TÉCNICO LISBOA

An analysis of the Portuguese energy storage strategy based on the Choquet multiple criteria preference aggregation model

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Dedicated to my family, for their never-ending support.

Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Acknowledgments

"It takes a village to raise a child."

– African proverb

This dissertation, and corresponding academic cycle closure, has only been accomplished due to the concerted effort of several meaningful individuals, working unaware, as a whole.

First, to all the Professors who over the course of my life helped me develop my hard and soft skills, especially my dissertation supervisors - Professor José Figueira and Professor Ilídio Lopes. Professor Carlos Silva helped in a different capacity in a number of situations.

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Then, to all of my friends, for taking my mind off work whenever I needed it.

To my girlfriend, for standing by me, being a voice of reason and always being right.

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To all of them, the most heartfelt appreciation, gratitude and praise. Thank you.

Resumo

Com o aumento da geração de energia renovável e os problemas de instabilidade que delas advêm, devem ser implementados em paralelo sistemas de armazenamento. Deste modo, compreender e estudar a performance das tecnologias de armazenamento nas suas várias categorias de aplicação tem valor. Consequentemente, desenvolveu-se um modelo de ordenação das várias opções disponíveis para os diversos setores do mercado de armazenamento de energia, com especialistas das várias áreas específicas no processo de decisão. Foi criado também um modelo metodologicamente semelhante para efeitos de políticas estratégicas públicas de energia, tendo o governo como principal decisor. Além de uma revisão crítica dos resultados, realizou-se uma análise de robustez, de modo a explorar possibilidades de futuro relevantes que possam ajudar a tomar decisões no presente. As melhores opções de armazenamento foram as químicas, tais como o Hidrogénio e o Metano, assim como várias baterias eletroquímicas, das quais as de Ião-lítio destacam-se consistentemente. Resultou que o armazenamento químico tem as características necessárias para a Categoria Rede de Longa Duração. Porém as baterias, incluindo as de Oxidação-redução no primeiro caso, obtiveram desempenhos acima da média nas Categorias Microgrid e Mobilidade. Nenhuma solução teve absoluto destaque na Categoria Rede de Curta Duração, apesar da Água Quente ter tido um grande desempenho nesta e na Microgrid. Sem supresa, os já mencionados sistemas de armazenamento químico, baterias e Água Quente apresentaram-se como as mais interessantes tecnologias do ponto de vista político, devido ao seu uso para múltiplos fins e características intrínsecas.

Palavras-chave: Política energética; Armazenamento de energia; Hidrogénio; Análise de decisão multicritério; Integral de Choquet.

Abstract

With the increase of renewable energy generation and its problems related to output instability, storage systems must be implemented in parallel to account for this effect. Therefore, it must be valuable to better understand and study the performances of these technologies in their several application categories, thus understanding the potential of each alternative in each category and as a whole. For this reason, a model was developed to rank the various available options in several sectors of the energy storage market, with experts from each sector participating in the decision-making process. A methodologically similar model for strategic energy public policy was also created, with the government as the main decision-maker. Beyond a critical review of the results, a robustness analysis was performed, to explore interesting future possibilities that may help make decisions in the present. Chemical storage solutions, such as Hydrogen and Methane, as well as several electrochemical batteries, from which Lithium-ion consistently stuck out, were the standout energy storage solutions. Chemical storage was shown to have the desired characteristics for the Long Term Grid Category. Meanwhile, batteries, including Redox Flow in the first case, have overperformed in the Microgrid and Mobility Category. No standout solutions appeared in the Short Term Grid Category, despite Hot Water having achieved very satisfying results, as well as in the Microgrid. Unsurprisingly, the aforementioned chemical storage systems, batteries and Hot Water have presented themselves as the most politically interesting technologies, due to their multipurpose uses and intrinsic characteristics.

Keywords: Energy policy; Energy storage; Hydrogen; Multi-criteria decision analysis; Choquet integral.

