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Efficient Management of Domestic Equipment for Active Participation in the Electric Grid

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Resumo

Nos dias de hoje, fruto da necessidade da implementação de ferramentas eficientes e sustentáveis para a gestão do comportamento evolvendo os conceitos de casa inteligente, tal desafio tem recebido uma crescente atenção por parte da comunidade científica um pouco por todo o mundo.

O impacto do crescente interesse e utilização dos veículos elétricos obriga a uma inevitável modernização e reforço da rede elétrica, e das casas a que estamos habituados. O conceito de rede inteligente está relacionado com a mudança do papel dos utilizadores, na transição como elementos passivos da rede para um papel mais ativo.

A modernização tecnológica de uma rede inteligente torna-a mais eficiente, controlável, e economicamente mais sustentável do que a rede convencional que vemos hoje em dia. Numa rede inteligente os utilizadores da rede são capazes de participar ativamente no mercado de eletricidade, e para isso é necessário o ajuste dos padrões de consumo e do funcionamento dos aparelhos domésticos, o que torna o conceito de casa inteligente real.

Nesta dissertação foi estudada uma comunidade de energia local onde se considerou casas com um sistema residencial de gestão de energia. Programas voluntários de *Demand Response* (DR) baseados no preço foram aplicados a cada casa de forma a incentivar o consumidor final a mudar os seus hábitos de consumo energético. Para além disto, a existência de tecnologias de microgeração renovável e sistemas de armazenamento de energia também foram consideradas.

A otimização do modelo matemático utilizado está baseado numa programação linear inteira normalizada, o que permite uma minimização ótima do preço diário de eletricidade enquanto respeita as restrições técnicas inseridas no modelo, permitindo a permutação de cargas durante o dia de forma otimizada.

Note-se que todos os consumidores que integram a comunidade de energia estudada estão equipados com tecnologias de microgeração renovável de energia e sistemas de armazenamento de energia, os quais permitem minimizar os custos de compra de eletricidade, através da flexibilidade existente entre a microgeração e o armazenamento devido à imprevisibilidade da produção ou dos momentos mais exigentes. Para além disso, tais sistemas permitem a transição de energia da casa para a rede o que, consequentemente, possibilita o consumidor ter benefícios com o excesso da energia produzida.

Os resultados mostram que um sistema de gestão de energia residencial é capaz de reduzir os custos diários de eletricidade, enquanto é considerado o conforto do consumidor. Para mais, a microprodução renovável de energia e a utilização dos sistemas de armazenamento de energia são tecnologias essenciais no conceito das casas inteligentes onde os programas de DR têm um papel essencial no incentivo ao consumidor em mudar os padrões de consumo, permitindo a necessária flexibilidade da rede elétrica.

Palavras-Chave: Casa inteligente, Electrodomésticos inteligentes, Energia renovável, Rede inteligente, Permutação de cargas, Sistema de armazenamento de energia, Sistema de gestão de energia residencial.

Abstract

Nowadays, due to the need to implement sustainable and efficient tools for the management behaviour involving Smart Home (SH), these concepts have received increasing attention in the scientific community all over the world.

The impact of the exponential growth in electric vehicle usage leads to an unavoidable need to modernise and reinforce the electric grid and houses we see to date. The concept of Smart Grid (SG) is related to the shift of users from the currently passive role to a more active role.

The technological modernisation of the SG makes it more efficient, manageable, and more economically sustainable than the traditional grid we see nowadays. In a SG, users are capable of actively participating in energy markets, to do this, it is necessary to adapt consumption patterns and residential appliances usage, this makes SH a real concept.

In this dissertation was studied a local energy community considering houses with a Home Energy Management System (HEMS). Price-based voluntary Demand Response (DR) programs were applied to each house to captivate end-users to change their consumption habits. Besides, the existence of Renewable Energy Sources (RES) micro-generation and an Energy Storage System (ESS) was also taken into account.

The optimisation of the mathematical model studied is based on a standard Mixed-Integer Linear Programming (MILP), which allows an optimal minimisation of daily electricity costs while respecting the different technical constraints of this model. This framework allowed optimal load shifting of the appliances throughout the day.

Note that all the consumers that integrate the energy community studied are equipped with RES generation technologies and ESS, this equipment minimises the costs of energy purchase during RES production and the ESS compensates for the unpredictability of renewable energy production. In addition, these systems allow the transaction of energy from the house to the grid, which allows the end-users to profit from a surplus of energy generated.

Finally, the results show that the HEMS model presented in this dissertation is capable of reducing daily electricity costs while considering end-users' comfort. Should also be noted that RES production and ESS are essential technologies in modern SH applications, as well as DR programs, which have an essential role in captivating prosumers to change their consuming habits, allowing the necessary flexibility of the electrical grid.

Keywords: Community Microgrid, Energy storage systems, Home energy management system, Load shifting, Renewable energy, Smart appliances, Smart grid, Smart house.

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Now, to the most important people in my life, my family. To my parents, a huge thank you for all the efforts you made to provide me with the best education possible and all the support in the good and bad moments, this would not be possible without you. To my sister, Beatriz, thanks for always having my back and being my role model throughout my life. There is no doubt that you showed me how to face the good and bad moments of academic life and made my journey easier. To the rest of my family members, thank you for all the knowledge you passed me during my life, without all of you I would not be here.

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To all, thank you.

Ricardo Cardoso

“Before things come together,
they have to fall apart”

Mac Miller

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Abbreviations

AI	Artificial Intelligence
CPP	Critical Peak Pricing
DLC	Direct Load Control
DR	Demand Response
EDRP	Emergency Demand Response Program
ESS	Energy Storage Systems
EV	Electric Vehicle
GHG	Greenhouse Gas
G2H	Grid-to-Home
HAWT	Horizontal Axis Wind Turbine
HEMS	Home Energy Management System
H2G	Home-to-Grid
IBDR	Incentive Based Demand Response
IoT	Internet of Things
MILP	Mixed-Integer Linear Programming
PBDR	Price Based Demand Response
RES	Renewable Energy Sources
RTP	Real Time Pricing
SG	Smart Grid
SH	Smart Home
SOC	State of Charge
TOU	Time of Use
VAWT	Vertical Axis Wind Turbine
V2G	Vehicle to Grid

Nomenclature

Indexes

I	Home appliances index
j	ESS devices index
k	Energy consumption in IBR mechanism index
t	Time intervals of scheduling index
ω	Scenario index

Sets

NT	Scheduling period
NA	Set of home appliances
NS	Total number of ESS devices
Ω	Set of scenarios

Variables

$S_{\omega,i,t}$	Operation status of the shiftable appliances
$P^{G2H}_{\omega,t}$	Power delivered from grid to home
$P^{H2G}_{\omega,t}$	Power delivered from home to grid
$D^{\text{Shift}}_{\omega,t}$	Demand of the shiftable load by hour
$\text{STUP}_{\omega,i,t}$	Start-up action binary variable
$\text{SHDN}_{\omega,i,t}$	Shut-down action binary variable
$\text{DI}^{+}_{\omega,i}$	Discomfort index regarding the use of the appliance *i* after the scheduled time
$\text{DI}^{-}_{\omega,i}$	Discomfort index regarding the use of the appliance *i* before the scheduled time
$\text{Energy}^{Tier}_{\omega,k}$	Amount of energy for each tier in IBR mechanism
$I^{\text{Tier}}_{\omega,k}$	Status of activated tier in IBR mechanism
$P^{Ch.}_{\omega,j,t}$	Charging power of ESS
$P^{Disch.}_{\omega,j,t}$	Discharging power of ESS
$I^{Ch}_{\omega,j,t}$	Charging status of ESS
$I^{Disch}_{\omega,j,t}$	Discharging status of ESS
$E_{\omega,j,t}$	Energy stored in the ESS

Parameters

π_t^{G2H}	Hourly electricity price sold to the house
π_t^{H2G}	Hourly electricity price sold to the grid
C_i^{ST}	Start-up cost of shiftable loads
C_i^{SD}	Shut-down cost of shiftable loads
IBR_k^{Tariff}	Stepwise tariff for IBR mechanism
T_i	Total number of time intervals
$LB_{i,b}$	Lower band of baseline operation time slot
$UB_{i,b}$	Upper band of baseline operation time slot
$LB_{i,s}$	Lower band of allowable operation time slot
$UB_{i,s}$	Upper band of allowable operation time slot
$B_{\omega,i,t}$	End-user's preferred usage status of the appliance
$D_{\omega,t}^{Fix}$	Hourly fixed demand
P_i	Rated power of appliance i
$P_i^{Ch.,\max}$	Maximum charging power of ESS
$P_i^{Disch.,\max}$	Maximum discharging power of ESS
$\eta_j^{Ch}.$	Charging efficiency of ESS
$\eta_j^{Disch}.$	Discharging efficiency of ESS
$E_j^{\min}$	Minimum acceptable energy stored at ESS
$E_j^{\max}$	Maximum acceptable energy stored at ESS
$E_{\omega,j,1}$	Initial energy stored in the ESS
$E_{\omega,j,T}$	Final energy stored in the ESS
$E_k^{\text{Tier,max}}$	Maximum energy consumption at tier k
σ	Penalty factor for discomfort index
ρ_ω	Probability of each scenario
Δt	Operation time interval

Chapter 1

Introduction

In this chapter, first, a framework about the concepts related to the worldwide power system is presented. Then, to raise the interest in this dissertation, the motivations, goals, and objectives will be presented. Lastly, the dissertation structure will be presented.

1.1 Background

Over the last few years, the scientific community have been studying ways to compensate for the rise of power consumption and sustainably produce energy. For example, the global electricity demand is expected to increase by 80% between 2012 and 2040, [1]. Beyond these facts, the increasing concern about climate change and Greenhouse Gas (GHG) emissions make clear the path for the future of energy production and consumption. The European Union (EU) is being a role model for the rest of the world due to the ambitious, but possible, goals set to achieve by 2030. One of these goals is to increase the share of renewable energy development in final energy consumption to 32%. Another example is the goal set by Germany, to phase out coal use in power generation by 2038, [2].

According to the "Renewables 2021 Global Status Report" issued by REN21 (Renewable Energy Policy Network for the 21st Century), [3], fossil fuel energy production stabilised since 2018 and decreased by 2% in recent years, while renewable electricity increased significantly. In Figure 1.1 can be seen an overall view of the global electricity production methods and their evolution in the past decade.

Unfortunately, the energy system seen today needs urgently to be improved to support the integration of all the unpredictable Renewable Energy Sources (RES), while being able to supply the increasing power needs without using energy produced by pollutant sources, [4]. All these efforts have contributed to a great improvement in renewable energy technologies, especially photovoltaic solar panels, and wind turbines. With the advancement of these technologies, the possibility of home micro-generation became a realistic idea that has the capability of transforming common houses into sustainable ones while making them more cost-friendly, more controllable and improving in other socioeconomic benefits.

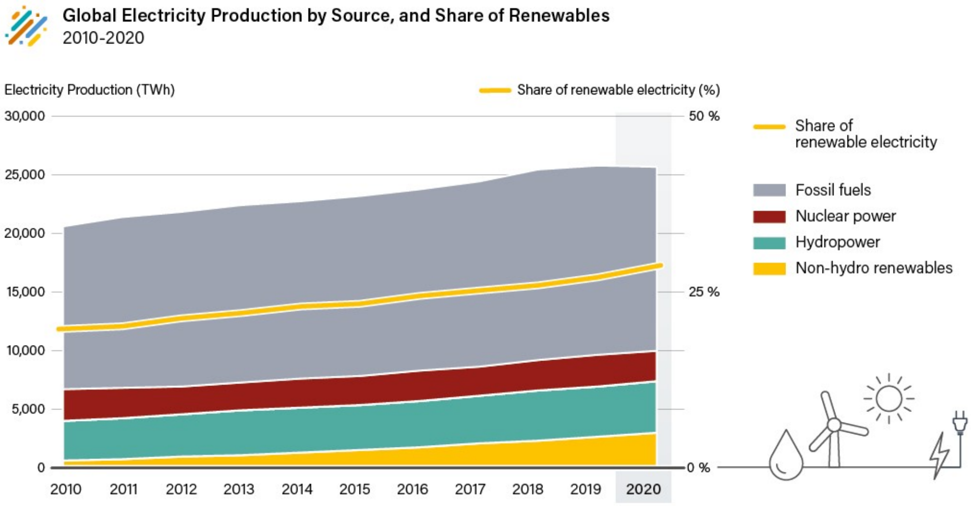


Figure 1.1: Global electricity production by source, and share of renewables, 2010-2020 [3]

Owners of houses with micro-generation can be considered as producers and consumers, this creates the capability to control when to sell or to buy energy from the conventional markets and, this way, reduce electricity costs while not contributing to the emission o GHG, [5]. Therefore, these prosumers can enrol in important positions in the local market. When integrating a group of houses with these capabilities with a Smart Grid (SG) topology we create a community with a highly reliable, scalable, and secure grid that has the capability of selling and buying energy from each other, this type of grid is unavoidable when integrating a large amount of RES due to its smoothing capabilities, [6].

In the future, the grid that we know to date has to suffer some changes to make it smarter. To achieve this goal, it is necessary to create SGs with two-way communication between grid, and consumer. With this, it is possible to exchange energy between consumers and, sell excess energy at a low price, reducing the electricity costs for the various users. To help, it is also necessary the introduction of demand-side management and Demand Response (DR) programs aiming to better in-house energy consumption behaviours, [7].

Following the incentives created in the EU for the improvement of RES, a similar path is being taken regarding Electric Vehicles (EV), the goal is to break the oil dependency and to improve the efficiency of transport in Europe. One of the strategies imposed by the member states was the review of the tax systems and the creation of incentives for zero- and low-emission vehicles and energy, also, in 2017 it was submitted a package of legislative manners seeking to make the EU a leader in clean mobility, [8].

With the constant development of EVs, consequentially, battery technologies were also studied and perfected to the maximum. This evolution, resulted in a big improvement in Energy Storage Systems (ESS), not only for EV use but also for in-home energy storage. Lithium-Ion batteries were the ones which improved the most due to their common applications being power electronics and EVs and the high research around these technologies, [9].

As a consequence of the advancement in battery technology, it is now possible to have an in-home ESS, and due to the evolution in EVs batteries, scholars have been studying the capability of reliable use of the EV as a storage system to shift load from peak to off-peak hours. This Vehicle-to-Grid (V2G) is also attractive for voltage and frequency control, the main goals of a V2G system are to maintain a charging equilibrium, eliminate power grid stress problems, power balance, stability and charging urgency. A V2G coordination is more effective than a Grid-to-Vehicle (G2V) system, but both are still some challenges to overcome, [10].

Systems with storage capability are a must to compensate for the unpredictability of RES. This way, the consumer has the power to choose when to buy electricity from the grid, so, when the price is low the prosumer buys his electricity, and in peak-hours clients can utilise the energy in storage for their use. When the RES are producing more than needed the prosumer can also sell this energy and, this way, create an income from the surplus of energy.

The combination of RES, ESS, EVs and the evolution in automated devices, such as sensors, actuators, smart metering, smartphones and Internet of Things (IoT) concepts made possible the introduction of the concept of a Smart Home (SH), [11]. Through these various systems, the residents can access information about the status of the house and the possibility to control its equipment. Although this improves customer comfort, house security, energy consumption optimisation, and cost minimisation. It also requires complex SH modules, decision-making algorithms, and big initial investments, [12].

All the systems mentioned before can be considered SH technologies due to the capability of being digitally connected and their objective being customer life improvement. SH has been the centre of attention in policy discussions about energy efficiency, climate change, sustainability, and technological innovation, thus, this type of house is one of ten pillars in the EU action areas for investments, [13].

Furthermore, studies have shown that SH benefits customers' lifestyles in various ways. The first one is by improving customer comfort and life quality, as well as reducing energy costs and energy consumption, [14]. Beyond this, SH can also provide reliable energy market prices reports and healthcare information, [15].

In light of this, the development of a SH should also integrate DR programs as a way of encouraging the consumer to change his energy utilisation habits to consume in low price hours and, this way, overcome peak demand periods and become a more active participant in the energy local market, [16].

As referenced before, to integrate RES, ESS, DR programs, and weather forecasting systems in a house while dealing with client's demand variations it is necessary to implement stochastic and probabilistic programs, this solution can better DR program predictions and other uncertain variables like the fluctuation of RES. In reference [17], was conducted a review on the generic steps of stochastic optimisation in renewable energy applications and it was concluded that the stochastic optimisation methods almost always outperform deterministic methods in terms of social, technical and economic aspects of renewable energy systems.

