + SP_t^u, \forall t > 1 : SP_t \neq NaN \tag{3.14}$$

$$P_t^{AC} = P_{AC}.u_t^{AC}, \forall t \tag{3.15}$$

where:

- M_a - Volume of the house;
- T_t^a - Outdoor temperature;
- P_{AC} - Rated power of the space heater;
- R^{eq} - Equivalent Resistance;
- C_a - Specific Bulk.
- ΔT - Duration of time interval (h);
- u_t^{EWH} - Binary variable - 1-ON, 0-OFF;
- COP - 2- for summer; -2 for winter.
- T_t^r - Temperature in the house;
- u_{t-1}^{AC} - Binary value 1- ON; 0- OFF;
- SP_t - Temperature set-point;
- $S_t^d t$ - Temperature Deviation;

Equation 3.13 is the calculation of the temperature in the room in each time slot. The binary variable (ON/OFF) will change to keep the temperature between acceptable values. The dead-band is considered 1°C and means that the air conditioning temperature may vary by 1 degree above or 1 degree below the expected value.

In reference 3.14 is formulated the restrictions of the temperatures deviations. In this sense, Equation 3.15 express the power spent on the HVAC system, which will be different than 0 only if the HVAC is working on that period.

Chapter 4

Case Study and Results

4.1 Introduction

The proposed model shown in Figure 4.1, is a model which connects the LM with the domestic energy management system (DEMS). The smart house is capable of buying and selling energy with the LM, and it is equipped with equipment that can ‘store’ energy like the battery and the EV. The DEMS is also equipped with a wind micro-turbine with the maximum capacity of 2 kWh.

The ESS can store between 0.48 and 2.4 kWh, with the maximum charge and discharge rate of 400 W, with a charge/discharge efficiency of 90%. The EV is capable of storing 1.77 and 5.9 kWh, with a charging/discharging rate of 3 kW, while the charging/discharging efficiency was rated at 90% too.

The EV is scheduled to leave home at 7:00 AM and returns at 17:00 PM. Moreover, The EV is programmed for the worst case scenario, which means that when it returns to home it is "out-of-charge" and, at 7:00 AM the EV needs to be totally charged. Moreover, the loss of energy between electric appliances is considered to be null.

Due to the unpredictability of wind, a stochastic parameter of the wind has been created. The wind parameterization is done in different scenarios with an associated probability, shown in Figure 4.2. For the first first stage, it was considered the predicted values on the Figure 4.3. Moreover in Figure 4.4 is described the stochastic results from the predicted values of HVAC system in the day-ahead market, and in Figure 4.5 expresses the stochastic results from the predicted values of the electric water heater tank considered in the day-ahead market.

To this end. $T_{c,wt}$ is considered to be the same as the temperature in the room, which is calculated below through Equation 4.1. The hot water flow rate is simplified as an average value of 2.5 gallons per minute which is the normal average consumption in a typical house. For the sake of simplicity, the exterior temperature was considered at 20^{o}C.

For the parameters R, C, M (capacity in liters), it was considered the values above, which are the typical values for a electric water heater tank. The value of Q is a typical value for the electric water heater power, which is 2 kWh. The time interval was in minutes so , *deltat* is 5/60. The showers are “programmed” to be used at 7:50 A.M., 1:30 P.M., and 8:30 P.M., with a 10 minute duration. During that time, the minimum hot water temperature is 20^{o}C, and the maximum is always 60^{o}C for safety reasons.

However, the minimum temperature in the tank, when people are using hot water, is 40^{o}C for safety and comfort reasons. So, when showers are being taken the temperature is always between 40^{o}C and lower than 60^{o}C. The binary variable *utEWH*, is chosen between 1 or 0, in order to maintain the temperature in the tank within viable values.

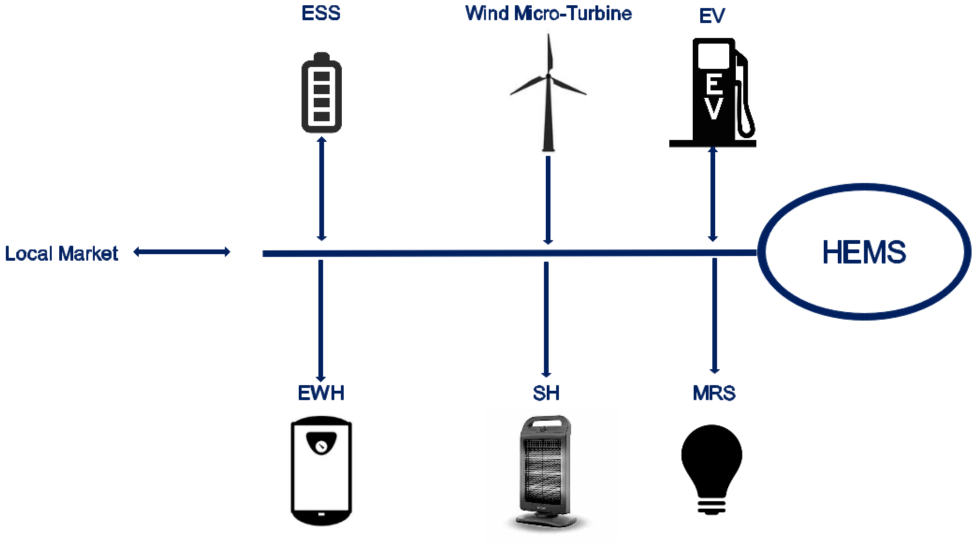


Figure 4.1: Model of the smart house

For this calculation, it is chosen a interval of temperatures and the water heating tank turns on/off to maintain the values on the intervals making the temperatures always around the temperature set-point. Moreover, the exterior temperature is expressed in Figure 4.6.

For this analysis, *DeltaT* was considered as the dead-band, and with +/-1°C, and constant. The value of *sPt* is the thermostat set-point and *Std* is the value of the max deviation. Normally, the density of the air and its thermal capacity depend on its thermodynamic properties (temperature, pressure, etc). However, for the sake of simplicity, in this model, such parameters were considered constant and utilize standard values ρ_{ar} = 1.225 kg/m3, and ca = 1.01 kJ/kg°C.

The equivalent thermal resistance considered was: $3.1965 \times 10^{-6}(^{o}C.h/J)$. The mass of air was considered as 1778.369 kg which results from the volume of the house which is 1451.729 m3. This volume was obtained by the following Equation 4.1:

$$V_{house} = L_1.L_2.L_3 + tan(\beta).L_1.L_2 \tag{4.1}$$

Moreover, each of these parameters described previously are described Table 4.1 [59]., and in Table 4.2, respectively. The *M* (mass of air) was considered as 28.964 g/mol. This calculation is done by obtaining the number of mol and from pressure Equations. The HVAC system has a rated power of 3 kWh, which is the appropriate value for a house with 1400m3.

So the proposed algorithm can determine the temperature in the House for each slot time, and maintain the value within the chosen thermostat values in order to spent less energy or obtain more comfort. Moreover, the demand for electricity for each time is calculated, where *PAC* is in kW and the *WAC,i* is a binary value depending if the space cooling is ON: 1, or OFF: 0. As mentioned in previous sections, there were 4 different cases scenarios considered: RTP, CPP, flat price and TOU. The flat price is the same for all the 24 hours, and it is based on the average value of the RTP.

For the TOU price, the values are 1.5 times from the flat price during the peak-hours, but for the lowest, relevancy tariff it the half of the flat price. For CPP, the tariffs in some of the hours,the critical ones, are three times the flat price. Figures 4.7 - 4.10 represent each one of the different prices strategies considered. For the selling and purchasing energy proposes, the RTP trend are the same in cases 2, 3, and 4, respectively.