Contents

List of Tables

List of Figures

[1] https://www.iea.org/countries/portugal
[2] https://www.statista.com/statistics/418111/electricity-prices-for-households-in-portugal/
[3] https://www.apren.pt/en/renewable-energies/production
[3] http://decspace.sysresearch.org/index.html

Glossary

ACAES Adiabatic Compressed Air energy storage. 21

APREN Associação Portuguesa de Energias Renováveis. xvii, 18

CAES Compressed Air energy storage. 22

Capex Capital expenditure. 43

DM Decision-maker. 3

EU European Union. 8

H_2 Hydrogen. 22

Hydro Hydroelectricity. 11

IEA International Energy Agency. xvii, 6

INE Instituto Nacional de Estatística. 19

LAES Liquid Air energy storage. 22

LiIon Lithium-ion. 22

MCDA Multi-criteria decision analysis. 35

$NaNiCl_2$ Sodium Nickel Chloride. 22

NaS Sodium Sulphur. 22

NiCd Nickel-Cadmium. 22

NiMH Nickel-Metal Hydride. 22

PCM Phase Change Materials. 22

PHES Pumped Heat electrical storage. 21

PHS Pumping Hydro storage. 21

SMES Superconducting Magnetic energy storage. 22

Solar PV Solar photovoltaics. 7

TCS Thermochemical storage. 22

VRF Vanadium redox flow. 22

ZnBr RF Zinc Bromine redox flow. 22

Chapter 1

Introduction

1.1 Motivation

"It's in the definition that if it is not renewable,
it's going to run out at some point."
– Elon Musk

This simple phrase states the obvious. If our power generating options are not renewable, there will inevitably be a power shortage and possible societal collapse. Even beyond any possible environmental concerns, the generation and consumption of sustainable energy must, inevitably, become a reality (Owen, Inderwildi, & King, 2010).

Due to recent technological developments in the generation of renewable energy, such as improvements in efficiency, the development of cost-cutting alternatives, and the creation of economies of scale, as well as an increase in environmental awareness, Europe, and the world, are transitioning towards sustainable energy (Child, Kemfert, Bogdanov, & Breyer, 2019). Either through governmental financial and fiscal stimuli or the decrease in the price of technology and its corresponding demand increase, the adoption of renewable solar and wind energy generation sources has been immense, bringing with them new challenges (International Energy Agency, 2020). Whereas crude oil, natural gas, and coal are simultaneously energy sources and their storage system, renewable sources tend to be only a momentaneous source. The generation of renewable energy, in its most well-developed and significantly well-implemented forms, tends to be at the whims of the Sun, the wind, or even the Earth's internal heat, which is far more consistent than the two previous examples.

As it has been stated, solar and wind energy sources are, and will continue to be, the two most significant origins of renewable energy for the foreseeable future, due to their technological superiority over the other options (in most cases) and decreasing costs (Nema, Nema, & Rangnekar, 2009). Eventually, due to the rapid increase in their deployment all over the world, a combination of renewable sources will have to represent close to 100% of the generation of new energy.

However, as renewable sources increase in significance, their related problems will also escalate. Because these problems will inevitably arise, and to some extent already have, storage systems will have to be implemented to counter these effects, therefore it is worth studying in greater depth what is available and what should be considered. This rationalisation and combination of factors and trends are what motivated the development of this project, with Portugal in focus, as this is the country of the author and the decision-makers taking part in the case study. If one believes that these vectors of massive change will endure and strengthen, the development of a model to study and compare energy storage solutions across multiple dimensions, while considering possible adaptations and improvements, is key to understand their impact in terms of strategic energy public policy.

Furthermore, since electricity has been available outside the scope of a laboratory, there has always been a need to balance the electric power provided to the grid and to follow natural demand shifts during the day. Historically, managing the grid was somewhat simple: some power plants provided the baseline amount of required energy with a constant output; others, the so-called *peaker plants*, adjusted the amount of coal, crude oil, or, more recently, natural gas being burned (Krieger, Casey, & Shonkoff, 2016). Nowadays, and towards the future, the amount of wind being blown or Sun hitting solar panels cannot be managed - both the excess or lack of energy is undesirable and unacceptable. Besides the obvious grid-scale energy generation-related issues, some decentralised solutions have been implemented in factories and homes to complement the energy obtained from the grid or to fully create an autonomous microgrid (Yu, Zhu, Han, & Holburn, 2019). Even besides this affair, the transportation industry, in particular, has been fully reliant on micro generating energy in the engines of cars, buses, boats, etc.