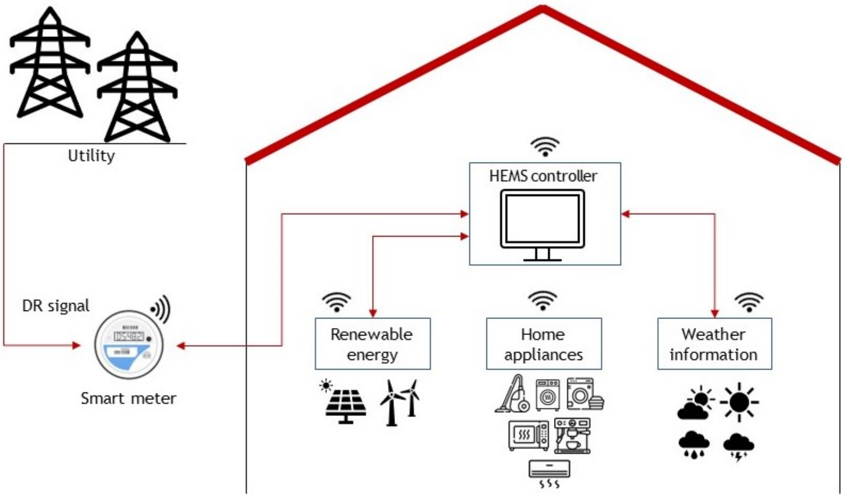


Figure 1.2: Architecture of home energy management system with demand response signal, adpated from [18]

The combination of all these technologies highly favoured the creation of the SH concept that is known today. Modern SH aims to minimise energy costs and customer discomfort, these homes utilise a Home Energy Management System (HEMS) which is responsible to coordinate and predict all the different technologies in an effort to reach the final goal of a SH, [19].

According to [20], the concept of SH began in the late 1990s with the widespread diffusion of high-speed internet, but it was not until the late 2000s that SH began to be installed with remote monitoring and control functions through smartphones and apps. In the late 2010s began to rise the interest in IoT and Artificial Intelligence (AI) concepts which had the function of context-awareness.

Nowadays, it is also practicable to have profit from buying electricity at low prices, utilising load-shifting capabilities, and DR programs, and selling surplus electricity to the local energy market, [18]. In Figure 1.2 is represented the architecture of a HEMS with demand response signal. This dissertation will investigate these capabilities and the integration of RES, ESS and EVs to minimise clients' electricity costs.

1.2 Motivation and Goals

In recent years the energy demand increased exponentially due to high energy consumption habits, electric vehicle introduction and the modernisation of daily appliances. Beyond this, the COVID-19 pandemic greatly impacted the energy demand and consumption, [21]. This creates immense pressure on energy production systems, the national grid and energy prices. Although renewable energy resources have been more and more used to compensate for this fact, their unpredictability and the lack of energy storage systems make this effort not enough, [22].

Another problem of the modern-day is the unpredictability of consumers' behaviour. The way of turning this problem around is by implementing demand response programs, and, in this way, increasing the flexibility of the system.

To solve this problem, it is necessary to implement modern-day solutions such as smart grids and smart home technologies. This dissertation aims to study the impact of demand response programs applied in a smart home, as well as, consider the integration of EVs, renewable energy generation, ESS and load shifting.

The growth of renewable energy generation and energy storage systems makes it possible to present a model in this dissertation which allows for a more sustainable environment and low electricity prices. However, this model needs to be optimised to operate under different scenarios and different consumer behaviours, while considering operating costs and environmental restrictions. The objectives for this project are based on the following three points:

- The development and improvement of a source code to allow demand management of a smart home, including renewable energy generation, electric vehicle charging methods and other possible smart appliances.
- Assess the effect of the operation of electric vehicles and storage, considering the customer's comfort level.
- Analyse the impact of demand response programs on the operation of electric vehicles, load management, renewable generation and storage in a smart home.

The different motivations and goals of this dissertation lead to the creation of some research questions based in the area of this study. These topics were summarised in the following research questions:

- What is the impact of smart management generation and consumption tools in the electric grid?
- Is it possible for small energy prosumers to have an active role in the efficient management of the electric grid?

1.3 Dissertation structure

The structure of this dissertation is divided into five chapters. Chapter one presents a general overview of the thesis topic, its motivation, goals, and structure.

Chapter 2 corresponds to the introduction of the literature review, where is compacted the knowledge obtained from diverse references studied. This chapter starts with the concept of renewable energies, divided into its evolution and residential applications. it is followed by a detailed review of smart grids and their different applications. Then it is presented an energy storage systems study, focused on the different systems, configurations and their pros and cons. Subsequently, different definitions of sustainability are presented, considering five dimensions. Following this, it is presented the home automation systems topic where is also talked about smart metering. After this, it is presented the different demand response concepts. Lastly, can be seen some related work similar to this project.

Chapter 3 consists of the explanation of the mathematical formulation, including the objective function and the various constraints of the problem. The objective of this problem is to minimise electricity costs and consumer discomfort while taking advantage of renewable energy sources, energy storage systems, load shifting, and demand response programs.

Chapter 4 presents the different results obtained in this study. Firstly, a brief review of the data used for the simulation of our model, and then, some comparative results of different scenarios. Finally, chapter 5 can be seen as the conclusions of this work and future work proposals.

This dissertation uses notations and abbreviations which are, normally, scientifically accepted. The figures, tables and mathematical formulas are numbered by the chapter they are included in (x) and sequentially (y). The numbering restarts when a new chapter begins, for example, "Figure x.y", "Table x.y", "Equation (x,y)".

Chapter 2

Literature Review

Aiming to acquire some updated knowledge and concepts that are going to be focused on in this dissertation work, this chapter contains relevant and detailed information associated with the state of the art and ideas regarding Renewable Energies, Smart Grids, Energy Storage Systems, House Automation Systems, Demand Response Programs and, lastly, some related work and research.

2.1 Renewable Energies

2.1.1 Global evolution Renewable Energy Sources

As is well known, during most of the lifespan of the energy production industry no attention was given to the way energy was produced. With the increasing concern about climate change and Greenhouse Gas (GHG) emissions, a need to change the energy production method was clear. Due to this, the global Renewable Energy Sources (RES) provide 15% to 20% of today's world total energy demand [23].

Since 2011, RES are part of more than half of the capacity additions in the power sector, with more than 140 countries currently having Renewable Energy targets in place [24]. The EU has recently made big efforts to reduce carbon emissions, developing a road map to foster a low-carbon European economy by 2050. The main goal of this plan is to reduce Europe's GHG emissions by 80% relative to the 1990 level [25]. Figure 2.1 presents the annual additions of renewable power capacity by technology from 2014 to 2020 [3].

Socially speaking, with the rise of RES, every consumer could have an independent energy source, for example, photovoltaic panels installed in rooftops of residential properties. This allows the consumer to produce the energy needed in his household, as well as sell extra energy to other consumers, drastically reducing electricity bills costs [26]. On the economic side, job creation is a key part of economic development and healthy economies. RES investments have the power to create a large number of jobs, especially if the materials and technologies are created locally [27]. Also, RES prices are lower than conventional energy production technologies, [23].

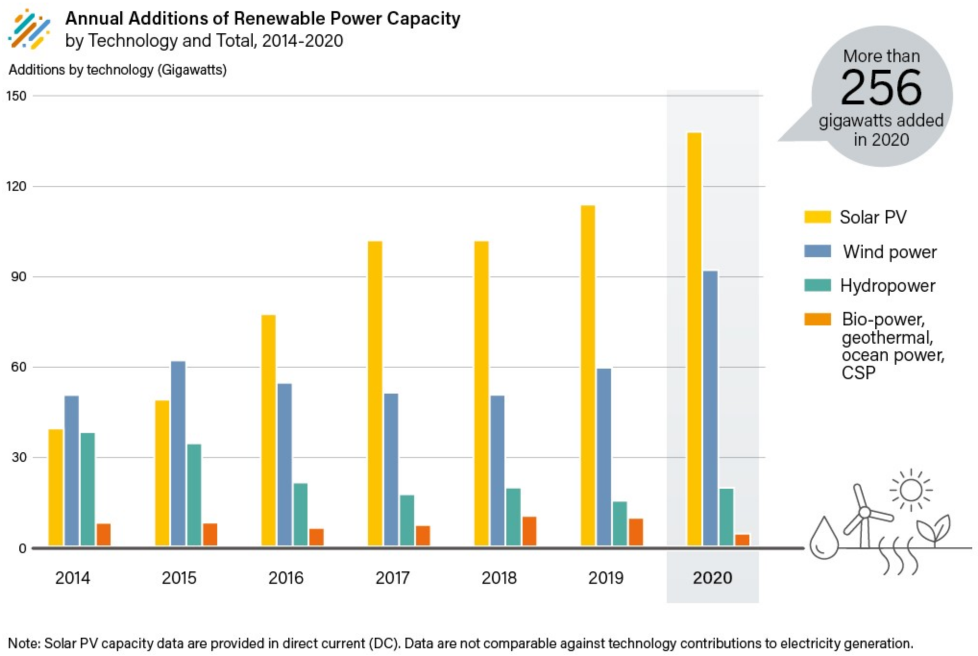


Figure 2.1: Annual additions of renewable power capacity by technology from 2014 to 2020 [3]

Despite the advantages that RES have in their favour, there are some disadvantages to consider. Firstly, renewable sources depend on weather conditions, drastically changing their potential according to meteorological events [28]. Secondly, there's a risk associated with RES integration in smart grids because of the frequency and voltage fluctuations. When RES penetration in the grid increases the stability and reliability of the system are endangered. Moreover, they do not participate in voltage regulation risking the voltage stability of the system [29].

Due to the RES dependency on meteorological conditions, forecasting these technologies is a difficult task due to the variability and unpredictability of the weather. With the need for ideal climate conditions, RES locations are a key matter when installing RES and have an impact on their costs [30].

Regarding these challenges, many solutions are being implemented, like the improvement of predictive algorithms for wind and solar energy production, an improvement in Energy Storage Systems (ESS) and energy management.

2.1.2 Renewable Energy Sources for Residential Applications

As stated in [31] it is estimated that the global energy consumption will increase by 71% from 2003 to 2030 which creates an immense pressure on energy production systems and increases energy prices, making it harder for low-income households and remote residents to access the energy they need. One of the solutions for this is to install RES for residential use, creating in this way a capability of in-house micro-generation which makes the consumer more independent from the electric grid.

2.1.2.1 Residential Wind Generation

Since the 18^{th}-century wind turbines have been used for power generation in rural areas or offshore sites, where there's plenty of wind to profit from the installation of big Horizontal Axis Wind Turbines (HAWT), as can be seen in Figure 2.2, the larger the turbine and the more intense the wind is more electricity its produced. On the other hand, this type of wind turbine size can't be used in built-up areas due to its volume and the structures and houses existing in these areas.

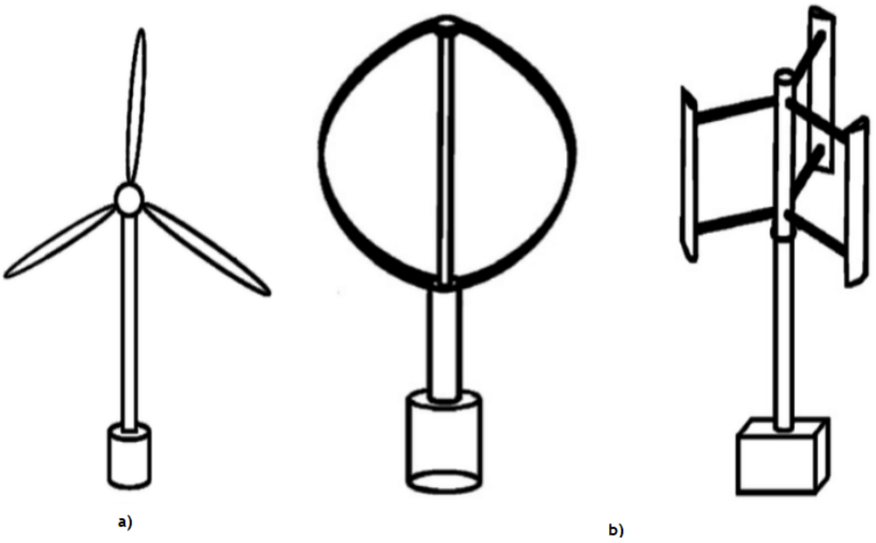


Figure 2.2: Wind turbine technologies, a) horizontal axis turbines, b) vertical axis turbines, adapted from [32]

Authors in [33] support that, for residential areas, vertical axis microturbines are the most advantageous technology. In this study was created a new vertical axis model which showed great results. However, it is also possible to operate horizontal axis microturbines in residential areas. Due to the low power production of these systems, both technologies should be used in a hybrid system with PV panels to supplement power demand on days with optimal meteorological characteristics for the use of these systems, this way it is possible to maximise the micro-generation of a house.

Even if studies show a great improvement in the capability to introduce wind generation in residential areas there is still a big need for improvement as can be seen by the disadvantages presented in Table 2.1.

In [34] is shown that the main difference between the two technologies is that horizontal axis turbines can only generate energy from only one direction and Vertical Axis Wind Turbines (VAWT) generate energy from the wind coming from all directions. Also, the study shows that an increase in VAWT blades also increases the maximum power, but in HAWT this does not happen.

Table 2.1: Advantages and disadvantages of wind energy generation, adapted from [35]

Advantages	**Disadvantages**
Short time to design and install	Wind is highly variable
Low emissions	Limited resource sites
Different modular size	Audible and visual noise
	Low availability during high demand periods
	Installation may break local residential laws

Wind turbines work based on converting kinetic energy of the wind to mechanical energy. According to [36] the wind power output (P^{wind}) is given by the multiplication between the wind power plant installed capacity (I^{wind}) and the capacity factor of the wind (Cf^{wind}), which is dependent on the area swept by the turbine blades and related to the average wind speed per period.

$$P_t^{wind} = I^{wind} Cf^{wind} \tag{2.1}$$

Authors in [37] present a VAWT design that fits residential areas with a dense population. The study results show that wind energy technologies can be a key renewable energy source in urban areas. The method to calculate the power of a wind turbine is the same for VAWT and HAWT technologies and can be expressed by:

$$P = \frac{1}{2}\rho A C_p v^3 \tag{2.2}$$

Where ρ is the air density, A is the area swept by the turbine blades, C_p is the power coefficient of the blade and v is the wind speed.

Nowadays, the scientific community have studied the possibility of a new bladeless wind technology with the capability to produce a big amount of power in a short amount of time. Authors in [38] [39], show great results in this type of technology. This type of bladeless turbine has simple designs with a lower production cost, lessens the danger of people and wildlife getting hurt, and provides less auditory and visual noise. Despite the power generated capability being smaller than the main wind turbine type, these studies show a promising future for the evolution of this technology.

In short, even with the recent scientific evolution of residential wind generation technologies, its disadvantages are still something to take into account. Also, the unavailability during high energy demand periods and its unpredictability leads to uncontrollable power output. Due to this, our use case will not integrate residential wind energy generation.

2.1.2.2 Residential Photovoltaic Generation

Photovoltaic solar panels (PV) gained popularity, not only due to government incentives but also because of technological improvement and economic competitiveness. As seen in [40] at the end of 2016 the total installed PV power in the EU was, approximately, 105GW and 65% of it were generated on rooftops of residential and commercial buildings. It's expected that these numbers rise between 100 and 150GW by 2030 due to current policies imposed in the EU.

A PV is made up of photovoltaic cells, which are used in different types of applications, being portable calculators one of the most known and common ones, but it's also used to power space projects, military needs, and remote locations.

As stated in reference [36] the formula for PV power output is similar to the one used for wind power. So, the PV power output (P_t^{pv}) is equal to the product between the PV power plant installed capacity (I^{pv}) and the PV capacity factor (CF^{pv}). This is dependent on the average global horizontal irradiance per period and related to the PV panels area.

$$P_t^{pv} = I^{pv} C f_t^{pv} \tag{2.3}$$

PV panels are a promising RES due to their different technologies and dimensions. These panels can be installed in big solar farms, or on the roof and walls of residential buildings. Also, the improvement in solar tracking technologies gives the capacity of installing it in structures that allow it to follow the movement of the sun improving its efficiency and power generation throughout the day, this is because solar panels reach peak performances when the sunlight is perpendicular to the surface of the panel, [41].

In reference [41] the authors show 2 different orientation systems. The first is a single-axis orientation, this system is placed on a north to south axis and will orient the sun from east to west, it has a simple structure with a 34% performance coefficient and lower manufacturing, installation, and maintenance costs. The second is a dual-axis orientation system which orients the sun from east to west and north to south, this is a more complex system but with a higher performance coefficient, 37%.

Nowadays, unique types of PV materials like monocrystalline, polycrystalline, and thin films are available. There are also different PV systems like hybrid thermal photovoltaic solar collectors, these systems have the capability of converting solar radiation into thermal and electrical energy. Other types utilise mirrors to focus the sunlight on solar cells to result in achieving peak production capability. Combining these systems with solar tracking technologies like the one presented in [42] increases PV systems' efficiency and can result in a 35%, or greater, energy gain.

Also, authors in [43], conclude that using mirroring technologies can improve the PV panel performance, especially from 7:00 to 10:00 AM and 4:00 to 5:00 PM. When combining this with solar tracking an is shown an even greater improvement in the energy production of the system.

Despite PV technologies having great advantages, there are also some weaknesses, being their efficiency the most notable one, PV panels only convert 30 to 40% of solar energy into electricity.