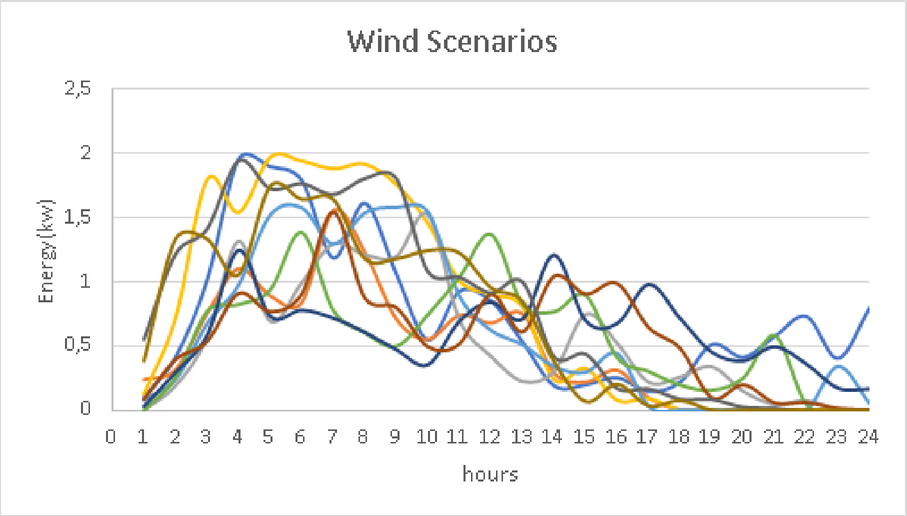


Figure 4.2: Different wind power scenarios in real-time.

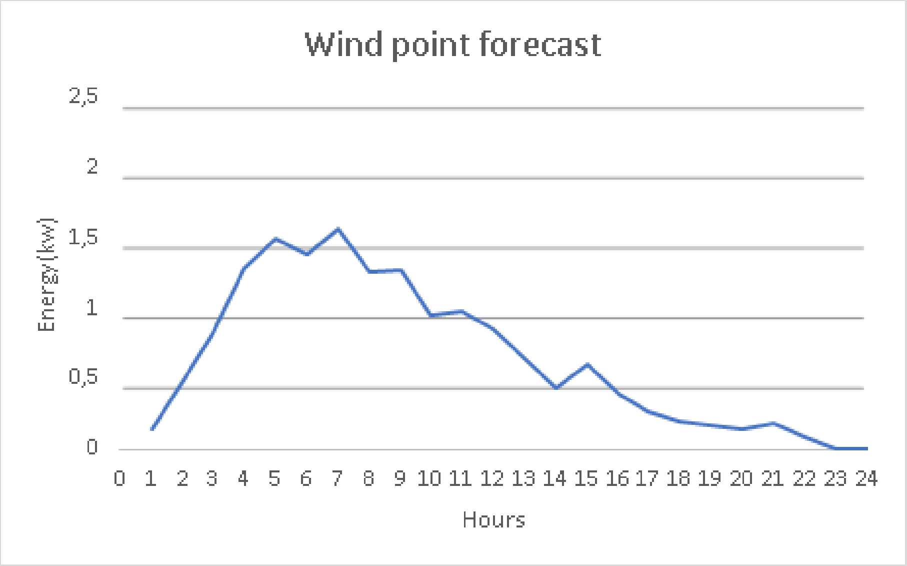


Figure 4.3: Wind power generation profile.

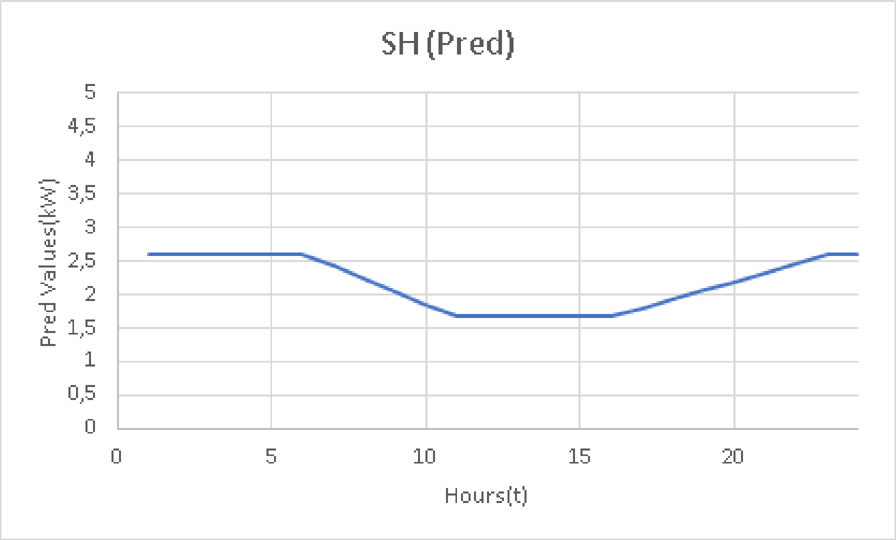


Figure 4.4: Stochastic HVAC predicted values (day-ahead-market).

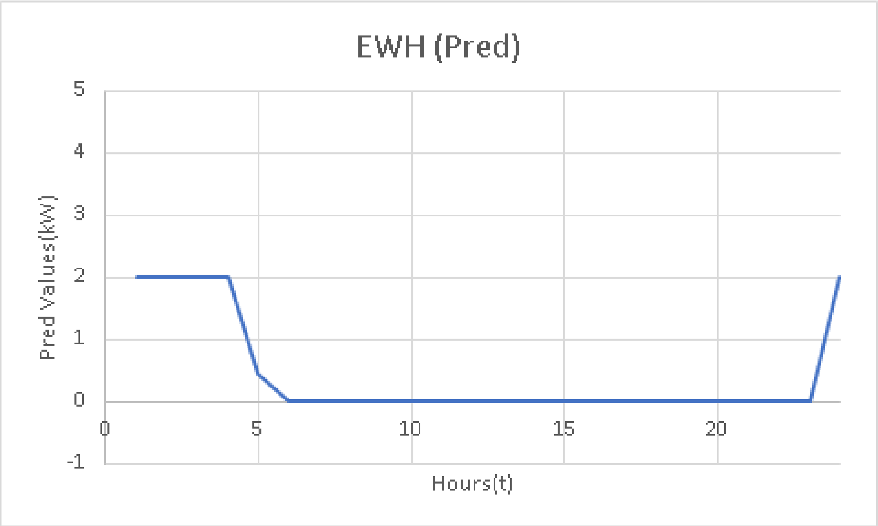


Figure 4.5: Stochastic predicted values of the electric water heater (day-ahead-market).

4.2 Results

In this section, the simulation was done based on the characteristics presented above. The model is based on different tariffs for this particular house, and the objective is to study how the tariffs affect the total price, and the distribution of the energy for the different most energy consuming devices in the smart house. The testing model is done on a 24 hour period.

The electric water heater and the HVAC algorithm have to attend some time restriction problems because these two devices were configured to turn ON/OFF every 5 Minutes, and the hourly configuration was a problem.

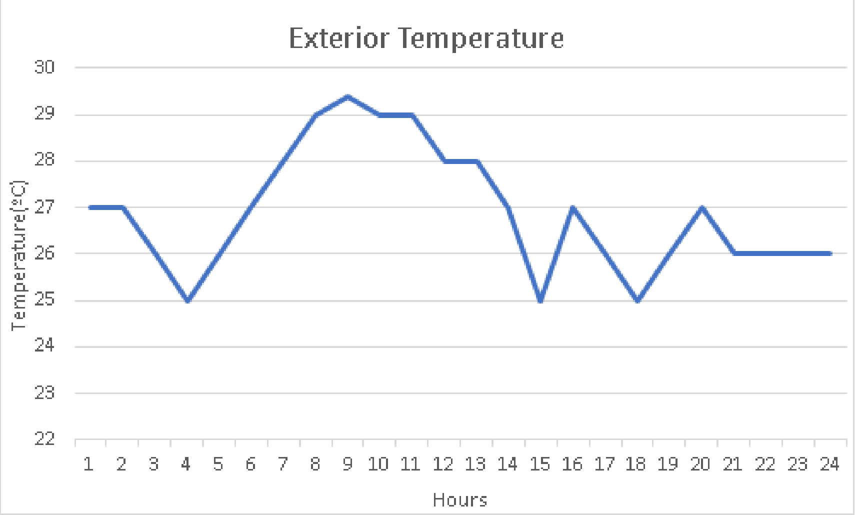


Figure 4.6: Considered values for outside temperature.

In Figures 4.11, and 4.12 are represented the average temperature during the day for the electric water heater, and HVAC, respectively, considering the different 10 wind scenarios for the 4 different case studies. For the Case 1, considering the RTP scheme, the executing time was under 5 seconds and the objective value was 0.4518 Eur.