As renewable energy generation is necessarily linked to storage systems, to balance and manage them on several dimensions, it is fundamental to study energy storage solutions, as the widespread adoption of renewable energy generation can not be fully implemented without the former, in a context of strategic energy public policy (Motyk, Slaughter, & Sanborn, 2018). Having established the necessity to analyse energy storage solutions according to multiple distinct criteria, it is then imperative to understand how the subject can and should be studied. Thus, the use of a multiple criteria decision analysis (MCDA) model is clear. To model this problem accordingly, it is invaluable to firstly identify the services and requirements on the energy side of the problem. Then, and only then, can a model be attuned in line with the issue and its key stakeholders. In the end, the model could not be considered complete without a critical review of the results and a robustness analysis, to ensure that the obtained results are credible and valid, serving as the foundation for future decisions.

1.2 Objectives

The scope and complexity of the subject of energy storage are too vast and complex to allow for one single study to define the installation of every application in every single situation, thus this is not what this dissertation sets out to achieve. In line with these limitations, a study can still be conducted for strategic energy public policy, and considering the growing interest not only philosophical but also monetary in the order of thousands of millions of euros, it is relevant to evaluate and rank every available storage solution regarding their overall importance.

It should be highlighted that this dissertation is not proposing to solve and appoint one storage solution for every situation, but rather suggest the single, or couple, of solutions most relevant for particular categories of the energy storage market or investment for Portugal. Several objectives can therefore be itemised in a temporally relevant manner:

– Develop a deep understanding of the energy generation and storage state of affairs in Portugal;

– Recognise the current capabilities and limitations of the available energy storage solutions on a technological level;

– Analyse and understand the issue, identifying how it is a multi-criteria problem;

– Recognise how the criteria interact with each other, requiring the use of the Choquet multiple criteria preference aggregation model;

– Evaluate each alternative according to the defined criteria;

– Create a ranking of technologies according to the preferences of the decision-makers (DMs) for each category, and at a governmental level;

– Analyse the results and preferences of the choices performed by the DMs;

– Conduct robustness analysis to explore future possibilities that may help make decisions in the present.

These goals can be rearranged in a more perceptible manner towards the ultimate purpose of this dissertation, as Figure 1.1 demonstrates.

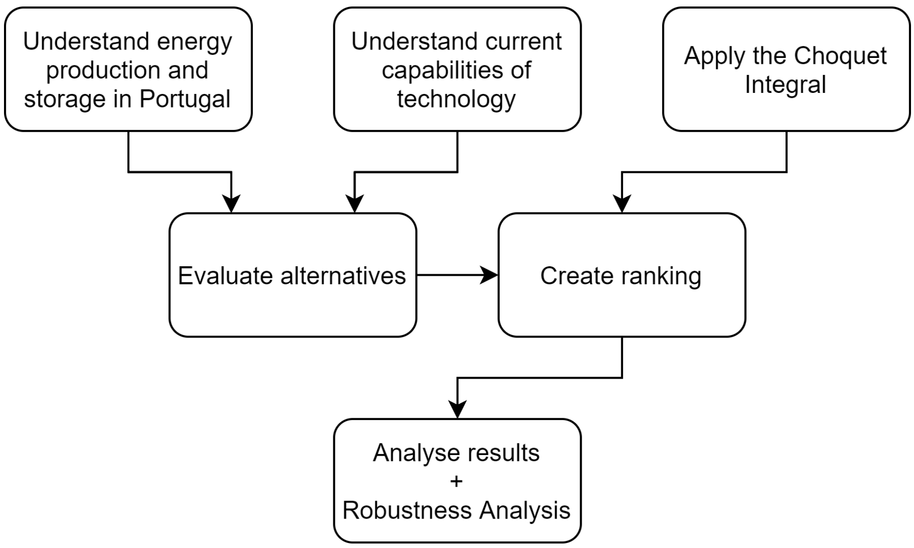

Figure 1.1: Dissertation objectives.