Another big default of these systems is the difficulty of integrating them in the grid, due to their voltage fluctuation and profile. Nowadays there's a need to improve grid infrastructures in an effort to support high penetration of distributed generations. So, despite rooftop PVs becoming popular due to the growth in environmental awareness and the increase of electricity prices, there are some drawbacks to these technologies, in Table 2.2 is shown some advantages and disadvantages of PV generation.

On the economic side, according to [44], for a block of flats with 24 apartments and two entrances, it was installed a 6.7kWp photovoltaic system with power losses lower than 0.79€ annually. With these values, it was concluded that 100% of the initial investment was recovered in 8 years and 20 years after the installation the return on investment was 240%.

Table 2.2: Advantages and disadvantages of PV generation, adapted from [35]

Advantages	Disadvantages
Flexible size and installation site	High investment costs
Low design and installation time	Large area required
Low maintenance	Low efficiency
No emissions	Low-capacity factor
No audible or visual noise	Low availability during peak hours
Simple operation	
Availability during peak demand hours	

In conclusion, solar energy production is a key technology for a sustainable future and is becoming more accessible for common family households due to government incentives and cost reductions, as a consequence of technological development. Although, when integrated as distributed generation leads to uncontrollable power output due to voltage fluctuations, this can be controlled with the integration of energy storage systems, which have the capability to smooth out fluctuations and improve the stability of the power system.

2.2 Smart Grid

The electric grid used today was created many years ago to support energy production in conventional power stations, which normally utilise non-renewable energies, and then to transport that energy to industries and residencies. This is known as a one-way interaction between suppliers and consumers. The grid was not projected to support the demand for energy of the present day, nor the technological advancements, like intermittent renewable energies, Electric Vehicles (EVs) charging, and so on.

Modern society requires a power system that is highly reliable, scalable, secure, interoperable, and manageable while being cost-effective [45]. According to the vision of Horizon Europe 2021–2027 [46], the next-generation electric power system will be a "smart grid" [47].

As seen in [48], a Smart Grid (SG) system is unavoidable since it has the ability to protect against cyber security, facilitating the enlargement of the grid system for the smooth integration of renewable energies like wind, EVs, and battery systems using power electronics, providing smart metering, allowing the energy observation and control, mitigating the fluctuations of the voltage, the frequency and the current, creating a good harmonisation between producers, prosumers, network operators and policymakers. In Figure 2.3 it's presented the requirements of a smart grid [48].

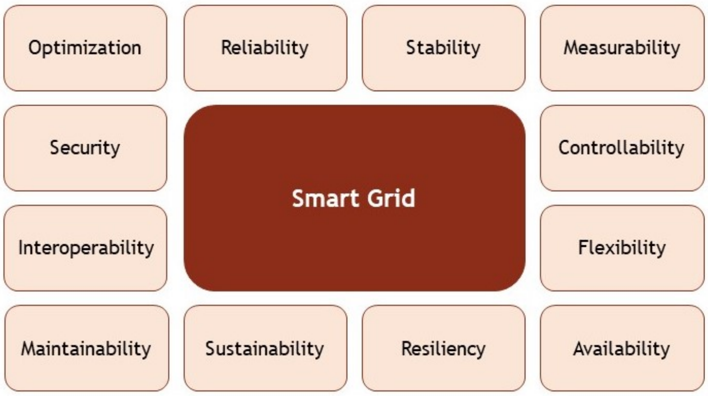


Figure 2.3: Requirements of a SG, adapted from [48]

A SG uses communication and information technologies along with smart meters and detectors to increase the flexibility and efficiency of the power grid, minimising the total cost of electricity consumption and reducing power loss [49]. As well as a two-way connection, allowing the exchange of electricity and information between producers and end-users. Despite the evolution to date, SG continues to evolve as shown in Figure 2.4.

The two-way communication used in a SG is an important characteristic, thus companies and networks operators must try to maintain the demand and the generation balanced within the network. With the increase of RES usage, it's becoming harder to keep this balance and it's necessary to use demand response programs, which can only be done by taking advantage of the two-way communication capabilities of the grid [50]. According to reference [51], there are some distinct characteristics when comparing a conventional grid to a SG, these can be seen in Table 2.3.

Table 2.3: Characteristics of a conventional and smart grid [51]

Conventional Grid	Smart Grid
Centralised distribution	Bi-directional communication
Electromechanical	Digital
Manual monitoring and restoring	Distributed generation
One way communication	High-quality power
	Self-monitoring and healing

The fast development of Artificial Intelligence (AI) technologies, Internet of Things (IoT), edge computing, sensor technology, and 5G communication technology can be implemented in a SG. Thus, improving sensor reliability, SG communication, and stability enhancing SG qualities.

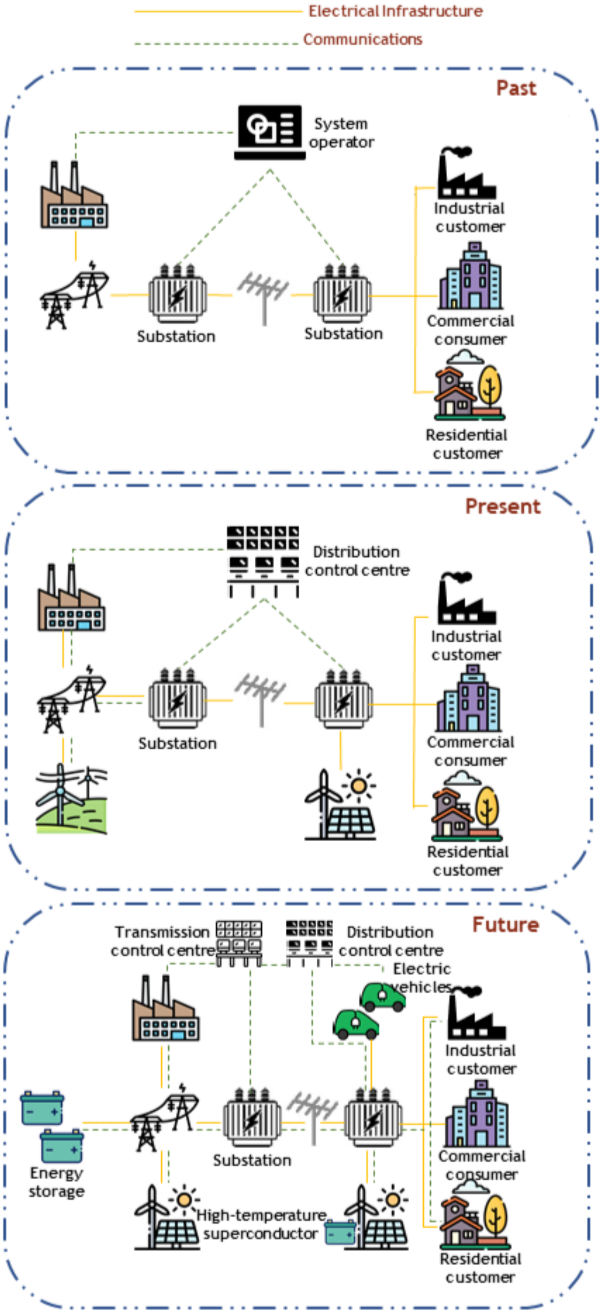


Figure 2.4: Evolution of a SG, adapted from [52]

Studies show that there are 3 main reasons to convert a conventional grid to a SG [51], these reasons are the following:

- The increased energy demand, due to new technologies

- Decreasing illegal usages seen in transmission and distribution lines
- The growth in production and transmission capacity in the existing plants, enabling the integration of RES to the system

To summarise, a SG brings important advantages to an energy system when compared to a conventional grid, and in some studies it is seen as the future due to the increase in power needs and its ability to support this demand. This type of grid is superior, when compared to a conventional grid, in power quality, communication, supporting distributed generation systems, operation, and maintenance.

2.3 Energy Storage Systems

Nowadays, energy storage systems are essential to accommodate the intermittency of RES, as well as improve the economy and security of the power system. These systems have the capability to store the excess energy that is produced, for example when the demand is low, to later discharge it in peak energy demand hours or when there is a shortage in renewable energy production [53].

The main ESS used today are batteries and pumped-storage hydropower, however as energy storage costs decrease and markets evolve, applications become more economic, more efficient and their utilisation expand alongside the number of technologies as seen in [54]. Thus, the ideal technology depends on each application as seen in Figure 2.5.

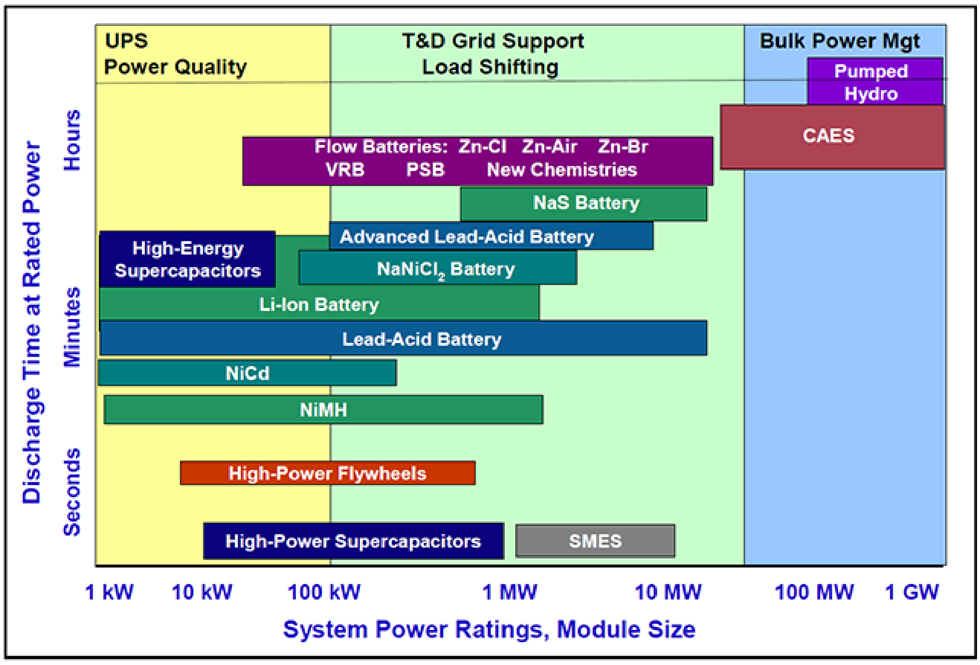


Figure 2.5: Energy storage power range, [55]

According to [56], investment in battery storage increased by almost 40% in 2020. Spending on grid-scale grew 60%, driven by the push for renewables investment. In 2020 Lithium-Ion (Li-ion) battery storage represented 93% of all the ESS utilised, due to the boost provided by the “spill over” of EV technology to grid-scale batteries.

As stated in [57], the ESS operation is categorised in two distinct periods: the charging period, which uses electrical energy during off-peak hours to charge the battery at lower prices; and the discharging period, the energy stored is discharged during times of peak energy demand when the energy prices are higher.

Authors in [58] and [59], defend peak shaving and peak shifting applications as optimal ESS control strategies. The peak shaving application consists in reducing peak loads by storing energy when energy prices are low and discharging when peak demands occur. Another method is the peak load shifting, the ESS acts as a load to absorb the excess power in the system when the load is low, and at peak load works as a generator to make up for insufficient power in the electric system. This type of application optimises energy costs while satisfying battery physical constraints.

Regarding ESS it’s important to consider which technology is optimal to maximise lifetime and minimise costs, environmental impact, response time and size. According to [60], Lithium-Ion (Li-Ion), Nickel-Metal Hydride (Ni-MH), Sodium Sulfide (Na-S), Nickel-Cadmium (Ni-Cd) and Lead-Acid (Pb-Ac) are the main battery types used for renewable energy and energy management applications. Table 2.4 displays some characteristics of the different battery types mentioned before.

After analysing the advantages and disadvantages of the different types of batteries, Li-Ion technology is the most used to date due to its high voltage per cell, lifetime, high power density and power range, and high efficiency. On contrary, this type of battery has high costs and bad overload tolerance.

As was stated before it’s important to consider which technology is optimal to maximise its performance, besides this, battery management is needed due to these technologies being deeply affected by environmental conditions, whereby results in a significant reduction of its lifetime and safety problems [61]. Thus, specific requirements should be studied namely charging and discharging control, thermal management, battery protection and state of charge control [62].

The State of Charge (SOC) of a cell is defined as the capacity currently available as a function of the rated capacity, [57]. This variable is critical to balance on an ESS. The authors in [63] show that a ESS can be divided into three types, as shown in Figure 2.6.

Table 2.4: Characterisation of the different battery types [24], [60], [64], [65], [66]

Battery type	Characteristics										
	Cell Voltage (V/cell)	Energy Density (Wh/kg)	Power Density (W/kg)	Power Range (MW)	Discharge Time (ms-h)	Response Time (ms-h)	Overload Tolerance	Lifetime (yr)	Efficiency (%)	Cost	Environmental Impact
Pb-Ac	2,0 - 2,35	30 - 50	200 - 400	<20	s - 5h	ms	-	5 - 15	50 - 92	Low	High
Ni-Cd	1,2	15 - 55	150 - 350	<40	1 - 8h	ms	Very Good	10 - 20	70 - 90	High	High
Na-S	2,1	150 - 240	150 - 230	10 - 34	6 - 7,2h	ms	-	10 - 15	70 - 90	High	High
Ni-MH	1,2	60 - 80	150 - 460	<0,03	hs	ms	Good	5 - 10	60 - 70	High	High
Li-Ion	3,6 - 4,2	120 - 230	150 - 2k	0,05 - 100	min - 1h	ms	Very Bad	20 - 25	90 - 95	High	Medium/Low

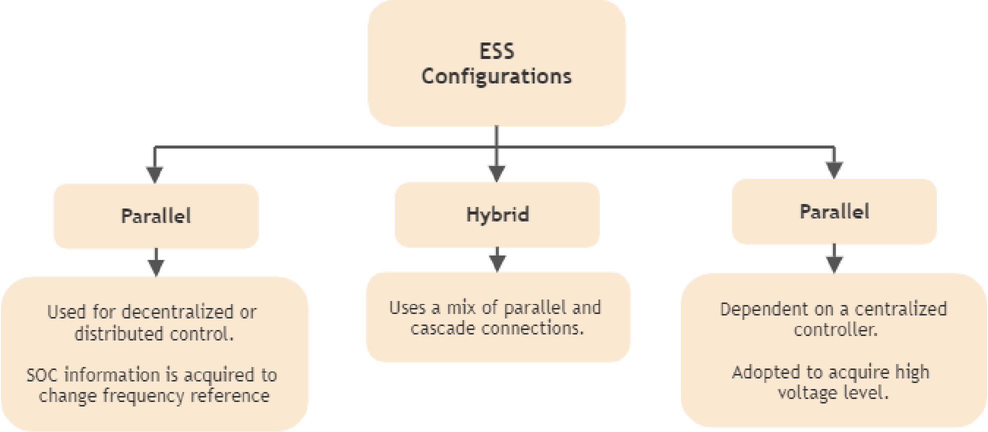


Figure 2.6: ESS configuration types

The battery's SOC value is based on load changes considering the current flow into or out of the battery cell, this can be estimated using the Coulomb counting method as stated in [63] and presented in the following equations:

$$SOC_t = SOC_0 - \frac{1}{C_a}\int_0^t \eta I_{L,t}\,dt \tag{2.4}$$

SOC_t represents the present SOC, SOC_0 is the initial value of SOC just before $I_{L,t}$ flows into or out the battery, $I_{L,t}$ is the instantaneous load current, which is assumed positive for discharge and negative for charge, η is the Coulomb efficiency coefficient this value is the function of the current and the temperature and C_a is the maximum battery capacity to store current, this value can differ from the rated capacity due to battery ageing effects [67].

On this basis, ESS can help provide a more stable and safe system, due to their potential of smoothing out the fluctuating output of RES. While also being a key factor in reducing energy costs when buying from the grid. Also, the authors in [68] prove that residential ESS inclusion with RES and time-variant pricing schemes reduce electricity bills. However, ESS need complex management systems to optimise their utilisation and its lifetime. Besides, different batteries have different limitations due to their chemistry and structure conditions and all these limitations must be considered in an energy storage management system.

In conclusion, with the fast growth of RES and the worldwide energy demand increase, ESS are a must add to our systems to compensate for the unpredictability of renewables and to our houses, to reduce electricity costs and to manage the substantial energy demand in modern homes.

2.4 Sustainability

The concept of sustainability is a relatively new idea, but its roots come from social justice, conservationism, internationalism, and other rich and historical movements, [69]. This term is used to describe the means of meeting our needs without compromising the ability of future generations to meet their own.

In recent literature, sustainability is often interlinked with sustainable development, and when linked to energy use is frequently confused with clean energy. Sustainable indexes are a must to assure a future for our society, but these indexes are often very general, especially when talking about energy sustainability, and normally exploit only numerical measurable values, like the ones seen in [70].

Authors in [71], characterise energy sustainability in five different dimensions: Environmental; Economic; Social-Cultural; Political-Territorial; and Technological. The characterisation of this dimensions is the following:

- Environmental dimension: this dimension evaluates the physical and biotic impacts, such as GHG emissions, chemical residues, water consumption, pollution, deforestation, land area occupation, and biodiversity loss.