In Figure 4.11, it can be noted the small steps of the temperature evolution. Each step, is related to the time-interval where the electric water heater is working. In the first 8 hours, a more or less constant temperature increase from hour to hour, from the initial point of 40 ºC, can be observed until reaching 46 ºC. It is noteworthy, the low rate of growth of the temperature every hour, so it can be concluded that the EWH, was only turned on few minutes every hour. After about 8 hours have passed since the beginning of the day, there is an accelerated decrease of the temperature in the water tank.

The decrease is related to the use of the hot water present in the tank. After use of the water, the tank is filled again with water at room temperature, which will be reheated. At 8:00 a.m, the EWH is switched on again, until the new hour of hot water usage by the users of the house. As can be seen from the Figure 4.11, the number of hours for heating again will be lower. The rate of increase of the water tank temperature between 8:00 a.m and 1:30 p.m., is higher than the tank temperature rise rate until 8:00 a.m..

Parameter	**Value**	**Units**	**Parameter**	**Value**	**Units**
House Length(L_1)	30	m	Area of Windows	1	m^2
House Width(L_2)	10	m	Wall thermal coeficient	136.8	J/h.m.ºC
House Height(L_3)	4	m	Window thermal coeficient	2808	J/h.m.ºC
Roof Angle (β)	40	deg	Thickness of windows	0.05	m
Number of Windows	6	-	Thickness of walls	0.15	m

Table 4.1: Different parameters of the smart house considered.

Values for a Water Heater		
R(°C/kW)	C(kWh/°C)	Capacity(liters)
1.52	863.40	189

Table 4.2: Typical values for the electric water heater, resistance, capacity, and C.

Between hour 1 and 2, the hot water is used again for the owner's new bath, thus verifying a marked decrease in the temperature of the tank. During the use of hot water, the temperature must always be higher than or equal to 40°C, which means that at the moment when the bath is finished, the temperature in the tank should be around 40°C. The maximum temperature at which the tank has been heated, around 46 °C, is what allows the heating system to be economical and comfortable.

As in the previous baths, the water exits the water heating tank, and the water enters again at room temperature so that it is necessary to reheat the 3rd daily bath that takes place at 8:30 p.m. After the third bath, it is not necessary to reheat the water for the day, since it will not be used again on that day. Of note, for the last hours of the day, the temperature is approximately constant, with slight decrease due to heat losses.

Moreover, in Figure 4.12, is about the temperature inside the house, and its changes over time. Each "peak" of temperature means that the HVAC system is not working, in order to sustain the temperature at allowable values. The ideal temperature is 23 °C, however, there are temperature oscillations around the reference point of plus or minus 1 °C.

By analysis of the Figure 4.12, it is observable the initial temperature of the daily house is 22 °C. For the first two hours, minute is observable, increasing the temperature, to the limit of close to 24 °C. At this time, the HVAC system, running as heater, is off. After the first few hours, the SH is turned on, in order to reduce the temperature inside the house, because the outside temperatures are high. For the hours of greater external heat, it is notorious that the SH switches on and off more frequently (from 8:00 a.m. to 14:00 p.m).

For the Case 2, considering the CPP scheme, the proposed model took the results under 5 seconds and the objective value was 1.0601 Eur. For the cases below, the temperatures of both the electric water heater and the HVAC were displayed at each time interval of 5 minutes.

In Figure 4.13, during the first few hours, the temperature increase is found to be slower until 7 a.m. At 7 o'clock the temperature rises about 3 oC in a short time. After the use of the water, it is verified that the temperature in the following hours does not change. This is due to the high tariffs that occur during these hours.

After lowering the tariffs, the EWH turns ON, and the temperature of the tank that water rises a lot faster. The hot water is then used, and again the tank water temperature is restored. This time, the temperature grows in 3 different hours, hour 15, 18 and 19. After it has finally finished heating, the hot water is consumed again and is not heated again.

In Figure 4.14, the initial temperature is about 22 °C. Comparing the graph 4.14, with The 4.12, it is verified that with the CPP model, a more constant temperature throughout the day. Moreover, For the Case 3, The Flat Price, the proposed model, again, provided a result under 5 seconds and the objective value was 2.987 Eur.

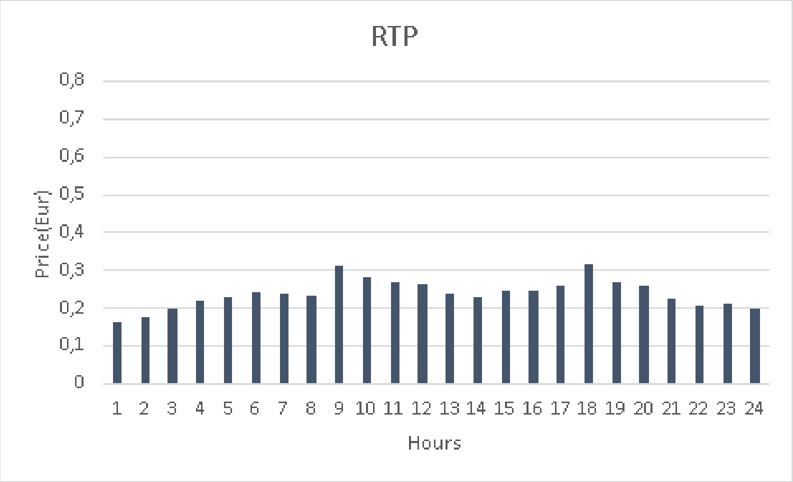


Figure 4.7: RTP scheme distribution.

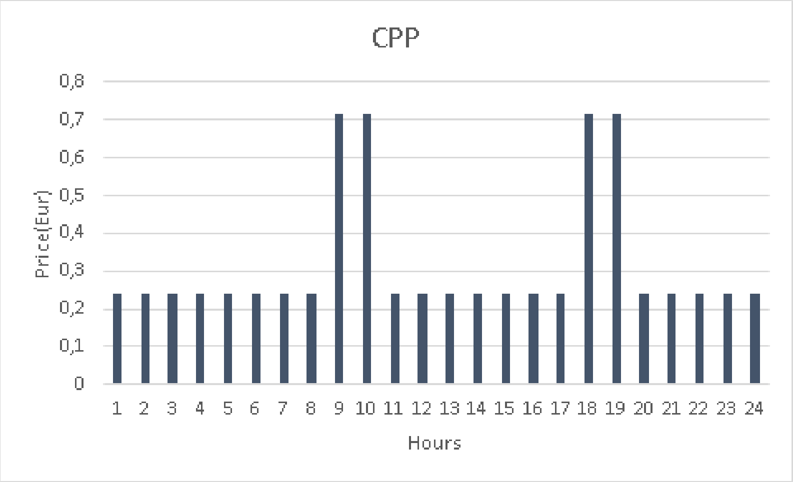


Figure 4.8: CPP scheme distribution.

In Figure 4.15, a fairly slow growth is visible with a step between 2:00 and 3:00 a.m., until 7:00 a.m. in the morning. Between 7:00 and 8:00 am, there is a faster temperature rise immediately prior to the use of water in order to avoid unnecessary losses. Water is then used, wherein it becomes visible the lowering of the temperature. The temperature rises after, a time when it remained near 40 ^{o}C. It rises once more to about 46 ^{o}C, and is then used again. From 13:30 p.m., the temperature of the water tank gradually rises until 19:00 p.m, at which point it abruptly comes on. The water is used again at 8:30, with a decrease of the temperature again. In Figure 4.16, it is to be noted, once again, the constant temperature, with small oscillations. In this case, the rates are the same for all hours. There is only the initial temperature variation, which, as already mentioned, is due to the initial temperature being about 22 degrees.

For the Case 4, the ToU price, the executing time was under 5 seconds and the objective value was 4.8870 Eur. In Figure 4.17, for both the use of the water of the tank at 7:50 a.m. and at 1:30 p.m., two large rises in temperature in each of the water uses are visible. For the third bath, it is noticeable an ascent in the hour 15 p.m. and another later near 8:00 p.m..

In Figure 4.18, when compared with the graphs presented previously, it is to be noted that the temperature is around 23 degrees, with slight minor oscillations in this case. As in previous cases, it is possible to observe the ON and OFF of the SH, according to the present temperature of the house.

Figure 4.9: Flat price distribution.