The accomplishment of these aspirations will be addressed in Section 6.1.

1.3 Research methodology

To accomplish the objectives set up in Section 1.2, the appropriate research methodological steps are enumerated in the next eight bullet points:

1. The first step relates to the identification of the monumental problem of managing the ever-changing electrical grid;
2. The second step takes on the problem by describing and detailing it;
3. The third step outlines the importance of performing in-depth research of the sector, setting up the foundations of the dissertation;
4. The fourth step delineates the step on which the model can be defined, although future improvements can always be incorporated upon the discovery of new information;
5. The fifth step is inevitably the collection of data, upon the creation of the model, to operationalise the criteria;
6. The sixth step is the implementation of the whole model, following the meetings with the DMs;
7. The seventh step demarcates the importance of the discussion of the model and its results with the DMs, as well as the development of a robustness analysis to verify how the results would change depending on different choices and performances;
8. The eighth, and final, step marks the final conjectures and conclusion of the project.

1.4 Outline

Aligned with the objectives previously outlined, the present dissertation will contain six chapters. These chapters will conveniently correspond to the major steps of the methodological process.

In the current chapter, the problem at hand has been introduced with broad strokes, having explained its importance and why it has been chosen. Chapter 2 will start to unfold some information regarding the point to which it is has been addressed and how the situation currently presents itself. Chapter 3 starts to finally investigate the issue in-depth, creating a full picture of the market and its specificities, as well as indicate the initial decisions upon which the model will be constructed. Chapter 4, with all the information obtained from the previous chapter, defines the creation of the second pillar of this project, the methodology, by which the problem will be studied; this fourth chapter will present and address how the theoretical methods will be shaped to correctly analyse the energy storage sector. Chapter 5 will then present, discuss and analyse the results provided by the models and the robustness analysis, from the decisions of the DMs and the database to be constructed. Chapter 6 will finalise and tie in all the conclusions and loose ends of the dissertation.

Chapter 2

Problem description

Managing the energy grid is not an easy task. Besides the usual and expected demand shifts during the day, and depending on the season, the growing inclusion of renewable energy has created several new variables in energy output on the supply side. Understanding in greater depth the setting up to now, as well as the current trends regarding energy generation, will be done in Section 2.1, while the energy storage situation at the global and national level is being addressed in Section 2.2.

2.1 Background

The objective of this section is to introduce the energy generation setting, therefore, the three main subjects - the energy supply, the prices throughout the years, as well as the energy necessities and excesses that get exchanged in the interconnections with other countries - will be addressed in Subsection 2.1.1, Subsection 2.1.2 and Subsection 2.1.3, respectively.

2.1.1 Energy supply

Portugal has been fairly efficiently and successfully investing in the generation of renewable energy in the past few decades. Europe, like much of the developed world, has a broad plan to transition its entire grid to the generation and consumption of zero-carbon and renewable energy (IEA, 2017).

Portugal is on a path or rather has the objective, to achieve 80% of renewable energy consumption by 2030, with an even more ambitious goal of achieving overall carbon neutrality in the entire country by 2050. Wind, solar and hydro - the three major renewable sources in Portugal - have steadily increased their market share, but these renewable technologies are still dwarfed by the non-renewable ones - oil, natural gas, and, for the time being, coal. Biofuels and waste may also be considered renewable sources, although this is highly debated. Nevertheless, biofuels usually produce a considerable amount of greenhouse gases and, for that reason, they can not be integrated into the 2050 plan. It is highly relevant to visualise certain concepts like energy consumption by source, renewable generation, electricity prices, among others to better understand their evolution. Numbers are helpful, but there is plenty of information more compactly and intuitively provided through an image.