- Economic dimension: in the economic dimension is evaluated the efficiency of the project (cost/benefit ratio), financial return, amount of capital invested, financial contribution to the community where the project is integrated, RES investment, and other economic factors.

- Social-Cultural dimension: in this dimension is assessed the employment income of the project, inequalities mitigation, population purchasing power levels, society participation in decision making, social and cultural innovation and, lastly, environmental education.

- Political-Territorial dimension: this dimension evaluates public power decentralisation, the society members have clear access to the project information, encouragements for renewable energy usage, the project should not be political but territorial, and the goal should be to improve the quality of the territory where it is integrated.

- Technological dimension: this last dimension evaluates the quality and reliability of the project technology, this technology must not increase accidents, must be developed RES technology, construction and implementation time must be controlled, and there must be technological skills with margin to improve.

With this information in mind, it is important that projects like power plants, smart grids, smart homes, and renewable energy sources installations are evaluated following the five sustainability dimensions. In a smart home, it is especially important to not only evaluate the environmental side, but also the economic and technological dimensions. The owner must take advantage of the investments he makes and see a cost reduction in energy costs.

2.5 Home Automation Systems

Smart Homes (SH) have become a key component of the smart grid in a large number of countries, due to their environmental and socioeconomic benefits. SH technologies have improved a lot in recent years and shown great results. The scientific community is studying ways to integrate smart technology into home automation, along the line of making SH more efficient. The principal motive to use a home automation system is to fully automate the control of various devices and appliances, in order to make the day-to-day life of the user easier, more sustainable, more economic, and more secure [72].

Home automation systems are essential for a SG, due to the capability of scheduling home appliances following DR programs enacted by energy providers. Consequently, optimising energy consumption and its predictability, reducing costs and magnifying the reliability and effectiveness of the electrical grid, [73].

The integration of home automation systems is done with sensors, to measure relevant data, controllers, actuators, and communication systems. Nowadays, communication platforms are very advanced and already integrated into a variety of systems. Communication technologies are divided into two different groups the first being wired media like Ethernet and Power Line Communication, and the second is wireless media. The wireless media group of technologies revolutionised automation systems, technologies such as Wi-Fi, wireless cellular networks low-rate wireless personal area networks have lower costs and easier deployment than wired media, [73]. Various communication platforms can be seen in use today, an example is the popular open-source Internet of Things (IoT) concept, thus uses a combination of smart software applications along with electronic devices and, with this, builds an effective data exchange network, [74].

Beyond all these home automation system advantages, there's also a very complex coding system and circuit integration, high initial investment in equipment, in-home implementation issues, and inflexible interfaces. Furthermore, threats and attacks on network communications systems result in difficult challenges regarding security and privacy for intellectual homes, [75].

In short, due to the dramatic jump in home automation systems and SH technologies seen in the past years, home automation systems are being used to create houses with efficient costs and with load shifting capabilities. This is a positive sign for the grid, due to the capability to reduce energy consumption and lessen the load [76].

Smart metering is a key component of SH due to its capabilities to record the consumption of electrical appliances. As stated in [77], smart metering systems allow an electric consumption reading and recording in time intervals, monitoring, and billing. It allows two-way communication between the meter and the central system, making it possible to gather interval data, time-based demand data, outage management, service interruption, service restoration, quality of service monitoring, distribution network analysis, distribution planning, peak demand, demand reduction, customer billing, and work management.

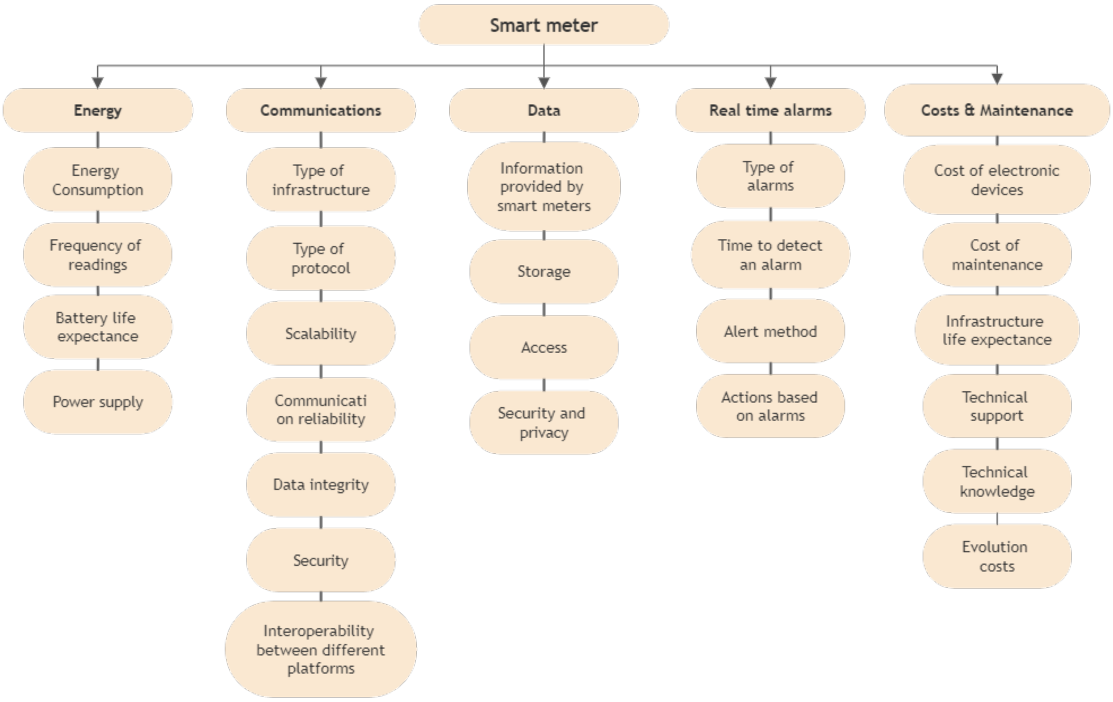


Figure 2.7: Smart meter features, adapted from [77]

With this in mind, smart meters have some advantages, such as having accurate information about power consumption and energy costs, improving client safety and the capacity to gather relevant data which can be used to develop the efficiency of the grid. In Figure 2.7 can be seen some smart meter features like the energy side, communications, data, real-time alarms, and costs.

To summarise, smart metering technology is an important tool in home energy management systems due to its capability to provide real-time load information, guarantee consumer comfort and security, and improve equipment's lifespan. Beyond this, it is also capable to provide a great improvement in energy savings.

2.6 Demand Response

The growth of energy demands has increased the pressure on electricity infrastructures. The result of this is an increasing gap between demand and supply, which creates fluctuations and causes stress in generators, leading to what's called a shedding load, [78]. These problems can be mitigated by utilising Demand Response (DR) programs to captivate consumers to modify their electricity usage in response to the network operating conditions, [50].

Authors in [78] state that DR "is shifting or curtailing of load from peak period to off-peak period which would help to balance the gap between the utility and load" and that by implementing DR programs consumers can shift their loads themselves or at peak demands. This load shifting process depends on various variables, such as Priority of Load, Comfort level, Time of Use tariff, Flexibility and DR events. In an electricity market, a DR program helps producers minimise risks by sending incentives to end-users to shift their demands and real-time prices will make end-users behave economically, [79].

DR programs literature shows two categories: Price-Based Demand Response (PBDR) and Incentive-Based Demand Response (IBDR). As can be seen in Figure 2.8, PBDR programs are all voluntary, however, IBDR programs include voluntary, mandatory and market clearing programs.

PBDR programs depend on costumer's choice to change their consumption as a response to the variation of the electricity market price in a day. On another hand, IBDR programs offer incentives to customers in times of high electricity prices, motivating the customer to reduce their consumption, [80].

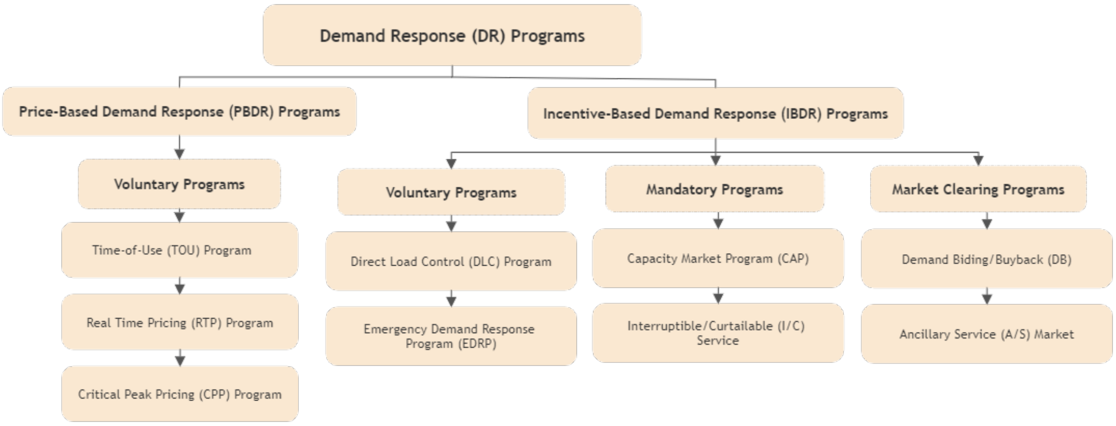


Figure 2.8: DR programs, adapted from [81]

Authors in [81] and [82] state that PBDR includes three different voluntary programs, such as:

- Time-of-Use (TOU) Program: in this method, a tariff is settled for each time period. This is very consistent but can not reflect the cost of electricity in the long term.
- Real-Time Pricing (RTP) Program: in this program the price rate changes hourly. Therefore, can cover all of the network changes costs, but it is very complex and less socially acceptable.
- Critical Peak Pricing (CPP) Program: is set based on TOU, RTP and fixed prices fusion. Uses real-time pricing when the peak load is high. it is used on the power system reliability is compromised.

There's also a variety of IBDR pricing methods, being the IBDR voluntary programs the following [83]:

- Direct Load Control (DLC) Program: This pricing method is a direct charge control program where the customer's electrical equipment is disconnected by the system operator, with short notice. As a consequence of this, the customer receives monetary incentives.
- Emergency Demand Response Program (EDRP): This program provides its end-users with incentive payments for reducing their loads during reliability triggered events.

In short, DR programs are an economic help for customers on account of the incentives received and lower electricity costs that bring a significant amount of savings. Also, a successful DR pricing method significantly improves system reliability, reduce price volatility and, as said before, reduce electricity prices, [80].

2.7 Related Work

In this final section, it is presented some previous work already investigated related to the theme of this dissertation. In the last few years this theme has been on the priority list of various scholars due to its innovative character and the need to implement it in the current days. On account of an increase in home appliances' power consumption and the different power variations during the day, new control strategies and Home Energy Management Systems (HEMS) were intensively developed and optimised in the last few years.

For example, in reference [84] it is proposed a HEMS to minimise the electricity costs of a home, to achieve this goal was used DR programs as well as Mixed-Integer Linear Programming (MILP) model. According to the authors, an end-user's cost might decrease up to 40% when employing these methods, and when ensuring battery and domestic appliances constraints.

In the same line of thought, authors in [85] utilise DR programs and a MILP framework-based modelling of a HEMS. However, this reference also considers EVs as a storage unit opportunity via Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) options instead of peak power procurement from the grid. Beyond this, a small-scale RES, an ESS and a two-way energy exchange allowed through net metering it is combined to reduce electricity costs and assure consumer comfort.

In [86], it is combined a smart thermostat with a MILP based HEMS which performs in day-ahead load scheduling and provides optimal DR and photovoltaic consumption, aiming to minimise the costs. The HEMS analysed in this study considers a bi-directional power flow between home, ESS, EV and grid. The results shown were very promising, achieving a daily cost reduction of 53.2% under some DR programs.

A MILP multi-objective problem can be seen in [87], where the main goal is to minimise electricity cost and a discomfort index, which incorporates the daily preferences of the end-user. This discomfort index has the capability to determine the optimal time slots for home appliances operations while keeping costs at a minimum. The proposed model in this paper was tested with various price-based DR programs, and scenarios like the presence of ESS were also investigated to study their impact on the optimal operation of the system. The simulation results show significant reductions in electricity costs.

In reference [88] it is applied a similar process as the previous ones, but this time as a pool trading model in a local energy community. A market-clearing mechanism is proposed as a tool to encourage active prosumers to trade their surplus energy within a rule-based pool market. Beyond this, a price-based DR program is considered to increase consumers' will to modify their consumption habits. The HEMS is based in a MILP in which the goal is to minimise the overall bills of all participants while being able to support their demands. This paper also shows two different scenarios, the first one being an independent simulation of the problem and the second an integrated operation mode to take into account the impacts of coordination amongst different end-users. The results show that in an independent operation the electricity costs reduced 16.63% and in an integrated case the reduction was 21.36%.

Often, a MILP HEMS is implemented due to its efficiency in terms of the objective function. On another hand, this technique requires high computational time and effort. According to [89], two different methodological approaches were studied, a MILP model and a metaheuristic (genetic algorithm). The aim was to minimise electricity costs whilst considering the dissatisfaction of the end-user while integrating local generation and storage, DR programs, shiftable, interruptible, and thermostatically controllable loads. The conclusion of this study shows that the MILP model obtained optimal results with a fifteen-minute computational budget, and the genetic algorithm obtained a result close to optimal with one minute of computation. This shows that, in this case, a genetic algorithm was revealed to be a better approach for a HEMS implementation.

Authors in [90] studied a HEMS with a different type of model used, this time it was proposed a stochastic model which considers EV availability and small-scale renewable energy generation. These models aim to optimise consumer costs in different DR programs while guaranteeing a high level of consumer comfort and satisfaction in operating electrical appliances. The model in this study decreased the electric bill up to 42%, by using the stochastic model the costumers' cost was decreased by 32% when comparing the results obtained by using a deterministic model. The main differences between the stochastic model and the deterministic one can be seen in DR services.

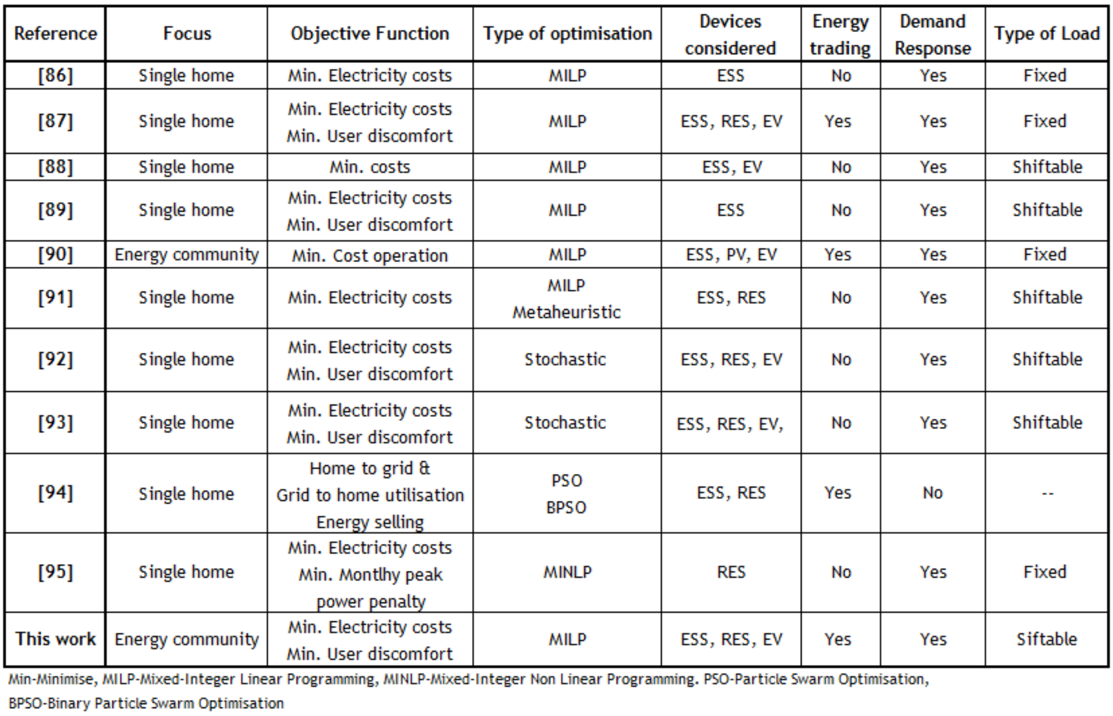
Similar to the study mentioned before, in [91], it was also proposed a stochastic model as a HEMS. In this case, the model simulates a SH and considers heating, ventilation, air conditioning, and a sanitarian water heater. The HEMS considers all the SH parameters together with costumer comfort and cost minimisation. it is also considered an EV, a battery-based ESS, micro-production generation, and DR tariffs chosen by the consumer, aiming to maximise benefits, and shifting the proposed loads. In short, the proposed model was able to manage the load system, within the constraints of the SH, while maintaining a high costumer comfort level.