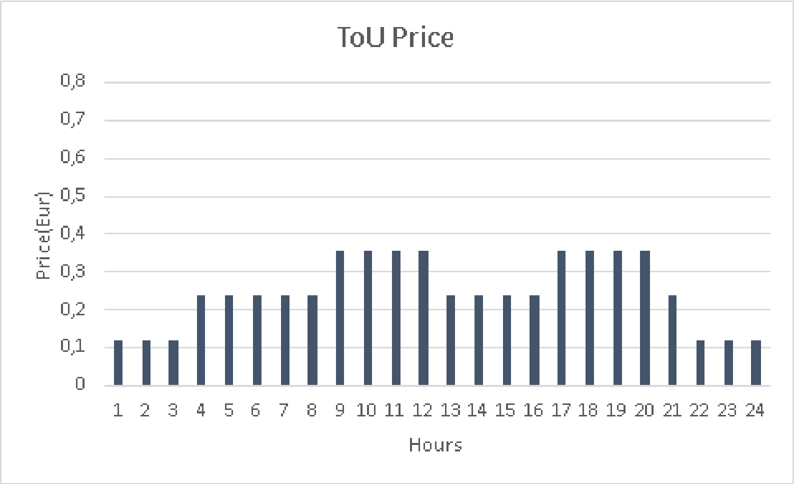


Figure 4.10: TOU Price distribution.

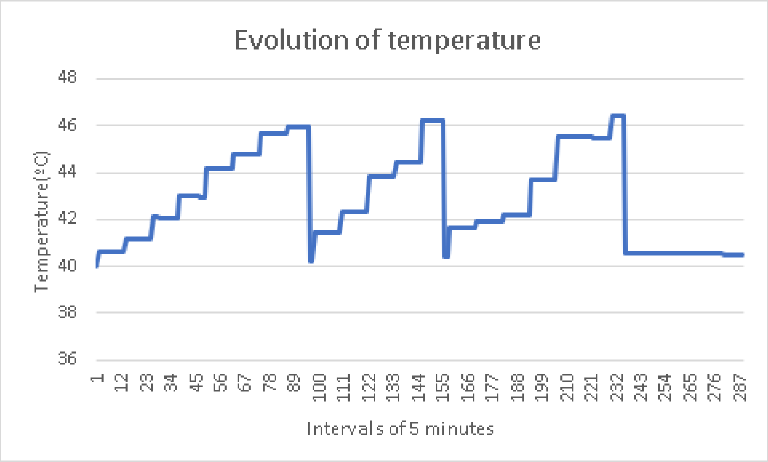


Figure 4.11: Evolution of the temperature in the water tank, during the day considering RTP scheme.

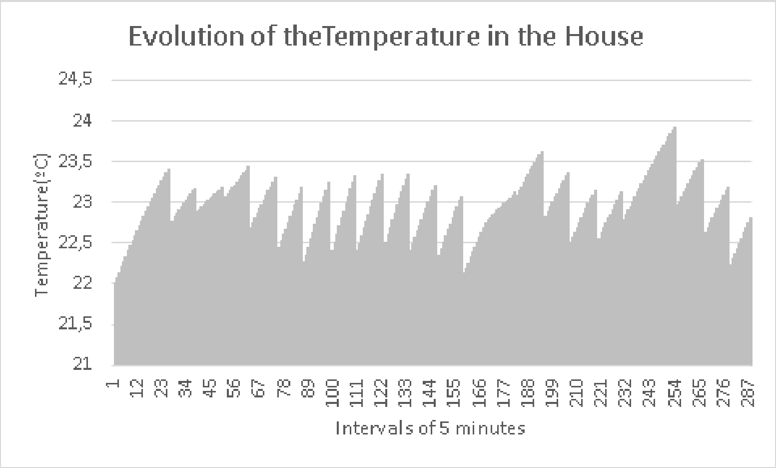


Figure 4.12: Evolution of the temperature in the house, during the day considering RTP scheme.

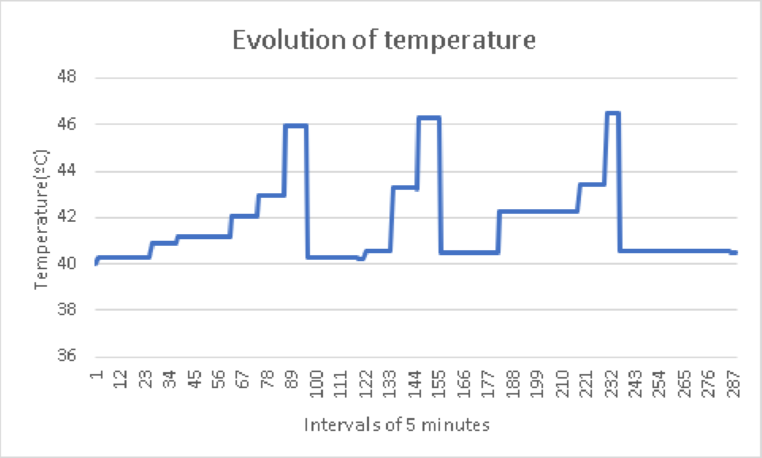


Figure 4.13: Evolution of the temperature in the water tank, during the day considering CPP scheme.

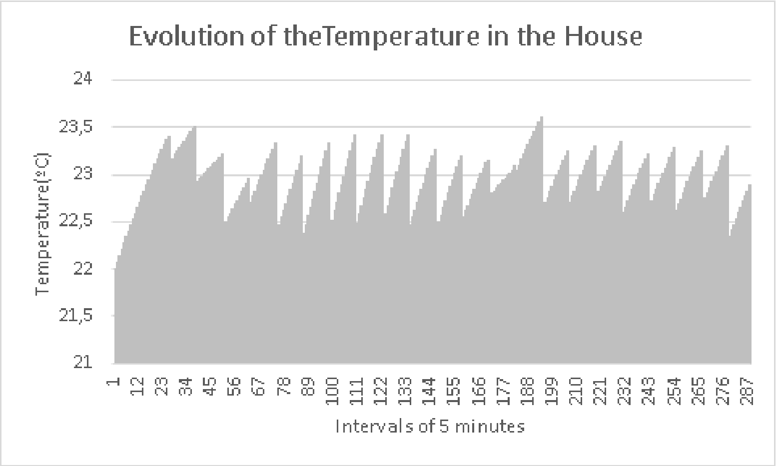


Figure 4.14: Evolution of the temperature in the house, during the day considering CPP scheme.

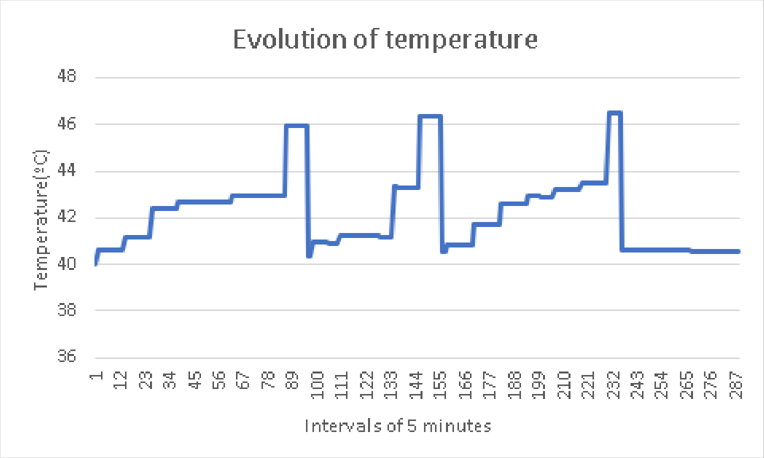


Figure 4.15: Evolution of temperature in the water tank, during the day considering flat price.

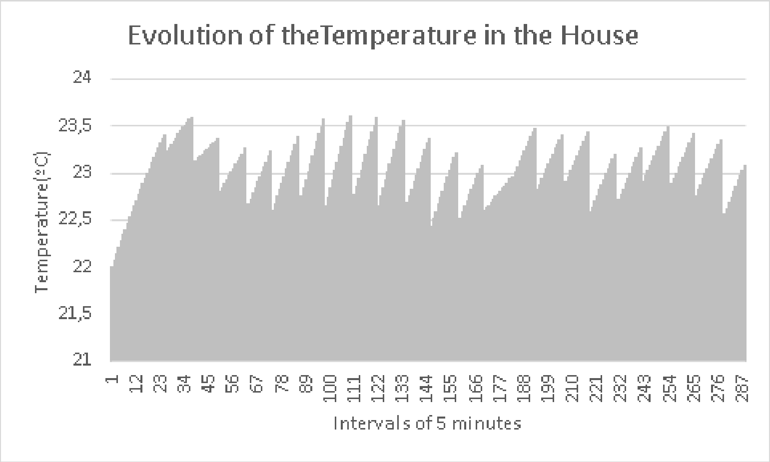


Figure 4.16: Evolution of the temperature in the House, during the day considering flat price.