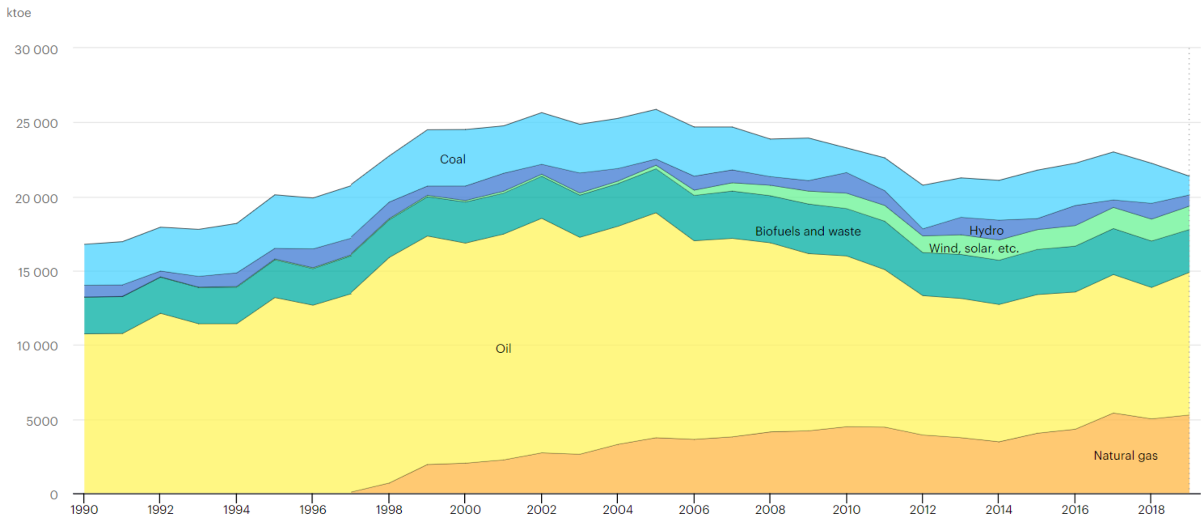

Figure 2.1: Aggregate energy supply in Portugal by source. Source: IEA [1].

Figure 2.1 is the quintessential energy production graph since through it we can analyse the overall cumulative progression of every energy source. It is logical and factual that, with time, energy consumption trends upward, as more devices are plugged into the network and the population grows, even though the devices that consume energy usually also have a better efficiency over time. From 1990 up to 2019, Portugal's population has increased by well over half a million people, with a maximum of 10.6 million people in 2009, which in turn is about half a million more than today. These fluctuations in population, as well as the increase in consumption, broadly explain the evolution of the graph.

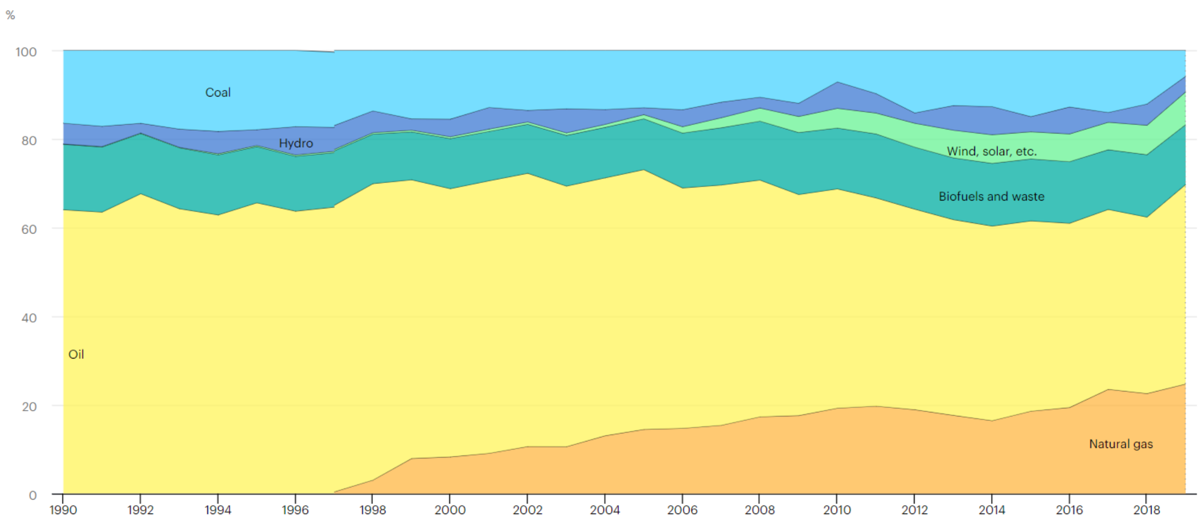

Figure 2.2: Energy supply in Portugal in percentage. Source: IEA [1].