Stochastic models are go-to models in this study, due to their minimisation of error between forecasted and real data. This provides HEMS with reliable and closer to real-life data. The previous studies show that this type of modulation can optimise the solution of the problems proposed.

According to [92], the main focus of the study is not to minimise energy cost but to study the utilisation of the main grid electricity, as well as, selling electricity. In this case, it was proposed a HEMS architecture with RES and ESS where the electricity of the main grid is utilised and sold, considering RES production. To optimise the formulas was used a Particle Swarm Optimisation (PSO) and a Binary Particle Swarm Optimisation (BPSO). The results show that this model is capable to decrease home energy cost by 19.7%.

In [93], was used a different model when compared to all of the previous studies. This time it is used a mixed-integer nonlinear high dimensional combinatorial problem. it is implemented an HEMS and DR programs, in order to minimise energy costs while taking into account the monthly basis peak power consumption penalty.

Table 2.5: Summary table of related work



Reference	Focus	Objective Function	Type of optimisation	Devices considered	Energy trading	Demand Response	Type of Load
[86]	Single home	Min. Electricity costs	MILP	ESS	No	Yes	Fixed
[87]	Single home	Min. Electricity costs Min. User discomfort	MILP	ESS, RES, EV	Yes	Yes	Fixed
[88]	Single home	Min. costs	MILP	ESS, EV	No	Yes	Shiftable
[89]	Single home	Min. Electricity costs Min. User discomfort	MILP	ESS	No	Yes	Shiftable
[90]	Energy community	Min. Cost operation	MILP	ESS, PV, EV	Yes	Yes	Fixed
[91]	Single home	Min. Electricity costs	MILP Metaheuristic	ESS, RES	No	Yes	Shiftable
[92]	Single home	Min. Electricity costs Min. User discomfort	Stochastic	ESS, RES, EV	No	Yes	Shiftable
[93]	Single home	Min. Electricity costs Min. User discomfort	Stochastic	ESS, RES, EV,	No	Yes	Shiftable
[94]	Single home	Home to grid & Grid to home utilisation Energy selling	PSO BPSO	ESS, RES	Yes	No	--
[95]	Single home	Min. Electricity costs Min. Montlhy peak power penalty	MINLP	RES	No	Yes	Fixed
This work	Energy community	Min. Electricity costs Min. User discomfort	MILP	ESS, RES, EV	Yes	Yes	Siftable

Min-Minimise, MILP-Mixed-Integer Linear Programming, MINLP-Mixed-Integer Non Linear Programming. PSO-Particle Swarm Optimisation, BPSO-Binary Particle Swarm Optimisation

Table 2.5 shows a simple summary related to the works referenced before, and the work that it is going to be developed in this dissertation. In short, the HEMS applied in the studies mentioned before achieved the proposed goals, being the main one electricity cost reduction. This concludes that this topic can be implemented with success and be an improvement in our houses and communities, especially when combining a HEMS, a RES micro-generation, a ESS and EV system and DR programs.

Chapter 3

Mathematical Formulation

In the following chapter it is demonstrated and described the mathematical formulation of a self-scheduling home energy management system taking into consideration the self-generation feature of renewable energy production. The main objective of this problem is to minimise daily electricity costs of the prosumers.

The mathematical formulation presented is applied in a mixed-integer linear programming model. This type of programming model was chosen due to its perfect characteristics for process scheduling and minimisation capabilities. MILP programming has rigorous, flexible, and extensive capability, which led to the increasing use of this method within the scientific community.

MILP solver is based on linear programming method, it applies a divide-and-conquer approach attempting to solve linear programming cases by solving a group of subproblems. These algorithms apply pre-solving and primal heuristics to improve the efficiency of the overall algorithm. Also, a variety of control options and solution strategies are possible in this type of model and there is various levels that can be enabled according to the type of project.

3.1 Objective Function

The objective function of the model developed is to minimise the daily electricity bills of the prosumers while considering a discomfort penalty in case the prosumer's load is shifted to unwanted time slots. Should be enhanced that the consumer has to change his energy-consuming habits to be capable of significantly decreasing the cost, [94].

Figure 3.1 shows the conceptual model of home appliances in what was considered a standard house within a local energy community. All the appliances that can be seen in the figure, as well as, the micro-generation systems, ESS and EV's charging station can be managed by the proposed HEMS.

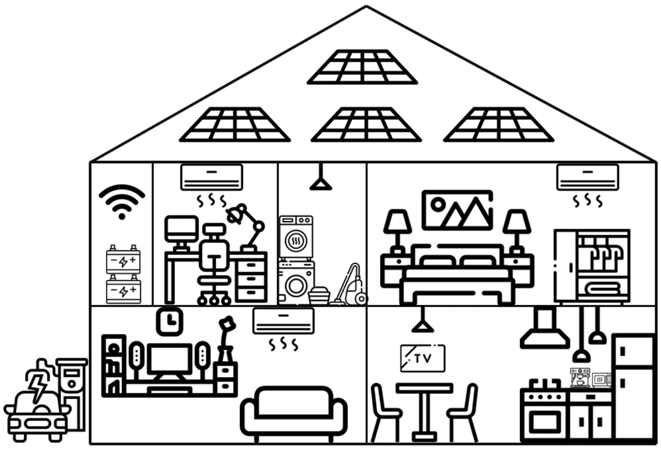


Figure 3.1: Standardised house with self-generation, adapted from [88]

As presented in Equation 3.1 the objective function of this model presents four different terms. Firstly, it is stated the expected cost of power transactions between the distribution grid and the HEMS while considering a TOU pricing mechanism. Secondly, it is calculated the start-up and shut-down costs of each appliance. The third term shows the discomfort costs of load shifting, this is taken into account when a load is shifted to unwanted periods. The fourth and last term calculates the cost of applying an IBR tariff to the load demand over.

In this model, the net power purchased from the grid is estimated based on the TOU. The energy purchased from the grid can be estimated if the hours at which the energy is going to be imported from the grid and the number of hours are known. Also, the energy sold to the grid can be appraised, [95].

As mentioned before, the second part of the objective function is related to the shut-down and start-up costs, this means that when a device is turned on it should stay on for a certain amount of time. In theory, a device can be turned on and off multiple times a day, but practically speaking this can not happen. An appliance can turn on and off during the scheduled periods and extra turning off can cause amortisation costs. Due to this, start-up, C_i^{ST}, and shut-down, C_i^{SD}, costs were considered high values to prevent unnecessary start-up and shut-down events.

In the third term of the function, σ represents the discomfort penalty factor, this penalty is applied when the load is shifted to unwanted time slots. The value of σ is considered a high value to prevent unwanted load shifting.

Lastly, the fourth term relates to the estimated value of extra costs due to purchasing energy from the grid. It is important to mention that energy purchase costs increase exponentially with the surge in consumption. Thus, to compensate for this, self-scheduling mechanisms seek to find the best solutions to generate power and store it so that this energy can be sold to the grid. Also, the investment in RES and ESS justifies the utilisation of this method, which reduces grid dependency and helps manage costs.

$$\begin{aligned} Minimise\ Z = \sum_{\omega\in\Omega}\rho_{\omega}\left(\sum_{t=1}^{NT}\left[\pi_t^{G2H}P_{\omega,t}^{G2H}\Delta t-\pi_t^{H2G}P_{\omega,t}^{H2G}\Delta t\right]\right)+ \\ \sum_{\omega\in\Omega}\rho_{\omega}\left(\sum_{i=1}^{NA}\sum_{t=1}^{NT}\left[STUP_{\omega,i,t}C_i^{ST}+\mathrm{SHDN}_{\omega,i,t}C_i^{SD}\right]\right)-\sum_{i=1}^{NA}\left[C_i^{ST}+C_i^{SD}\right]+ \\ \sum_{\omega\in\Omega}\rho_{\omega}\left(\sum_{i=1}^{NA}\sigma\left[DI_{\omega,i}^{+}+DI_{\omega,i}^{-}\right]\right)+\sum_{\omega\in\Omega}\rho_{\omega}\left(\sum_{k=1}^{NK}IBR_k^{\text{Tariff}}\ \text{Energy}\ _{\omega,k}^{\text{Tier}}\right) \end{aligned} \tag{3.1}$$

The objective function presented is used in a Mixed-Integer Linear Programming (MILP) algorithm which works as a HEMS to minimise client costs. The following sections are described the three different constraints for this HEMS.

3.2 Home Energy Management System Scheduling Constraints

In this section, it is specified the HEMS scheduling constraints, these limitations relate to technical and economic restrictions imposed by the algorithm. In Equation 3.2 is shown that the total of shiftable load at each time slot, $D_{\omega,t}^{Shift}$, is related to the nominal power of the asset, P_i, and its operation is determined by the binary variable $S_{\omega,i,t}$.

$$D_{\omega,t}^{Shift}=\sum_{i=1}^{NA}S_{\omega,t,t}P_i \tag{3.2}$$

Normally, the time authorised to use the different devices is greater than the time required to use them, this comes in hand when operating with load shifting capabilities. With this in mind, $S_{\omega,i,t}$ is equal to "0" before and after the time intervals where the use of the assets is authorised by the prosumer and "1" within these time slots. The limitations of the binary variable are stated in Equations 3.3 and 3.4.

$$S_{\omega,i,t}\leq\begin{cases}0 & t<LB_{i,s}\\ 1 & LB_{i,s}\leq t\leq UB_{i,s}\\ 0 & t>UB_{i,s}\end{cases}\qquad S_{\omega,i,t}\in\{0,1\} \tag{3.3}$$

$$\sum_{t=1}^{NT}S_{\omega,i,t}=T_i\quad\forall i=1,2,\ldots,NA \tag{3.4}$$

On the right side of Equation 3.5 is represented the period in which the service of the device is authorised by the owner. Alike to this, similar constraints can be used to calculate the costs of the base case, as shown in Equation 3.6. The main difference between the two constraints talked about before is the fact that the binary variable is not used in the authorised time, instead, it is equal to "1" over the operating time of the appliance and "0" the rest of the time.

$$B_{\omega,i,t} = \begin{cases} 0 & t < LB_{i,b} \\ 1 & LB_{i,b} \leq t \leq UB_{i,b} \\ 0 & t > UB_{i,b} \end{cases} \quad B_{\omega,i,t} \in \{0,1\} \tag{3.5}$$

$$\sum_{t=1}^{NT} B_{\omega,i,t} = T_i \quad \forall i = 1,2,\ldots,NA \tag{3.6}$$

As mentioned before, a penalty is applied to prevent redundant start-up and shut-down of the assets. This is, only one start-up and one shut-down are permitted and any more beyond this will be penalised. It is important to mention that in practice this schedule is not real for appliances like washing machines and spin dryers. With this, the start-up and shut-down variables are determined as shown in Equation 3.7.

$$STUP_{\omega,i,t} - SHDN_{\omega,i,t} = S_{\omega,i,t} - S_{\omega,i,t-1} \quad \forall t > 1 \tag{3.7}$$

The variables $STUP_{\omega,i,t}$ and $SHDN_{\omega,i,t}$ represent the start-up and shut-down of the different appliances. To calculate the costs of each asset it is necessary to multiply the costs, C_i^{ST} and C_i^{SD} by its corresponding variables.

In Equation 3.8, for a given controllable asset the discomfort index deals with the time intervals for shifted operations. So, for the baseline operation period, the discomfort index is equal to zero while for shifted operation one of the positive variables would be non-zero. It is important to note that DI_i^- and DI_i^+ are positive variables, this way there are no conflicts when the right-hand side of the equation is less than zero.

$$DI^-_{\omega,i} \geq \frac{1}{T_i}\left[\sum_{t=1}^{NT} t \times B_{\omega,i,t} - \sum_{t=1}^{NT} t \times S_{\omega,i,t}\right] \tag{3.8}$$

$$DI^+_{\omega,i} \geq \frac{1}{T_i}\left[\sum_{t=1}^{NT} t \times S_{\omega,i,t} - \sum_{t=1}^{NT} t \times B_{\omega,i,t}\right] \tag{3.9}$$

To summarise, the optimal scheduling of home appliances needs to be managed by the HEMS operator according to the TOU tariff and the prosumer needs. The operator is capable of modifying the way controllable loads are managed and costs are minimised accordingly to the costumer's preferences.

3.3 Energy Transition and Energy Storage System Constraints

The following section aims to explain energy transition limitations between the prosumer and the grid and ESS constraints. First, in Equation 3.10 is reflected the role of ESS and in-house micro-generation, the model shown balances the power for each time interval.

$$P_{\omega,t}^{G2H} + P_{\omega,t}^{PV} - P_{\omega,t}^{H2G} = D_{\omega,t}^{Fix} + D_{\omega,t}^{Shift} + \left[\sum_{j=1}^{NS} P_{\omega,j,t}^{Ch.} - \sum_{j=1}^{NS} P_{\omega,j,t}^{\text{Disch.}} \right] \tag{3.10}$$

On the left-hand side of the equation, is presented the power purchased from the grid and the power generated by the photovoltaic system to this, is subtracted the power sold by the prosumer to the grid. The right-hand side includes the power demanded by fixed and shiftable loads, the charging power of the ESS and with a negative sign the discharging power.

It should be noted that the power generated by the photovoltaic system, $P_{\omega,t}^{PV}$, and the load demand, $D_{\omega,t}^{Fix}$ and $D_{\omega,t}^{Shift}$, are predetermined values while the rest are variables of the stochastic self-scheduling problem.

In Equations 3.11-3.12 are utilised binary variables which serve as a representation of the charging and discharging status of the ESS, $I_{\omega,j,t}^{Ch.}$ and $I_{\omega,j,t}^{Disch.}$. Thus, to restrict the ESS to be either in charging or discharging mode at one specific time, this is mathematically formulated in Equation 3.11 , while Equations 3.12-3.16 are associated with the limitations of the ESS daily operations.

$$0 \leq I_{\omega,j,t}^{Ch.} + I_{\omega,j,t}^{\text{Disch.}} \leq 1 \tag{3.11}$$

Equation 3.12 restricts the power of charge in the ESS, this way, when the ESS is in charging mode, $I_{\omega,j,t}^{Ch.}$ value is "1" and the power of charge has to be less, or equal, to the maximum power of charging. In the same line of thought, Equation 3.13 assures that when the ESS is in discharging mode, $I_{\omega,j,t}^{Disch.}$ value is one, the power of discharge is less or equal to the maximum power of discharging.

$$P_{\omega,j,t}^{Ch.} \leq I_{\omega,j,t}^{Ch.} P_j^{Ch.,\max} \tag{3.12}$$

$$P_{\omega,j,t}^{\text{Disch.}} \leq I_{\omega,j,t}^{\text{Disch.}} P_j^{\text{Disch., max}} \tag{3.13}$$

According to a normalised operation of an ESS, the energy stored in it at a certain time is a function of the energy stored in the previous period plus the results of all of the charging and discharging that occurred. This constraint is shown in Equation 3.14, as well as the efficiency factor of charging and discharging the ESS.

$$E_{\omega,j,t} = E_{\omega,j,t-1} + \eta_j^{Ch.} P_{\omega,j,t}^{Ch.} \Delta t - \frac{1}{\eta_j^{\text{Disch.}}} P_{\omega,j,t}^{\text{Disch.}} \Delta t \tag{3.14}$$

The model presented considers that the initial value of energy stored in the ESS should be fixed at the end of the operation. This means the value of the energy stored in the first time interval has to be equal to the energy stored in the last as shown in Equation 3.15.

$$E_{\omega,j,1} = E_{\omega,j,T} \tag{3.15}$$

Equation 3.16 limits the amount of energy stored in the ESS, this implies that the system is constrained by a minimum and a maximum limit of energy stored and the value of $E_{\omega,j,t}$ can not surpass this limit.

$$E_j^{\min} \leq E_{\omega,j,t} \leq E_j^{\max} \tag{3.16}$$

Similar to what is seen in [92], the ESS's main role is to make use of the micro-generation system and the electricity of the main grid in the most efficient way possible. With this, it is possible to reduce electricity costs due to the capability of storing energy from the grid or RES when the prices are low and provide it to the home load at peak hours.

Next, Equations 3.17 and 3.18 refer to the energy purchased from the grid in each scenario. To calculate the cost of the energy purchased is used in a stepwise manner according to an IBR tariff, normally the electricity bill is calculated for one month, but it is possible to estimate a value for a day by adapting the tariff proportionally to the amount of energy over the day.

Equation 3.17 represents the total energy over the scheduled time. Each energy tier is equal to $Energy_{\omega,k}^{Tier}$ and the sum of each of them is equal to the total energy in the total time scheduled. The number of energy tiers acquired from the grid is mathematically formulated in Equation 3.18, it should be taken into account that these tiers do not need to be identical.