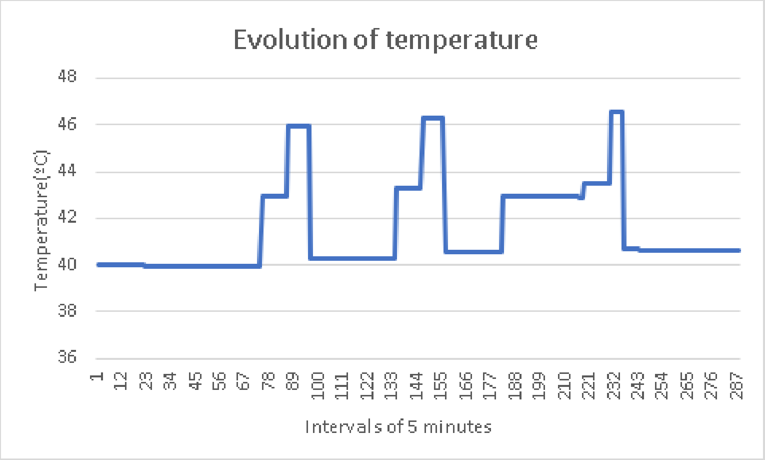


Figure 4.17: Evolution of the temperature in the water tank, during the day considering TOU scheme.

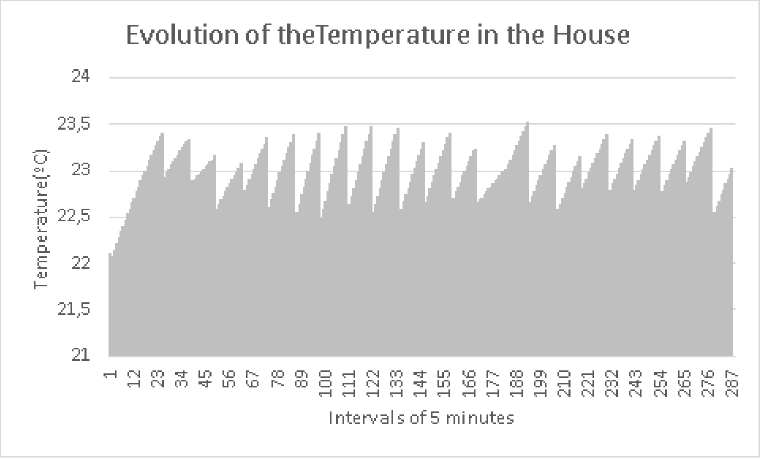


Figure 4.18: Evolution of the temperature in the house, during the day considering the TOU scheme.

4.2.1 Comparing Case 2, 3, and 4

After running the program, with the same inputs for all the cases except for the tariff itself, it can be noted that the best tariff for a house with these parameters, is the TOU tariff. This is expressed in Table 4.3.

Figure 4.19 shows the electric consumption of the HVAC for the different tariffs presented. The restrictions of the HVAC are necessary in order to maintain the comfortable environment in the house. The allowable temperature is in a very-short interval of the values which makes the shift of loads more difficult. These values obtained were an average value from the 10 scenarios considered, having different behaviour over the time and a consequent different energy distribution over the time.

Table 4.3: Objective function results - Revenue in euros.

	Tariff	Objective Function
Case 2	CPP	1,06 €
Case 3	Flat Price	2,99 €
Case 4	ToU	4,89 €

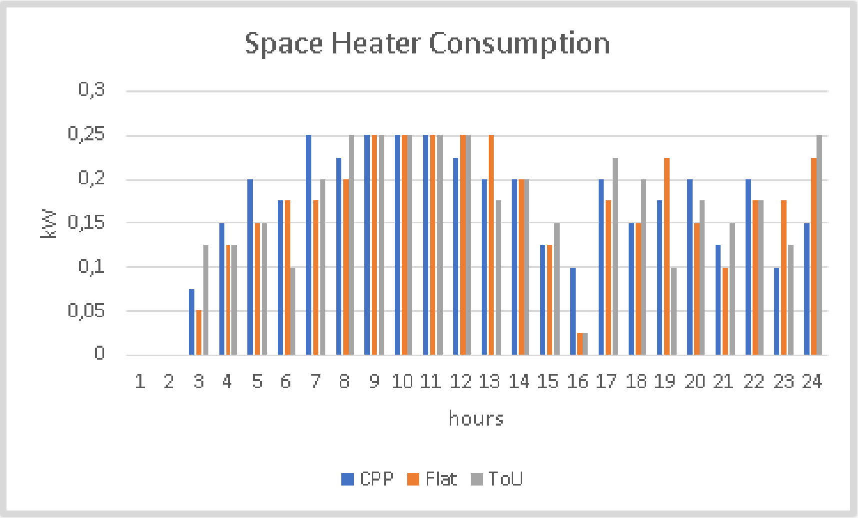


Figure 4.19: Energy consumed by HVAC system in cooler mode - Comparison between tariffs (1).

By analyzing Figure 4.19, it is proved that for the beginning of the day, when temperatures are not so high, the system will run for less time, thus spending less energy. However, the temperature starts to rise, and will require a higher power consumption.For the three different tariffs, it is possible to observe consumption does not exceed 0,25 kW per hour. After the hottest hours, the HVAC system, working as cooling, reduces the time required to heat the environment.

Moreover, Figure 4.20 shows the electric consumption of the electric water heating for the different tariffs presented. It should be noted that the loads are adjusted so as to obtain the lowest possible price, however, for all the restrictions and limitations presented, it is not always possible to obtain a total shift of loads as desired.

In Figure 4.19, for the first two hours, the Space Heater is OFF for every rate represented. The reason why this happens is because the initial value of the temperature in the room is lower than the value of the set point of the SH, so it is not necessary to lower the temperature further. For hour 3, in which case the ToU tariff is lower, it is verified that the consumption for this tariff is higher. From hour 4 to hour 7, the value consumed by SH in the CPP tariff is higher than the rest.

Between hours 9 and 11, the same consumption for the 3 tariffs is the same and high, which coincides with a high increase of the outdoor temperature. From this time, there is a decrease in consumption in all tariffs, until 4pm. At that time it is observed that consumption for the CPP tariff, is much higher than the other two. In the next hour, there is an increase in the outside temperature, which leads to a higher consumption of SH in all tariffs.

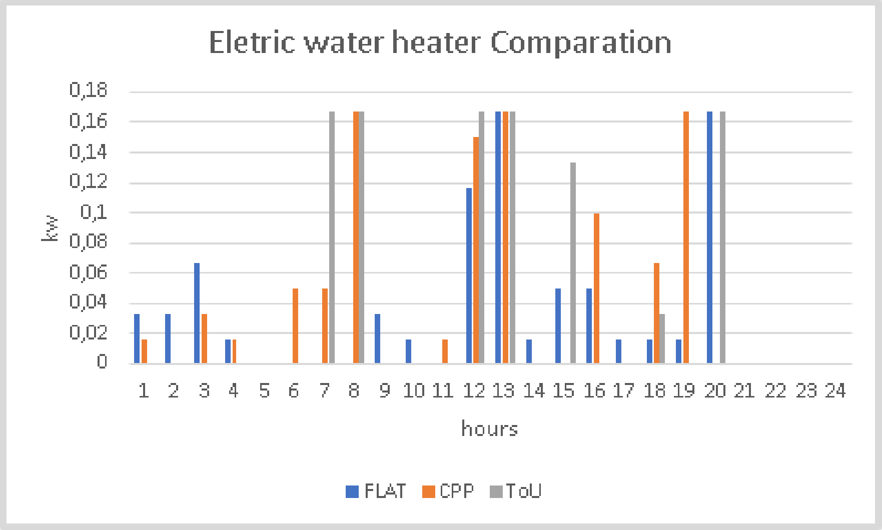


Figure 4.20: Energy consumed by the electric water heater - Comparison between tariffs (1).

For that same hour, hour 17, the ToU tariff is the highest. For hour 19, in which case the ToU tariff and the CPP are higher, it is observed that the greater consumption is done in the Flat Price tariff. Between hour 20 and hour 21, there is a decrease in consumption for all tariffs. For hour 22, the consumption in the ToU tariff is equal to the consumption in the Flat Price tariff, and the CPP is slightly higher. From 22 to 23 hours there was a decrease of consumption in the CPP and ToU tariffs, and the consumption for the Flat Price tariff remained the same. For the last hour, there was an increase for all case studies.