With similar information, but with the twist of normalising each energy source with the yearly output, energy consumption trends by source become clearer in Figure 2.2. Hydropower and biofuels and waste have maintained their somewhat stable importance throughout the years. Natural gas, as well as wind and solar on a different level, have started to carve out their significance in the market, and it is only expected to continue increasing. These sources have been chipping away at oil's market share, as well as coal, although here the decrease has been significantly more unstable. Be that as it may, coal appears to be on its way out.

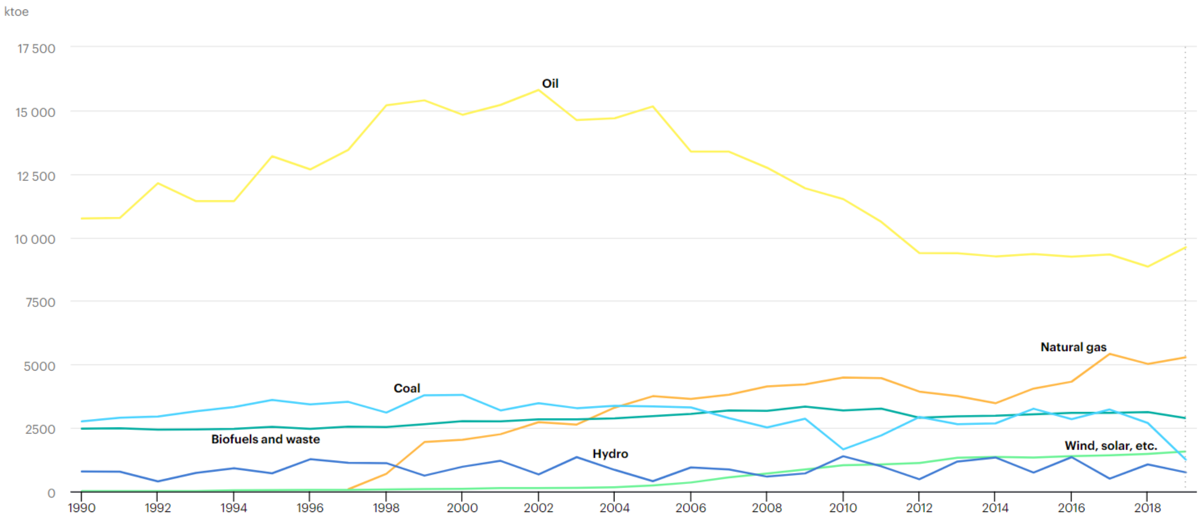

Figure 2.3: Energy supply in Portugal individually by source. Source: IEA [1].

Changing on a season by season basis, as well as on the amount of rain that falls in a particular year, hydro is stagnant, and Subsection 2.2.2 will further explain how this resource has been practically fully explored. Coal has substantially declined in the last few years due to the phase-out of coal peaker plants, some of which have even been anticipated, but oil has been the greatest success (or decline) story with total consumption declining by one third. Figure 2.3 is particularly good at evidencing the enormous decline in oil, a fact that remained somewhat hidden in plain sight inside the other images. Coming from a peak on a league all of its own, oil is now a few years away from the grasp of natural gas. Even though both these energy sources are non-renewable, the increase in diversification is commendable. Overall, renewables still only hold about 5% of the market share, therefore this decade will have to witness a major wave of investment as the goal is to increase this number by well over 1000%. The last two decades have witnessed the steady and slow increase of solar and wind, but the main energy source that has been able to significantly curb the momentum of oil and coal has been natural gas. This energy source has been eroding the market share of oil, which came down about 20%, the same 20% gas has increased from the mid-1990s. Natural gas peaker plants are also an option, and for that reason, coal will be fazed out in the coming years. Although also a non-renewable and polluting energy source, natural gas has positioned itself as a rather better option over the two other main polluting competing sources. Having said so, the same national security and independence concerns exist as Portugal fully depends on other countries to source these compounds.