Bear in mind that the energy price is exponentially determined while the energy tiers are selected from the cheapest to the most expensive. $Energy_{\omega,k}^{Tier}$ should always be less than the maximum energy of each tier, $E_k^{Tier,max}$, this is modelled by the binary variable $I_{\omega,k}^{Tier}$.

$$\sum_{t=1}^{NT} P_{\omega,t}^{G2H} \Delta t = \sum_{k=1}^{NK} \text{Energy}_{\omega,k}^{\text{Tier}} \quad \forall \omega \in Q \tag{3.17}$$

$$\text{Energy}_{\omega,k}^{\text{Tier}} \leq E_k^{\text{Tier, max}} I_{\omega,k}^{Tier} \quad I_{\omega,k}^{Tier} \in \{0,1\} \tag{3.18}$$

In short, within the constraints mentioned it is possible to reduce the energy bill of the prosumer by decreasing the HEMS dependency on the electrical grid, shifting the load to off-peak hours and the adaptation of consumption patterns. Beyond this, the capability to sell the extra energy produced by the RES to the community grid creates some profit for the house owner reducing even more the electricity bill.

Chapter 4

Numerical Studies and Results

In this fourth chapter, it is presented the use case, which describes all the system data used to test the mathematical formulation demonstrated in the previous chapter. Beyond this, it is also presented a discussion regarding the numerical results obtained by the simulation of the operational model. The goal is to analyse the engineering and economic side of the model presented, this is, to implement state-of-the-art technology and minimise costs.

4.1 Use Case

The proposed model is evaluated in this chapter to show the effective behaviour of a HEMS in ten different scenarios and exhibit that load shifting capabilities and energy transactions between the grid and the houses can reduce the final energy bill of the end-users. This use case includes ten houses with different consumption patterns integrated into a local energy community where it is possible to inject power into the grid when there is a surplus of energy, this is represented in Figure 4.1.

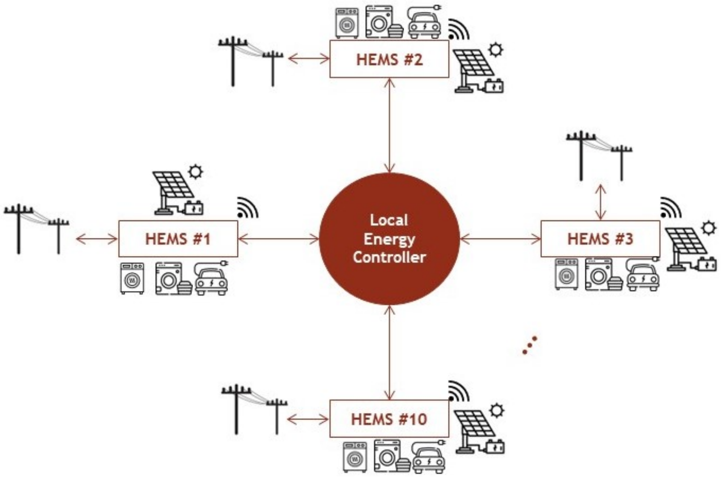


Figure 4.1: Local energy community and interconnections between the different agents, adapted form [88]

This model considers that the installed capacity of PV technology on the rooftop of each house is 3 kW. Since the community studied is a small one, the PV power generation was considered equal for all ten houses. Figure 4.2 shows the PV power generation for ten different scenarios over the day [92]. To clarify, this model studies forty-eight different time slots, this is, data is evaluated daily in thirty minutes periods. The ten different scenarios are generated using the historical data and day-ahead meteorological forecast, [94].

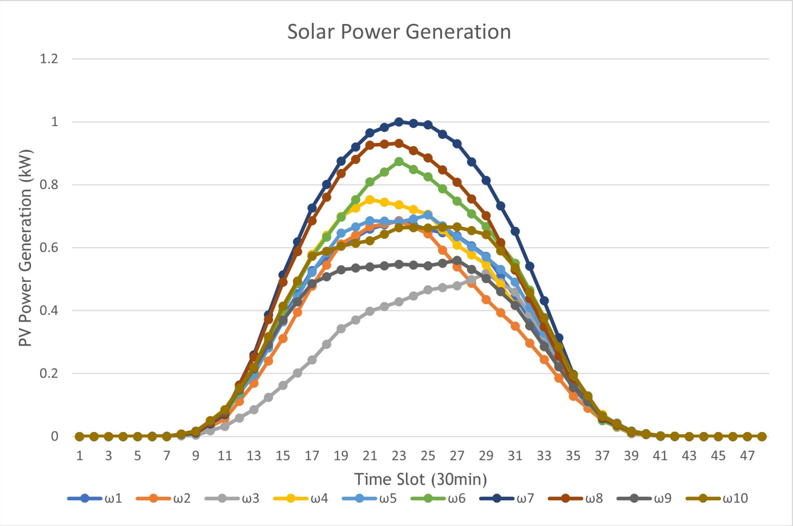


Figure 4.2: Solar power generation scenarios for the target day

It was also considered in this model that every house was equipped with an ESS with a maximum capacity of 4 kW and minimum energy of 200 Wh, as shown in Table 4.1. The ESS has a charging efficiency of 90% and an 85% discharging efficiency, it should be referenced that the maximum power of charging and discharging are both equal to 500 W. The main goal of the ESS is to store the energy bought in off-peak hours or the surplus of the energy produced to then use it in peak hours.

Table 4.1: ESS technical parameters

E_1 (KWh)	E_T (kWh)	$P^{Ch.,max}$ (kW)	$P^{Disch.,max}$ (kW)	$\eta^{Ch.}$ (%)	$\eta^{Disch.}$ (%)	E^{max} (kWh)	E^{min} (kWh)
0.2	0.2	0.5	0.5	0.9	0.85	4	0.2

Figure 4.3 illustrates the IBR tariff applied on the different energy consumption tiers, this mechanism is used to limit the amount of high energy usage during off-peak periods, this way the load profile is relatively flat, assisting in maintaining the grid stable. The tariff is applied to the daily energy injected from the grid to the house.

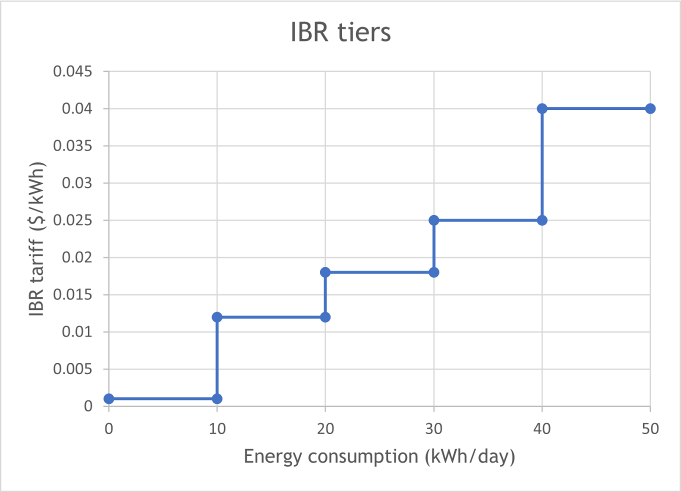


Figure 4.3: IBR tariff proportional to the daily energy consumption

Table 4.2 gives information about the DR programs used in this model, namely, time of use and real-time pricing. Both of them are categorised as price-based voluntary DR programs, meaning that the end-user has the choice of participating in these programs or not. It should be mentioned that both programs impact the electricity bill by captivating the consumer to change his normal energy consumption habits. This modulation studies the impact of load shifting on the daily energy bill and the energy tariffs are used to calculate the costs of purchasing energy from the grid.

Table 4.2: Daily tariffs for time of use and real time pricing DR programs, adapted from [96]

Hour	**TOU**	**RTP**
1	0.01	0.014
2	0.01	0.015
3	0.01	0.015
4	0.01	0.013
5	0.01	0.01
6	0.01	0.014
7	0.01	0.017
8	0.02	0.019
9	0.02	0.024
10	0.04	0.024
11	0.04	0.025
12	0.04	0.037
13	0.04	0.034
14	0.04	0.033
15	0.04	0.04
16	0.04	0.047
17	0.04	0.047
18	0.04	0.047
19	0.04	0.043
20	0.04	0.034
21	0.02	0.038
22	0.02	0.037
23	0.01	0.024
24	0.01	0.018

In this study, it is considered that each prosumer has a predefined load pattern which follows the consumer's preferences. Tables 4.3-4.12 provide the specific load profiles of the end-users shiftable loads, where it is possible to get the information about the flexible home appliances of each house, their nominal power, their working time, the base start and end time slots and, finally, the acceptable periods of operation. So, the first bound presented in the tables is the base one, which means that it is the preferred period to utilise this appliance and the second one regards the shiftable periods, which means that the asset can work in the different time slots, however, it must be operated for a consecutive number of time slots due to its duration. Note that each house has a different load pattern and an average shiftable load power demand of 30.70 kW.

House A	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Dishwasher	2.5	4	19	22	15	33
Washing Machine	3	3	19	21	16	23
Spin Dryer	2.5	2	27	28	25	35
Cooker Hob	3	1	17	17	16	17
Cooker Oven	5	1	37	37	36	37
Microwave	1.7	1	17	17	16	17
Laptop	0.1	4	37	40	33	47
Desktop Computer	0.3	6	37	42	31	47
Vacuum Cleaner	1.2	1	19	19	18	33
Electric Vehicle	3.5	6	37	42	31	47

Table 4.3: Shiftable loads - House A

House B	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Washing Machine	2.4	8	2	9	2	12
Spin Dryer	3	4	15	18	12	23
Cooker Hob	1.2	1	16	16	15	16
Television	0.25	2	26	27	24	28
Microwave	1.8	1	26	26	24	26
Dishwasher	2.2	4	26	29	23	35
Vacuum Cleaner	1.8	1	33	33	32	34
Electric Vehicle	3.2	6	37	42	31	47
Cooker Oven	1.2	1	38	38	35	45
Treadmill	1.6	1	40	40	39	42

Table 4.4: Shiftable loads - House B

House C	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Dishwasher	2.4	16	2	17	2	20
Washing Machine	3	4	15	18	12	23
Microwave	1.2	1	17	17	16	17
Laptop	0.28	10	18	27	17	30
Rice Cooker	1.8	2	21	22	21	22
Hair Dryer	1.5	1	22	22	22	23
Food Processor	0.8	2	23	24	21	27
Television	0.2	10	24	33	20	40
Iron	1.4	2	38	39	14	44
Sewing Machine	0.5	2	38	39	35	44

Table 4.5: Shiftable loads - House C

House D	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Vacuum Cleaner	2.5	1	7	7	6	7
Desktop Computer	3	4	15	18	12	23
Television	1.5	16	2	17	2	20
Laptop	0.3	10	18	27	17	30
Rice Cooker	1.9	1	22	22	22	23
Washing Machine	2.3	4	26	29	23	35
Electric Vehicle	1.9	6	37	42	31	47
Spin Dryer	3.3	1	38	38	35	45
Iron	1.3	2	16	17	14	18
Treadmill	1.7	1	40	40	39	42

Table 4.6: Shiftable loads - House D

House E	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Washing Machine	2.5	4	19	22	15	33
Spin Dryer	3	3	19	21	16	23
Dishwasher	2.5	2	27	28	25	35
Cooker Hob	3	1	17	17	16	17
Cooker Oven	5	1	37	37	36	37
Microwave	1.7	2	38	40	35	44
Laptop	0.2	10	24	33	20	40
Desktop Computer	3.5	3	2	4	2	7
Vacuum Cleaner	2.2	1	22	22	22	23
Treadmill	2	1	19	19	18	33

Table 4.7: Shiftable loads - House E

House F	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Microwave	2.5	1	16	16	15	16
Electric Vehicle	3.1	4	15	18	12	23
Desktop Computer	1.3	8	2	9	2	12
Television	0.35	2	26	27	24	28
Rice Cooker	1.9	1	26	26	24	26
Washing Machine	2.3	4	26	29	23	35
Vacuum Cleaner	1.9	6	37	42	31	47
Spin Dryer	3.3	1	38	38	35	45
Iron	1.3	2	16	17	14	18
Treadmill	1.7	1	40	40	39	42

Table 4.8: Shiftable loads - House F

House G	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Vacuum Cleaner	2.5	1	7	7	6	7
Desktop Computer	3	4	15	18	12	23
Television 1	1.5	16	2	17	2	20
Laptop	0.3	10	18	27	17	30
Rice Cooker	1.9	1	22	22	22	23
Food Processor	1.7	2	23	24	21	27
Sewing Machine	0.8	2	38	39	14	44
Television 2	0.2	10	24	33	20	40
Iron	2	2	28	29	15	45
Treadmill	0.5	2	38	39	35	44

Table 4.9: Shiftable loads - House G

House H	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Washing Machine	2.5	4	19	22	15	33
Spin Dryer	3	3	19	21	16	23
Dishwasher	2.5	2	27	28	25	35
Cooker Hob	3	1	17	17	16	17
Cooker Oven	5	1	37	37	36	37
Vacuum Cleaner	2.2	4	26	29	23	35
Microwave	1.8	1	33	33	32	34
Electric Vehicle	3.2	6	37	42	31	47
Hair Dryer	1.2	1	38	38	35	45
Treadmill	1.6	1	40	40	39	42

Table 4.10: Shiftable loads - House H

House I	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Dishwasher	2.4	16	2	17	2	20
Washing Machine	3	4	15	18	12	23
Microwave	1.2	1	17	17	16	17
Laptop	0.28	10	18	27	17	30
Rice Cooker	1.8	2	21	22	21	22
Microwave	1.7	3	38	40	35	44
Laptop	0.2	10	24	33	20	40
Desktop Computer	3.5	3	2	4	2	7
Vacuum Cleaner	2.2	1	22	22	22	23
Spin Dryer	2	1	19	19	18	33

Table 4.11: Shiftable loads - House I

House J	Power (kW)	Duration	Base_S	Base_E	Valid_S	Valid_E
Washing Machine	2.5	1	16	16	15	16
Electric Vehicle	3.1	4	15	18	12	23
Dishwasher	1.3	8	2	9	2	12
Television	0.35	2	26	27	24	28
Vacuum Cleaner	1.9	1	26	26	24	26
Hair Dryer	1.5	1	22	22	22	23
Laptop	0.8	2	23	24	21	27
Television	0.2	10	24	33	20	40
Iron	1.4	2	38	39	14	44
Work Laptop	0.5	3	38	40	35	44

Table 4.12: Shiftable loads - House J

Finally, in the houses considered in this model, the non-shiftable load demand must be supplied exactly at the specified time. This means, that certain appliances can not be shiftable and have to work exactly at the time that the end-user wants, examples of this are lights and refrigerant appliances. The average non-shiftable power demand of the ten different houses is 14.371 kW. Figures 4.4-4.13 represent the non-shiftable loads of each house and its working time intervals, as can be analysed the refrigerant appliances work the whole day due to the need to maintain the low temperature inside of the appliance.