In Figure 4.20, on the first 4 hours, the EWH is active on FLAT price and CPP. For case 3, the flat price, it should be noted that the Energy value consumed for the first hours is higher than the CPP and grows from hour 2 to 3, and decreases from 3 to 4. In relation to CPP, there is an increase and decrease in the same hours, but on a smaller scale. For the CPP scheme, it was noted that there was a relative shift, so the energy was not consumed in the hours of higher cost, heating the water tank (hour 7 and 8) two hours earlier, which in this case was possible.

At hour 9 and 10, energy is only consumed at flat price tariff. The tariffs for CPP and ToU cases are quite high at these times. During hour 11, little energy is consumed, and only for the CPP case, whose value would increase for the next two hours (hour 12 and 13).

However, it is not just for case 2 that there is a growth in the value of energy for these hours. For the two other tariffs there is in the 12th and 13th hour, the increase for high consumption values. This is due to the need to restore the hot water in the tank after the first bath of the day has been taken. So at 13:30 the second bath is taken, with the temperature being within acceptable limits. In this way, the system will have to be switched on again for the future use of hot water, For hours 14 and 15, for the Flat Price, there is growth in consumption at these hours, but with low Energy consumption.

In the case of the ToU tariff, it is worth noting the high consumption for hour 15. This consumption is explained due to the low value of the ToU rate at that time. Between hour 16 and 17, the value of the consumption for the flat price tariff, goes down and remains constant and with very low values until the hour 19. Also in relation to hour 16, there is a median consumption for the CPP tariff, which will be extinguished at the 17th hour.

From the hour 18 to the hour 20 there is an increase of the general consumption since another bath of the user is programmed for 20:30, causing that there is need of heating of the water. From the hour 18 to the hour 20 there is an increase of the general consumption since another bath of the user is programmed, causing that there is need of heating of the water. After 8:30 there are no more baths programmed by the user, so there is no need to reheat the water to the optimum operating point.

4.2.2 Comparison case 1 and 4 (best case)

On this sub-chapter, a comparison is done between the RTP and the best possible case scenario. Firstly, The revenue or profit, as it is seen in Table 4.4, achieved by the user is bigger on ToU price, meaning the ToU tariff is the most appropriate in a situation as it was described before.

Firstly, comparing the HVAC consumption with Figure 4.21, as mentioned above, for the first two hours the energy consumed is 0, since the initial room temperature of the room is about 22 ^{o} C, which makes the value far from the setpoint 23 ^{o}C. Since there is this initial difference of registered values, it is possible to observe the increase of the temperature, according to the registered values of the external temperature, until it is necessary to turn ON the Space Heater, in this case in cooling mode.

Secondly, it is noticeable between hour 3 and 5, in relation to the RTP scheme, the power decreases. In the following hours, it is noteworthy for both cases a rise in energy, which corresponds to an effective rise in temperature outside the house, which causes the appliance to have to be working more time. HVAC system remains with consumption of 0,25 kW/h during 4 Hours, considering the TOU scheme, and 7 hours for the RTP scheme.For hours 13 and 14, the operation for the RTP scheme continues to have a peak value of 0.25 kW/h, however, in the case of the ToU tariff, a decrease in usage is observed in relation to the consumption of the RTP rate.

After that, the consumption of the HVAC under RTP scheme decreases to 0, at hour 15 and 16. On the same hours, but on the TOU tariff the values of energy is decreasing slowly until the minimum of 0,1 kW/h at 19 p.m. The high value of the consumption in the hour 17 and 18 is due to a new rise in the exterior temperature of the house.

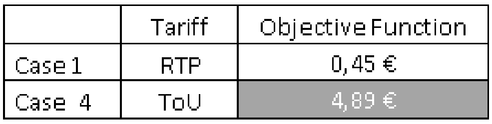
Moreover, under RTP tariff, at hour 17, the consumption increases and start its decreasing from hour 18 until hour 20. Then, it increases again and stabilizes to 0,25 kW/h until hour 23. The same does not happen under TOU tariff, where during this periods is falling up and down, until hour 24. For the last periods of the day, it is necessary to maintain the temperature values within the acceptable levels, so it is again necessary to cool it.

In Figure 4.22, it is possible to observe large discrepancies in relation of how the energy is consumed between both cases. For RTP, the consumption is divided into short intervals where the electric water heater is working. However, for the TOU tariff it is possible to observe that the consumption is divided into groups of hours where the consumption was higher, in order to restore the temperature of the water tank. By analyzing each section of the Figure 4.22 in detail, it is possible to observe the non-functioning of the water rise for the first 6 hours of the day. For the 7th and 8th hour, it should be noted the high consumption of EWH, for case 4.

After the use of the hot water, the tank temperature will have to return to the optimum point of bath of the user for which it will be necessary to reheat the water tank. Between hours 9 and 11, there is only the energy consumption in case 1, RTP, which leads to a slower heating of the temperature. In the case of the ToU tariff, the high consumption again at hours 12 and 13 is noted, as already mentioned. At time 14, the EWH is turned off for the case rate 4, and is ON for the RTP one. For case 1, there exists from hour 13 to hour 15, a decrease in consumption, which corresponds to the increase in the price of the RTP rate.

Between hour 17 and 18, there is an increase on the consumption in the RTP case, and a small consumption only for hour 18 in the ToU tariff. At hour 20, a high consumption with TOU is observed and only a slight consumption for the tariff of case 1. From the 21 hour on, the hot water is no longer used, so there is no need to heat the water. Thus, the energy values for case 1 are distributed over the time, which does not happen considering ToU. For ToU, there are high consumption in a few hours of the day.

Table 4.4: Objective function results - Revenue in euros (best case).



	Tariff	Objective Function
Case 1	RTP	0,45 €
Case 4	ToU	4,89 €

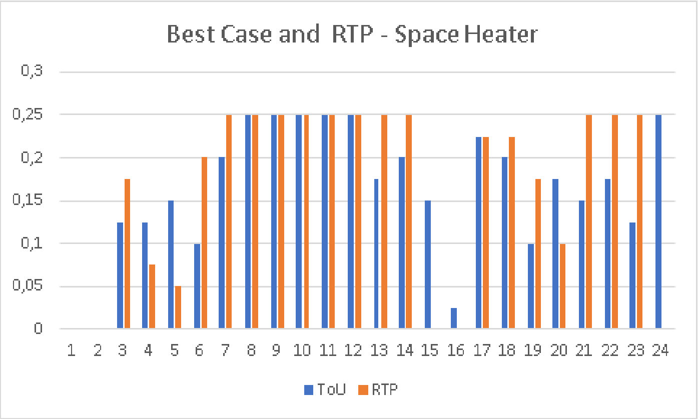


Figure 4.21: Energy consumed by the HVAC system - Comparison between tariffs (2).

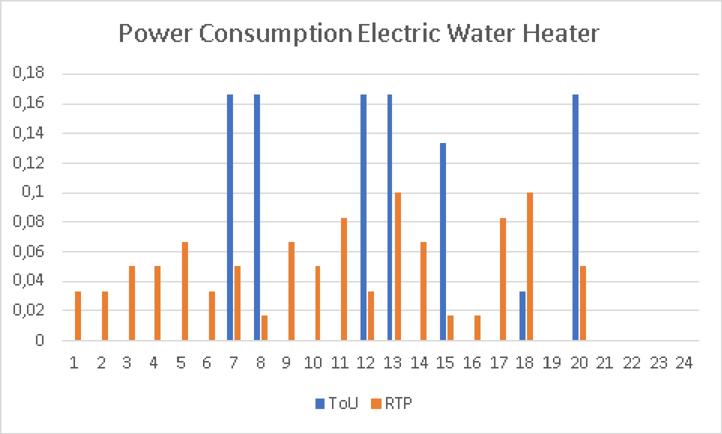


Figure 4.22: Energy consumed by the electric water heater - Comparison between tariffs (2).

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this dissertation, the proposed problem was modeled in two stages, considering several wind power scenarios, due to the natural uncertainty from wind. Moreover a house with certain characteristics was modeled in order to be able to use a real physical model, closer to the reality. To this end, an electric water heating and a HVAC system, in cooling mode, were implemented in order to obtain a better approximation to the reality.

The proposed model was implemented in a smart house with EV, ESS, and also, with a wind micro-turbine, allowing the possibility of exchange energy with the grid with certain limits. The results obtained allows to conclude that for the smart house in analysis, the best rate is the TOU scheme. It is the tariff where the objective function is maximized, i.e., the profit is maximum. It can also be concluded that depending on the tariff considered, the system will reallocate certain load values, within the constraints imposed by the network, temperature restrictions, equipment load limits, among others.

The relationship between the house and the customer allows the customer to define the time when the electric water heater will work, so that there is no undue expense in the water heating process, thus improving the efficiency. The algorithm applied considering the HVAC and the electric water heater is also a smart house technology, since the equipment itself will have the ability to switch ON/OFF automatically, accordingly with the required and measured temperature levels.

Finally, this work also demonstrates how a smart home, interconnected with the grid, and with user-adjustment interface, serves not only to make a the smart home concepts a reality, but also helps to define the best tariff for each situation, as well as the reduction of the load profile, guaranteeing the comfort levels and technical and safety constraints .

5.2 Future Work

For future work the proposed problem analyzed in this work may also include the comfort factor analysis, where there are several levels of comfort, and the algorithm calculates the energy consumption for each level. Another task is related with other incentive-based schemes, where customer would be rewarded in case of load reduction in some periods of the day when the system is more overloaded.

References

[1] Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions energy 2020 a strategy for competitive, sustainable and secure energy, November 2010. , disponível em `https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1409650806265&uri=CELEX:52010DC0639`.

[2] M. Masera, E. F. Bompard, F. Profumo, and N. Hadjsaid. Smart (electricity) grids for smart cities: Assessing roles and societal impacts. *Proceedings of the IEEE*, 106(4):613–625, April 2018. `doi:10.1109/JPROC.2018.2812212`.

[3] D. Baimel, S. Tapuchi, and N. Baimel. Smart grid communication technologies- overview, research challenges and opportunities. In *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pages 116–120, June 2016. `doi:10.1109/SPEEDAM.2016.7526014`.

[4] `https://www.statista.com/statistics/471264/iot-number-of-connected-\devices-worldwide/`.

[5] G. Le Ray, E. M. Larsen, and P. Pinson. Evaluating price-based demand response in practice—with application to the ecogrid eu experiment. *IEEE Transactions on Smart Grid*, 9(3):2304–2313, May 2018. `doi:10.1109/TSG.2016.2610518`.

[6] Junyon Kim. HEMS (home energy management system) base on the IoT smart home. *Contemporary Engineering Sciences 9*, pages 21–28, 2016.

[7] Abhishek Bhati, Michael Hansen, and Ching Man Chan. Energy conservation through smart homes in a smart city: A lesson for singapore households. *Energy Policy*, 104:230 – 239, 2017. URL: `http://www.sciencedirect.com/science/article/pii/S0301421517300393`, `doi:https://doi.org/10.1016/j.enpol.2017.01.032`.

[8] Quynh Lê, Hoang Boi Nguyen, and Tony Barnett. Smart homes for older people: Positive aging in a digital world. *Future Internet*, 4:607–617, 2012.

[9] `https://dspace.cvut.cz/bitstream/handle/10467/62043/F3-DP-2015-Makarova-Anastasiia-Diploma%20thesis%2c%20Makarova%20A..pdf?sequence=2&isAllowed=y` (8/10/18),.

[10] `http://www.trusted-objects.com/smart-home.html`(23/10/18),.

[11] Hong, X., C. Yang, and C. Rong. Smart Home Security Monitor System. *15th International Symposium on Parallel and Distributed Computing (ISPDC)*, page 247–51, 2016.

[12] D. Benyoucef, P. Klein, and T. Bier. Smart meter with non-intrusive load monitoring for use in smart homes. In *2010 IEEE International Energy Conference*, pages 96–101, Dec 2010. `doi:10.1109/ENERGYCON.2010.5771810`.

[13] B. Pilich. Engineering smart houses. Master's thesis, Informatics and Mathematical Modelling, Technical University of Denmark, DTU, Richard Petersens Plads, Building 321, DK-2800 Kgs. Lyngby, 2004. Supervised by Assoc. Prof. Christian D. Jensen. URL: `http://www2.imm.dtu.dk/pubdb/p.php?3256`.

[14] Amer, M., A. Naaman, N. K. M'Sirdi, and A. M. El-Zonkoly. A hardware algorithm for PAR reduction in smart home. *International Conference on Applied and Theoretical Electricity (ICATE)*, pages 1–6, 2014.

[15] S. Shao, M. Pipattanasomporn, and S. Rahman. Development of physical-based demand response-enabled residential load models. *IEEE Transactions on Power Systems*, 28(2):607–614, May 2013. `doi:10.1109/TPWRS.2012.2208232`.

[16] Zhe Yu, Shanjun Li, and Lang Tong. On market dynamics of electric vehicle diffusion. pages 1051–1057, 09 2014. `doi:10.1109/ALLERTON.2014.7028571`.

[17] Y. He, B. Venkatesh, and L. Guan. Optimal scheduling for charging and discharging of electric vehicles. *IEEE Transactions on Smart Grid*, 3(3):1095–1105, Sep. 2012. `doi:10.1109/TSG.2011.2173507`.

[18] R. G. Gago, S. F. Pinto, and J. F. Silva. G2V and V2G electric vehicle charger for smart grids. In *2016 IEEE International Smart Cities Conference (ISC2)*, pages 1–6, Sep. 2016. `doi:10.1109/ISC2.2016.7580786`.

[19] J. Vasudevan and K. S. Swarup. Price based demand response strategy considering load priorities. In *2016 IEEE 6th International Conference on Power Systems (ICPS)*, pages 1–6, March 2016. `doi:10.1109/ICPES.2016.7584019`.

[20] M. C. Vlot, J. D. Knigge, and J. G. Slootweg. Economical regulation power through load shifting with smart energy appliances. *IEEE Transactions on Smart Grid*, 4(3):1705–1712, Sep. 2013. `doi:10.1109/TSG.2013.2257889`.

[21] S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain and K. S. Kwak. The Internet of Things for Health Care: A Comprehensive Survey. *IEEE Access*, 3:678–708, 2015. `doi:10.1109/ACCESS.2015.2437951`.

[22] S. Erfani, M. Ahmadi, and L. Chen. The internet of things for smart homes: An example. In *2017 8th Annual Industrial Automation and Electromechanical Engineering Conference (IEMECON)*, pages 153–157, Aug 2017. `doi:10.1109/IEMECON.2017.8079580`.

[23] I. Pătru, M. Carabaş, M. Bărbulescu, and L. Gheorghe. Smart home iot system. In *2016 15th RoEduNet Conference: Networking in Education and Research*, pages 1–6, Sep. 2016. `doi:10.1109/RoEduNet.2016.7753232`.

[24] N. Dou, Y. Mei, Z. Yanjuan, and Z. Yan. The networking technology within smart home system - zigbee technology. In *2009 International Forum on Computer Science-Technology and Applications*, volume 2, pages 29–33, Dec 2009. `doi:10.1109/IFCSTA.2009.129`.

[25] Zhenyu Zou, Ke-Jun Li, Ruzhen Li, and Shaofeng Wu. Smart home system based on ipv6 and zigbee technology. *Procedia Engineering*, 15:1529 – 1533, 2011. CEIS 2011. URL: `http://www.sciencedirect.com/science/article/pii/S1877705811017851`, `doi:https://doi.org/10.1016/j.proeng.2011.08.284`.

[26] `https://iot.ieee.org/newsletter/july-2015/the-case-for-ipv6-as-an-\enabler-of-the-internet-of-things.html`.

[27] A. Durand. Deploying ipv6. *IEEE Internet Computing*, 5(1):79–81, Jan 2001. `doi:10.1109/4236.895146`.

[28] Jingang Lai, Hong Zhou, Wenshan Hu, Dongguo Zhou, and Liang Zhong. Smart demand response based on smart homes. *Research article. Mathematical Problems in Engineering*, 2015.

[29] D. Tejani, A. M. A. H. Al-Kuwari, and V. Potdar. Energy conservation in a smart home. In *5th IEEE International Conference on Digital Ecosystems and Technologies (IEEE DEST 2011)*, pages 241–246, May 2011. `doi:10.1109/DEST.2011.5936632`.