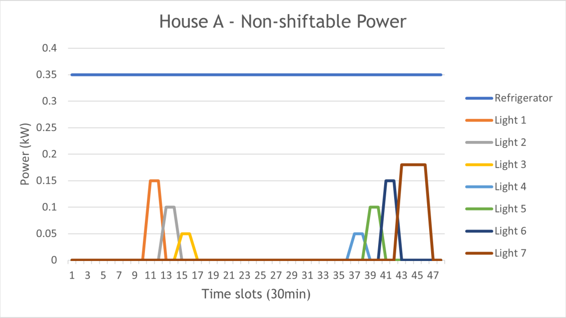


Figure 4.4: Non-shiftable loads - House A

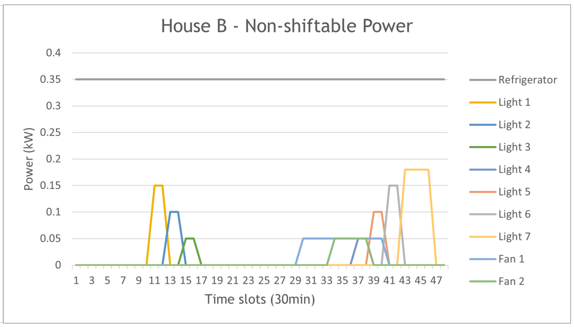


Figure 4.5: Non-shiftable loads - House B

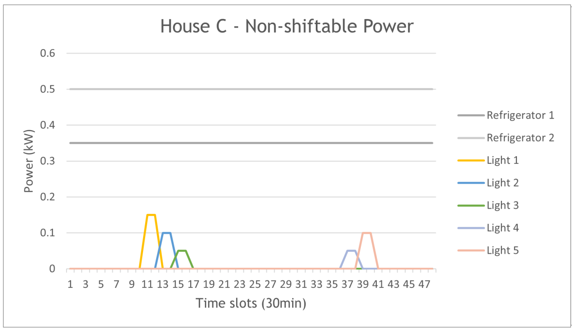


Figure 4.6: Non-shiftable loads - House C

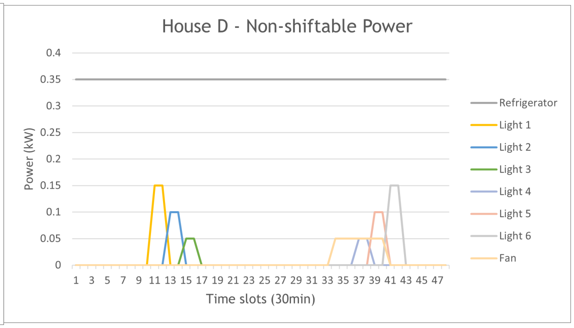


Figure 4.7: Non-shiftable loads - House D

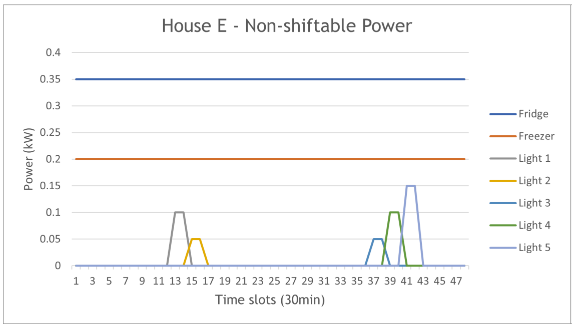


Figure 4.8: Non-shiftable loads - House E

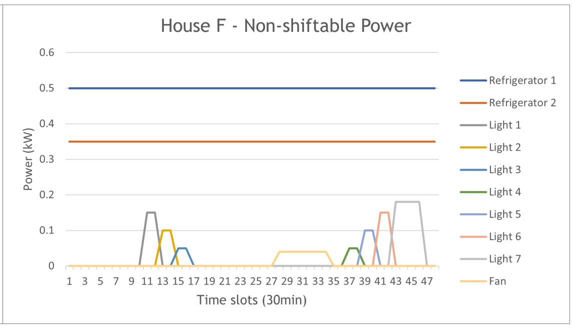


Figure 4.9: Non-shiftable loads - House F

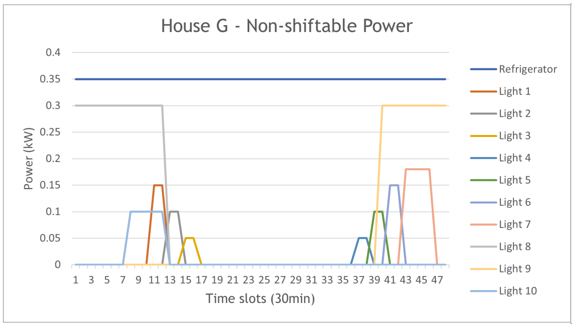


Figure 4.10: Non-shiftable loads - House G

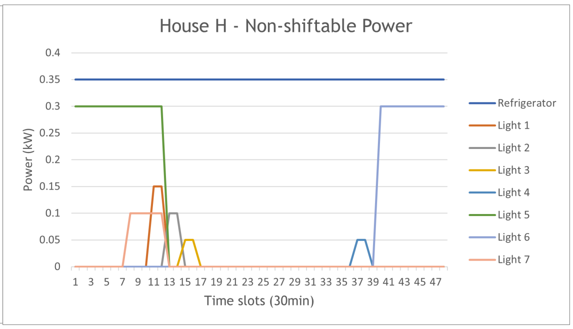


Figure 4.11: Non-shiftable loads - House H

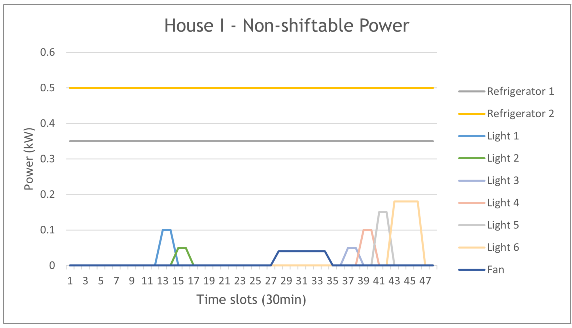


Figure 4.12: Non-shiftable loads - House I

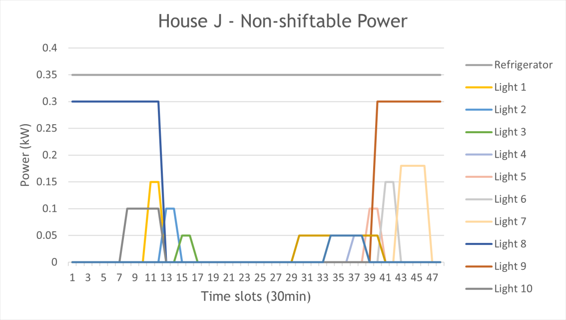


Figure 4.13: Non-shiftable loads - House J

4.2 Discussion and Results

In the present section, it is going to be evaluated and discussed the results obtained through the mathematical optimisation model. The HEMS studied is a mixed-integer linear programming model and the simulation results were obtained by a CPLEX solver through the General Algebraic Modelling System (GAMS). Using the CPLEX solver allows a complex problem formulation and an efficient high-level modelling solution.

4.2.1 Energy Stored in the ESS

The results presented in this segment were simulated following the ESS constraints and it was utilised a penalty factor for discomfort index, σ, equal to 0.002. As stated before, each house has been installed with an ESS with a 4 kWh capacity. It is expected some ESS energy losses due to being considered a real case, this is, the ESS is not 100% efficient, as seen before. So, the residual value of the sum of the energy transacted with the grid, the PV generated energy and the load demand of the system is the ESS energy losses.

Figure 4.14 represents the energy stored in the ESS installed on each house. As already stated previously, it is easily noted this graphic has two different constraints, one being the maximum value of energy stored (4 kWh) and the minimum (0.2 kWh) that can be seen at the beginning and end of the day. Also, it fulfilled the need for the energy in the ESS in the first time slot to be equal to the energy in the last period.

Bear in mind, for most of the ten houses the ESS starts charging in the first hours of the day and reaches its highest value when the PV generation is at its maximum performance, this is, during the afternoon period. The energy stored in the system is then utilised to support the typical peak demand seen in the evening hours, around time slot 48 all of the ESS are completely discharged and have reached the minimum value of energy stored.

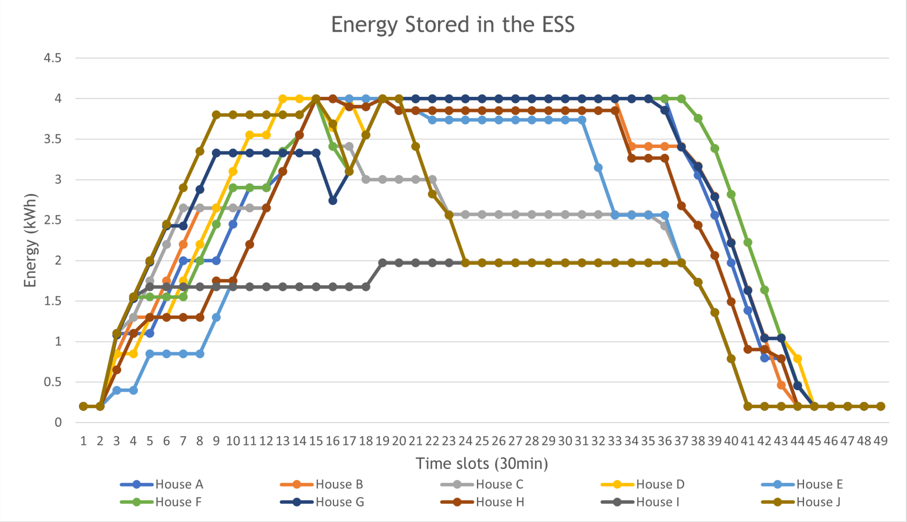


Figure 4.14: Energy stored in the ESS

4.2.2 Loads Shifted

This section investigates the self-scheduling problem with shiftable loads based on the TOU tariff. In the base case of our study, all house's assets worked in the end-user's preferred time slot. Now, to minimise the costs of electricity bills, these loads were shifted to less expensive and with fewer demand periods. Should be noted that the average shiftable load power demand remains equal to the one in the base case, this is because all the appliances work normally, and the only difference is the period in which they do that. Also, just like before, the working of an asset can not be interrupted, so, the active time of an appliance should be in consecutive time slots.

Figures 4.15-4.24 show the loads shifted for all ten houses, as well as the load power of each appliance. As an example, in "House A" the preferred period to charge the electric vehicle was from time slot 37 until 42, after simulating our model the EV was charged between time 42 and 47. This way, the EV is not charged at peak demand periods, which normally occur around time slots 36 to 38, and it is going to be ready for the owner to use the next morning.

It is important to note that the results were simulated using a penalty factor for discomfort index, σ, equal to 0.002. If this value was higher there would be less load shifting capability and, consequently, the costs wouldn't be as minimised as possible, however, the assets would function in the end-user's preferred time slots.

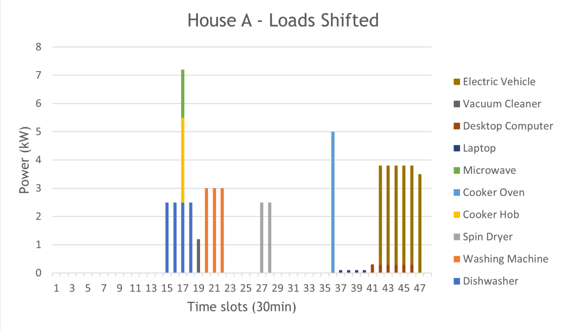


Figure 4.15: Loads shifted - House A

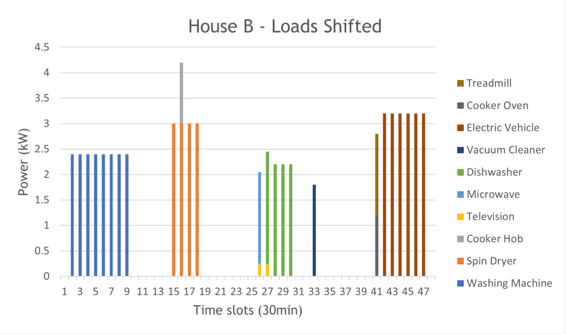


Figure 4.16: Loads shifted - House B

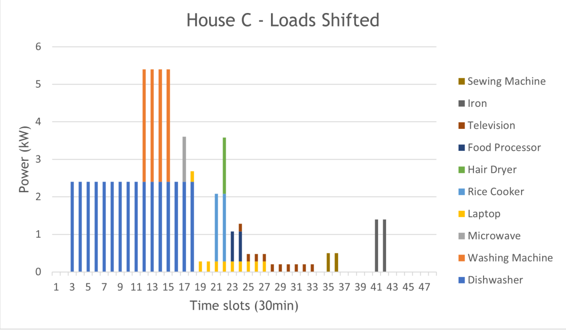


Figure 4.17: Loads shifted - House C

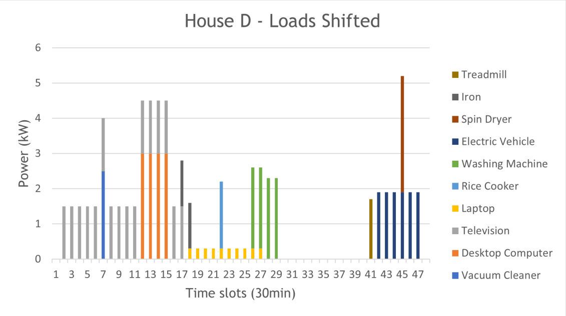


Figure 4.18: Loads shifted - House D

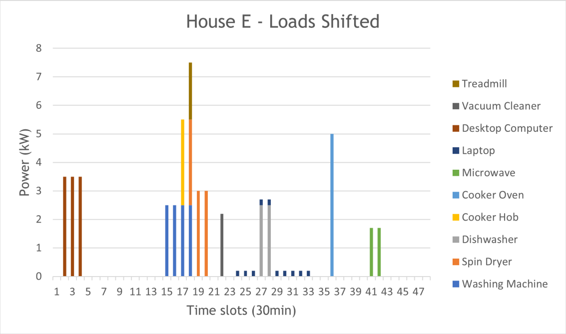


Figure 4.19: Loads shifted - House E

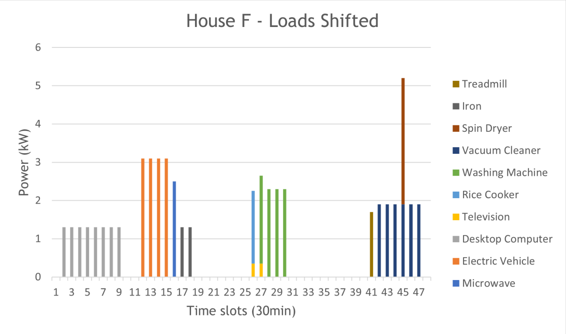


Figure 4.20: Loads shifted - House F

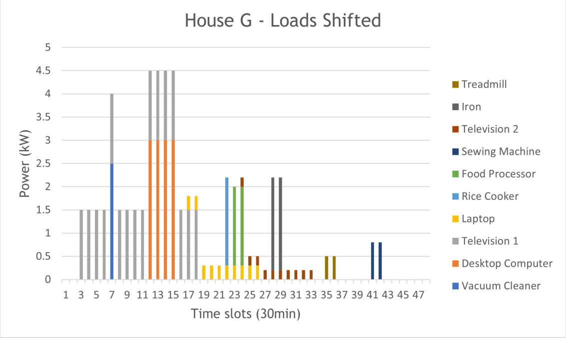


Figure 4.21: Loads shifted - House G

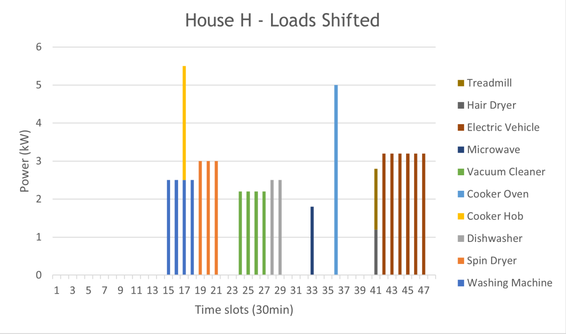


Figure 4.22: Loads shifted - House H

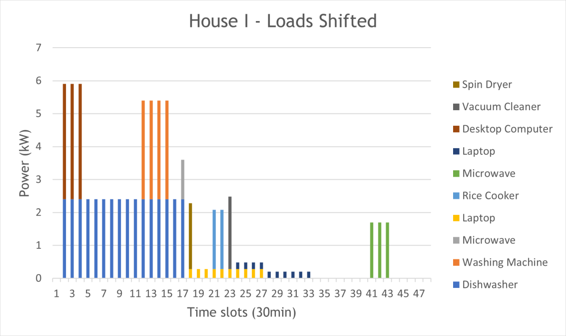


Figure 4.23: Loads shifted - House I

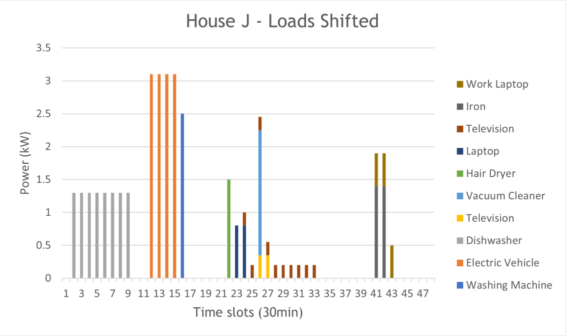


Figure 4.24: Loads shifted - House J

According to the results shown can be confirmed the fact that no assets suffered redundant start-ups and shut-downs while being able to shift loads effectively according to the TOU tariff. This expresses the good function of the model regarding the HEMS scheduling constraints and the capability of satisfying the end-user's needs.

4.2.3 Energy Transaction with the Grid

Next, it is going to be evaluated the energy transaction with the grid of all ten houses. Again, like the results previously shown, it is confirmed that all of the values respect the model restrictions, more specifically the energy transition constraints.

Figure 4.25 shows the energy injection from the grid to the house in the different time slots. Generally speaking, all ten houses follow a similar behaviour regarding the Grid-to-Home (G2H) injection. The results show that, more often than not, the G2H energy injection is larger at the beginning and the end of the day. It is noticeable energy transactions at peak demand time slots like 12 to 19 and 40 to 44, representing the time from 6:00h to 9:30h and from 20:00h to 22:00h.

The primary reason for the G2H injection being more notable in the first and last hours of the day is due to the unavailability of RES, more specifically PV generation, and the incapability of the ESS to compensate for this RES absence. Due to this, it is necessary to inject energy into the house in order to support the load demand.

Keep in mind that the price of buying energy from the grid is regulated by the incentive-based tariff, IBR, and each tier refers to a certain amount of energy per day as already mentioned in the use case.