[30] Charlie Wilson, Tom Hargreaves, and Richard Hauxwell-Baldwin. Benefits and risks of smart home technologies. *Energy Policy 103*, page 72–83., April 2017.

[31] A. Mageroski, A. Alsadoon, P. W. C. Prasad, L. Pham, and A. Elchouemi. Impact of wireless communications technologies on elder people healthcare: Smart home in australia. In *2016 13th International Joint Conference on Computer Science and Software Engineering (JCSSE)*, pages 1–6, July 2016. doi:10.1109/JCSSE.2016.7748862.

[32] A. Jacobsson, M. Boldt, and B. Carlsson. On the risk exposure of smart home automation systems. In *2014 International Conference on Future Internet of Things and Cloud*, pages 183–190, Aug 2014. doi:10.1109/FiCloud.2014.37.

[33] N. Komninos, E. Philippou, and A. Pitsillides. Survey in smart grid and smart home security: Issues, challenges and countermeasures. *IEEE Communications Surveys Tutorials*, 16(4):1933–1954, Fourthquarter 2014. doi:10.1109/COMST.2014.2320093.

[34] N. Hajibandeh, M. Shafie-khah, S. Talari, S. Dehghan, N. Amjady, S. Mariano, and J. P. S. Catalão. Demand response based operation model in electricity markets with high wind power penetration. *IEEE Transactions on Sustainable Energy*, pages 1–1, 2018. doi:10.1109/TSTE.2018.2854868.

[35] V. S. K. Murthy Balijepalli, V. Pradhan, S. A. Khaparde, and R. M. Shereef. Review of demand response under smart grid paradigm. In *ISGT2011-India*, pages 236–243, Dec 2011. doi:10.1109/ISET-India.2011.6145388.

[36] Gadham K. R. and T. Ghose. Importance of social welfare point for the analysis of demand response. *IEEE First International Conference on Control, Measurement and Instrumentation (CMI)*, page 182–85, 2016.

[37] M. Shafie-khah, S. Javadi, P. Siano, and J. P. S. Catalão. Optimal behavior of smart households facing with both price-based and incentive-based demand response programs. In *2017 IEEE Manchester PowerTech*, pages 1–6, June 2017. doi:10.1109/PTC.2017.7981248.

[38] Cherrelle Eid, Elta Koliou, Mercedes Valles, Javier Reneses, and Rudi Hakvoort. Time-based pricing and electricity demand response: Existing barriers and next steps. *Utilities Policy*, 40:15 – 25, 2016. URL: http://www.sciencedirect.com/science/article/pii/S0957178716300947, doi:https://doi.org/10.1016/j.jup.2016.04.001.

[39] B. Chai, J. Chen, Z. Yang, and Y. Zhang. Demand response management with multiple utility companies: A two-level game approach. *IEEE Transactions on Smart Grid*, 5(2):722–731, March 2014. doi:10.1109/TSG.2013.2295024.

[40] S. Maharjan, Q. Zhu, Y. Zhang, S. Gjessing, and T. Basar. Dependable demand response management in the smart grid: A stackelberg game approach. *IEEE Transactions on Smart Grid*, 4(1):120–132, March 2013. doi:10.1109/TSG.2012.2223766.

[41] Pu yan Nie and Pei ai Zhang. A note on stackelberg games. In *2008 Chinese Control and Decision Conference*, pages 1201–1203, July 2008. doi:10.1109/CCDC.2008.4597505.

[42] P. T. Baboli, M. Eghbal, M. P. Moghaddam, and H. Aalami. Customer behavior based demand response model. In *2012 IEEE Power and Energy Society General Meeting*, pages 1–7, July 2012. doi:10.1109/PESGM.2012.6345101.

[43] Ailin Asadinejad and Kevin Tomsovic. Optimal use of incentive and price based demand response to reduce costs and price volatility. *Electric Power Systems Research*, 144:215 – 223, 2017. URL: http://www.sciencedirect.com/science/article/pii/S0378779616305259, doi:https://doi.org/10.1016/j.epsr.2016.12.012.

[44] Liu, Chen-Ching and Stephen McArthur, and Seung-Jae Lee. *Smart Grid Handbook*, volume 3. John Wiley Sons, August 2016.

[45] Stenner Karen, Elisha R. Frederiks, Elizabeth V. Hobman, and Stephanie Cook. Willingness to participate in direct load control: The role of consumer distrust. *Applied Energy 189*, pages 76–88, March 2017.

[46] H. Aalami, G. R. Yousefi, and M. Parsa Moghadam. Demand response model considering edrp and tou programs. In *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, pages 1–6, April 2008. doi:10.1109/TDC.2008.4517059.

[47] Muhammad Saad. Methods of demand site management and demand response. *Research Reviews: Journal of Engineering and Technology*, August. 2016.

[48] A. M. Pirbazari. Ancillary services definitions, markets and practices in the world. In *2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T D-LA)*, pages 32–36, Nov 2010. doi:10.1109/TDC-LA.2010.5762857.

[49] I. P. Panapakidis, S. I. Frantza, and G. K. Papagiannis. Implementation of price-based demand response programs through a load pattern clustering process. In *MedPower 2014*, pages 1–8, Nov 2014. doi:10.1049/cp.2014.1686.

[50] N. S. Hussin, M. P. Abdullah, A. I. M. Ali, M. Y. Hassan, and F. Hussin. Residential electricity time of use (tou) pricing for malaysia. In *2014 IEEE Conference on Energy Conversion (CENCON)*, pages 429–433, Oct 2014. doi:10.1109/CENCON.2014.6967542.

[51] E. Celebi and J. D. Fuller. Time-of-use pricing in electricity markets under different market structures. *IEEE Transactions on Power Systems*, 27(3):1170–1181, Aug 2012. doi:10.1109/TPWRS.2011.2180935.

[52] Guy R. Newsham and Brent G. Bowker. The effect of utility time-varying pricing and load control strategies on residential summer peak electricity use: A review. *Energy Policy*, 38(7):3289 – 3296, 2010. Large-scale wind power in electricity markets with Regular Papers. URL: http://www.sciencedirect.com/science/article/pii/S0301421510000510, doi:https://doi.org/10.1016/j.enpol.2010.01.027.

[53] W. Trabelsi, R. Azzouz, S. Bechikh, and L. Ben Said. Leveraging evolutionary algorithms for dynamic multi-objective optimization scheduling of multi-tenant smart home appliances. In *2016 IEEE Congress on Evolutionary Computation (CEC)*, pages 3533–3540, July 2016. doi:10.1109/CEC.2016.7744237.

[54] A. Mohsenian-Rad and A. Leon-Garcia. Optimal residential load control with price prediction in real-time electricity pricing environments. *IEEE Transactions on Smart Grid*, 1(2):120–133, Sep. 2010. doi:10.1109/TSG.2010.2055903.

[55] Henrique F. Lacerda, Allan R. S. Feitosa, Abel G. Silva-Filho, Wellington P. Santos, and Filipe R. Cordeiro. Smarthome energy saving using a multi-objective approach based on appliances usage profiles. In Malek Mouhoub and Philippe Langlais, editors, *Advances in Artificial Intelligence*, pages 142–147, Cham, 2017. Springer International Publishing.

[56] Ullah, Ihsan, Nadeem Javaid, Zahoor A. Khan, Umar Qasim, Zafar A. Khan, and Sahibzada A. Mehmood. An Incentive-based Optimal Energy Consumption Scheduling Algorithm for Residential Users. *Procedia Computer Science, The 6th International Conference on Ambient Systems, Networks and Technologies (ANT-2015), the 5th International Conference on Sustainable Energy Information Technology (SEIT-2015)*, pages 851–57, 2015.

[57] Kosuke Uchida Cirio Celestino Muarapaz Abdul Motin Howlader Yasuaki Miyazato, Hayato Tahara and Tomonobu Senjyu.

[58] N. G. Paterakis, O. Erdinç, A. G. Bakirtzis, and J. P. S. Catalão. Optimal household appliances scheduling under day-ahead pricing and load-shaping demand response strategies. *IEEE Transactions on Industrial Informatics*, 11(6):1509–1519, Dec 2015. doi:10.1109/TII.2015.2438534.

[59] P. Du and N. Lu. Appliance commitment for household load scheduling. *IEEE Transactions on Smart Grid*, 2(2):411–419, June 2011. doi:10.1109/TSG.2011.2140344.