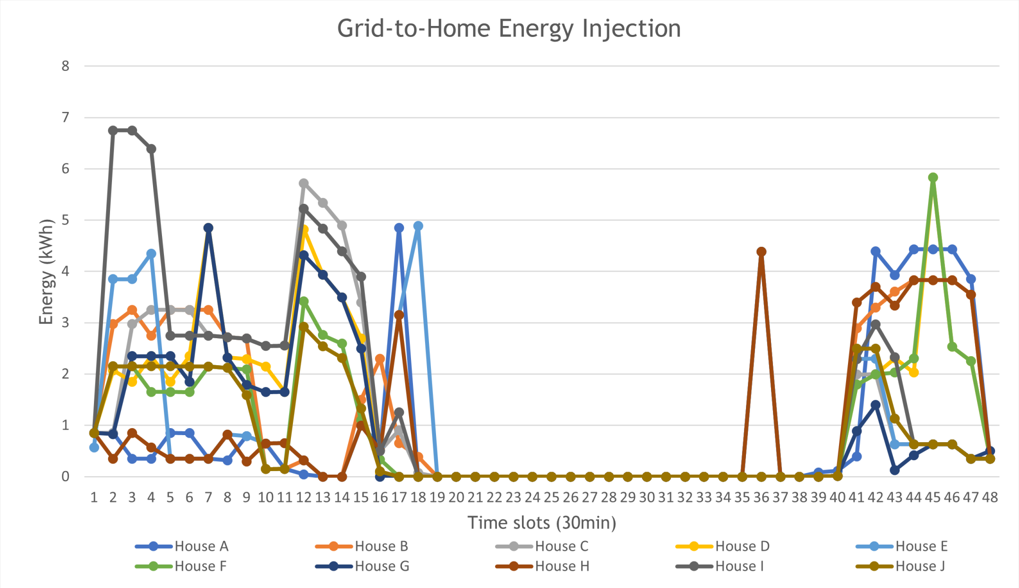


Figure 4.25: Grid-to-Home energy transaction

Figure 4.26 presents the results of energy transactions from the house to the grid. The ten curves show that H2G energy injection occurs on the contrary time slots of the G2H transaction, which respects the fact that the end-user can not buy and sell energy at the same time. The period of H2G injection is generally from time slot 16 to 37, from 8:00h to 18:30h, this period also represents the hours with sunlight.

The simulation results confirm that the H2G injection is related to solar power generation. This is, in the time slots with a large PV power generation can also be seen a large amount of energy injection to the grid, an example of this is time slot 24, 12:00h, at this time the micro-generation is at its maximum, thus, the H2G injection curves follow the same behaviour.

The economic side of the H2G transaction is the most impactful one for the end-user, this is a great way for every prosumer to make some profit from selling the energy to the grid. This way, it is going to be noticeable a minimisation of price in the electricity bill, while not wasting the surplus of energy produced by RES. It should be noted that similar to several European countries, the Portuguese regulation for the prices of injecting energy into the grid is 90% of the average monthly energy prices, [97].

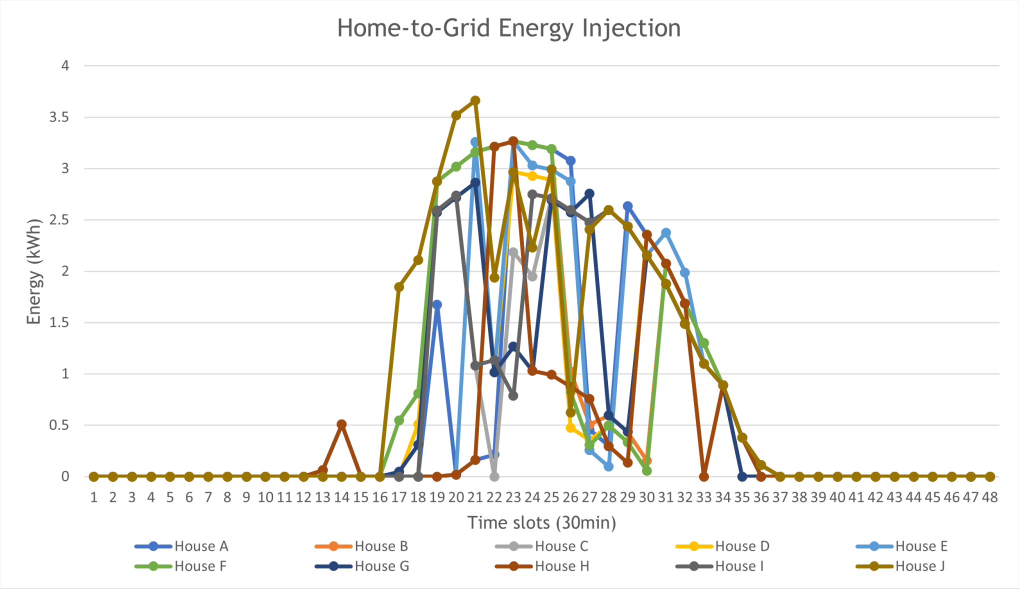


Figure 4.26: Home-to-Grid energy transaction

Keep in mind that the model studies ten different houses integrated in a energy community and controlled by the local energy controller. This makes it possible to transact energy between houses to support the different consumption patterns of each end-user. Table 4.13 shows the total energy transacted with the grid for both H2G and G2H injection.

House	A	B	C	D	E	F	G	H	I	J
H2G (kWh)	27.477	30.389	30.874	28.930	28.700	31.777	28.386	18.702	31.900	40.201
G2H (kWh)	43.556	55.644	55.725	58.694	38.753	46.064	42.042	41.281	69.801	35.688

Table 4.13: Total energy transaction with the grid per house

The results show that the houses with larger load demand, such as houses "B", "C", "D" and especially "I", are the ones with a bigger G2H energy transaction. Thus, it is due to the PV generation and the ESS not being capable to support the total demand of the house. However, the H2G results are similar in all the ten houses due to all of them having the same PV installation characteristic and ESS with equal parameters.

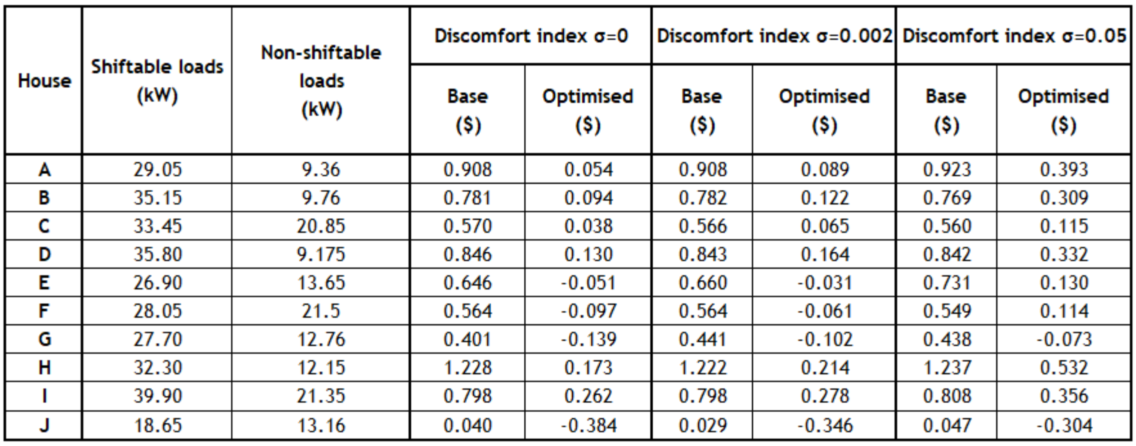
4.2.4 Economic analyses

This section shows the economic results acquired after simulating the mathematical model with three different penalty factors for discomfort indexes, more specifically $\sigma = 0$, $\sigma = 0.002$ and $\sigma = 0.05$. Table 4.14 shows the daily energy bill for the different houses and the discomfort index penalty factor, also can be seen the shiftable and non-shiftable load demand of each residence.

Analysing the results can be seen that the model worked as expected and was able to minimise the daily electricity bill in all cases. For a penalty factor for discomfort index equal to zero were obtained the optimal minimisation results, on average was saved a total of 0.670 $ per house. Next, for the discomfort index penalty used throughout this dissertation, $\sigma = 0.002$, the model minimised the daily electricity costs of each house by an average o 0.642 $. Finally, for the largest value of the discomfort index penalty, the results were not as minimised as in the previous ones, either way, it was still possible to minimise the daily electricity bill of each house by an average of 0.500 $.

It is important to note that in some results presented the net daily energy bill is negative, this means that the revenue obtained from selling energy to the grid was superior to the rest of the electricity costs. Analysing these values is easily noted that this occurs, normally, in the houses with lower load demand, for example in house "J". However, when the discomfort index penalty is higher this does not happen so frequently due to the incapability of moving the shiftable loads to the more cost-friendly time slots.

Note that the base case values for the three simulations shown also vary, this is not due to the variation of the penalty factor for discomfort index, but because of the different scenarios possible in this model, for example, the PV generation has ten possible scenarios has already shown before.



House	Shiftable loads (kW)	Non-shiftable loads (kW)	Discomfort index σ=0		Discomfort index σ=0.002		Discomfort index σ=0.05	
			Base ($)	Optimised ($)	Base ($)	Optimised ($)	Base ($)	Optimised ($)
A	29.05	9.36	0.908	0.054	0.908	0.089	0.923	0.393
B	35.15	9.76	0.781	0.094	0.782	0.122	0.769	0.309
C	33.45	20.85	0.570	0.038	0.566	0.065	0.560	0.115
D	35.80	9.175	0.846	0.130	0.843	0.164	0.842	0.332
E	26.90	13.65	0.646	-0.051	0.660	-0.031	0.731	0.130
F	28.05	21.5	0.564	-0.097	0.564	-0.061	0.549	0.114
G	27.70	12.76	0.401	-0.139	0.441	-0.102	0.438	-0.073
H	32.30	12.15	1.228	0.173	1.222	0.214	1.237	0.532
I	39.90	21.35	0.798	0.262	0.798	0.278	0.808	0.356
J	18.65	13.16	0.040	-0.384	0.029	-0.346	0.047	-0.304

Table 4.14: Daily energy bill for different discomfort indexes

Figure 4.27 presents a more visual reference of the daily electricity bill results for each house. Taking these values into account, it is possible to say that a penalty factor for discomfort index equal to 0.002 is a great balance between load shifting capabilities and end-users appliance usage preferences.

It is also important to mention that the utilisation of DR tariffs has a big impact on reducing electricity costs due to the capability of encouraging the end-users to shift their consumption to off-peak hours, this way the G2H transactions when energy prices are at peak values are kept to a minimum.

In short, it is possible to say that the combination between load-shifting capabilities, RES micro-generation, ESSs and DR programs have the capability of minimising the electricity costs. Also, the capability of profiting from H2G injection is a great source of income for prosumers to save on electricity costs and to recover the initial investments needed to create a house with these specific characteristics.

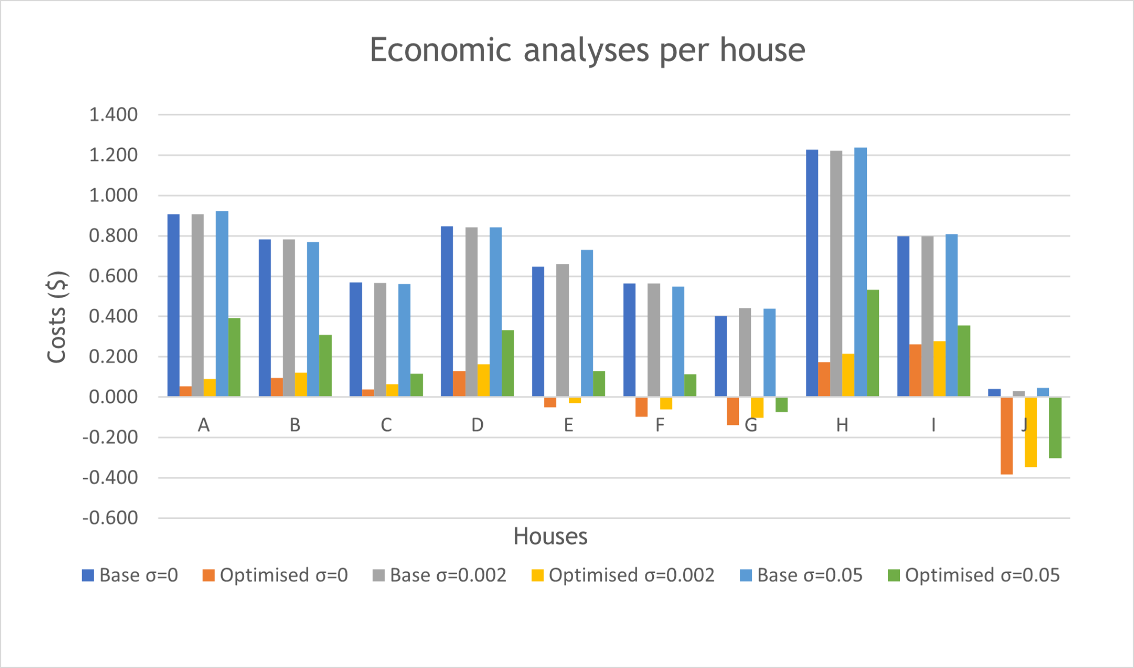


Figure 4.27: Daily energy bill per house

Chapter 5

Conclusions

In this final chapter, it is described the various conclusions of the work developed in this dissertation. Also, it is presented some future works could be studied to improve some areas of the model presented.

5.1 Conclusion

In this dissertation, it was modelled a home energy management system (HEMS) with load shifting capabilities, in which the main objective was to minimise the daily energy bill, while always taking into account the end-users comfort. The HEMS studied is seen as a mixed-integer linear programming (MILP) model and it was simulated in a General Algebraic Modelling System (GAMS) environment with a CPLEX solver.

The case study includes a community of ten houses with different load demands and integrated into a local energy community where it is allowed to transact energy into and from the grid, profit from energy surplus production and compensate for the lack of this production in peak hours, respectively.

Also, it was considered that all ten residences were equipped with renewable energy sources (RES) micro-generation, more specifically solar power, and an energy storage system with the capability to store energy to later utilise it in peak-demand hours. Note that all houses have different shiftable and fixed loads, which makes their consuming patterns different. In this case, was also applied price-based voluntary demand response programs to incentivise the end-users to shift their loads according to the more affordable energy price periods.

Regarding the energy storage system (ESS) installed in the different residences it was noticed that this technology is fully charged when there is a peak in photovoltaic (PV) production, this is, during the afternoon hours, and its charging process has a start when the energy prices are lower, around 1:00h. It can also be confirmed, that in high-demand hours the system starts its discharge process to compensate for the high load demand, this happens generally between 18:30h and 22:30h.

The load-shifting results show that with a HEMS model it is possible to manage the appliance's demand to more economic friendly time slots. This study was simulated utilising a penalty factor for discomfort index equal to 0.002, this value can be changed by the end-user, however, the one used was considered a great balance between load-shifting capabilities and end-users appliance usage preferences.

Moreover, as mentioned before, all ten houses have different consumption patterns for fixed and shiftable loads but have in common the incapability of not shifting the fixed loads and can not interrupt a working asset, this means, the active time of an appliance should be consecutive even when the load is shifted.

Regarding the energy transacted between the house and the grid, the results manifest that grid-to-home (G2H) energy injection occurs mostly in the first and last hours of the day to support the large demand. Keep in mind that this is also due to the unavailability of PV production in those time slots and the incapability of the ESS to compensate for this load demand.

Additionally, the house-to-grid (H2G) energy injection results show that this phenomenon happens on the contrary time slots of the G2H transaction. H2G injection is notably larger when there is a peak in PV production. This is due to the capability of selling the surplus RES energy to the grid, and, by doing this, profiting from the in-house micro-generation. This method is a great way of compensating other electricity costs.

The results from the simulation of this model for three different penalty factors for discomfort indexes, $\sigma = 0$, $\sigma = 0.002$ and $\sigma = 0.05$, show that the HEMS implemented can reduce the electricity bill of a residence. For $\sigma = 0$, the economic results were optimal, on average it was possible to minimise the daily electricity bill by 0.670 $ per house, but even though the economic results were minimised to a maximum, a penalty factor for discomfort index equal to 0.002 was a perfect combination between costs minimisation and end-users appliance usage preference. With this value, the model minimised the daily costs, on average, by 0.642 $ per house. Lastly, with a discomfort index penalty factor equal to 0.05 it was given a bigger priority to the end-users asset usage preference, this means that the costs were not as minimised as before, however, it was still possible to minimise the daily electricity costs by 0.500 $, on average.

In short, it was concluded that the implementation of the HEMS model like the one studied in this dissertation is capable of significantly reducing energy costs while considering end-users preferences. Also, the results showed confirmed the important role of RES micro-generation and ESS in smart home applications of the modern day. Beyond this, note that DR program tariffs have an important role in captivating prosumers to change their consumption habits, and, consequently, minimising daily electricity costs.

5.2 Future Work

In this section is going to be mentioned some future work possibilities to be done within the same subject of this dissertation. First, the problem studied could be extended to a model with the capability to integrate a large number of smart houses within a smart energy community. This community could also integrate different non-residential buildings, like schools, commercial centres, community services and industrial buildings.

Another future work possibility is a smart energy community with community energy storage systems, such as batteries, and local renewable energy production to reduce community energy costs and, this way, create a local energy market with energy transactions between community buildings.

In addition, to improve the model presented can be study houses with a big variety of loads and renewable energy generation. The load patterns of the different house assets can be adapted to a more realistic situation to have more real-life-like results.

Lastly, with the increase of variables in a model, consequently, there will be an increase in the number of constraints. So, the mixed-integer linear programming technique can lose its accuracy in solving the energy management problem. To solve this can be studied different heuristic and metaheuristic approaches for the problem presented, with the final goal of achieving the optimal solution.

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