Before moving onto the next subsection, it is worth studying in more detail how renewables integrate with the energy grid and how much electricity they generate by source. This can be seen in Figure 2.4.

The ebbs and flows of hydro have already been addressed, but what becomes clear is the spectacular increase in wind generation, surpassing even hydro in recent years. In contrast, Solar PV may be a better known, or even the most well known, renewable energy generation alternative but its significance is still minimal. Significant investments can be expected in the coming years, especially in this underde-

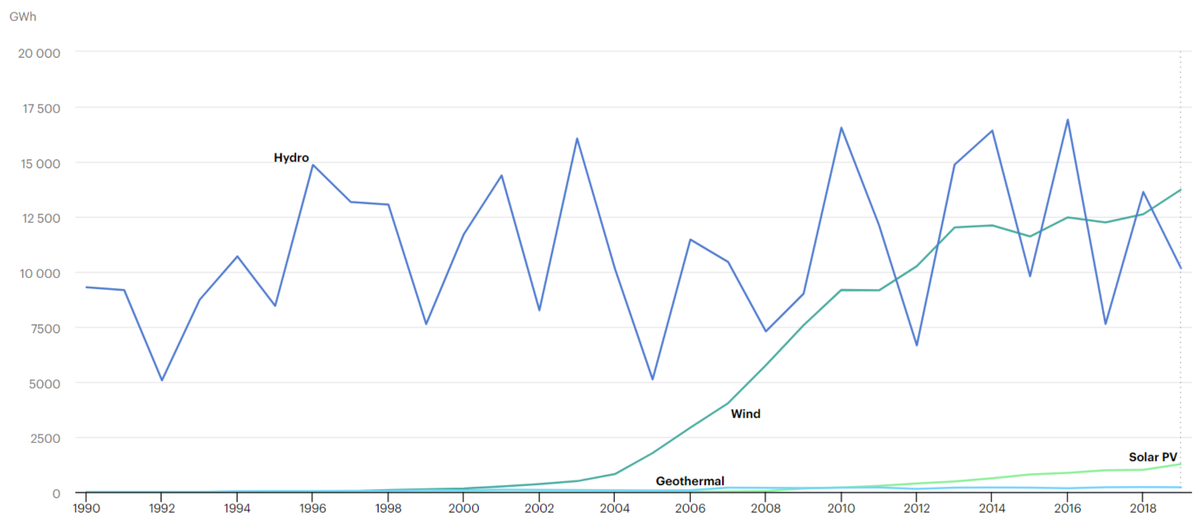

Figure 2.4: Renewable electricity generation in Portugal by source. Source: IEA [1].

veloped technology, if the pace of Spain's construction of solar PV farms is anything to go by. Electricity consumption has been levelling out at around 50 TWh of energy per year, as can be seen in Figure 3.7, and cumulatively renewables already generate consistently over 25 TWh per year and growing. A final note to geothermal energy, that as of 2019 generated 216 GWh. For any number of reasons, this technology has already been surpassed by two more recent renewable alternatives, maintaining a very local focus. Although its expression at a national level is not significant, for the Portuguese islands, paired with other energy sources, it may be more than enough, considering also how reliable it is during the whole day/year.

2.1.2 Price

Although much can be said regarding purchasing price parity (PPP), Portugal has managed to converge with its neighbours, especially on the electricity industry cost, although Italy's industrial price has spiked, that is not the subject of this dissertation. Beyond some minimal temporary variances, most EU southern countries follow the same price patterns, as can be seen in Figure 2.5.

This dissertations' analysis does not intend to be outdated, although more recent images were not freely available. Therefore, Figure 2.6 helps contextualise the missing years in what can only be concluded as price stabilisation, with a slight decline in recent years. The price follows a similar progression to the one seen in Figure 2.1.

Aside from price, each country also sets their taxes and in this subject, Portugal has over the years decided for low environmental taxation on oil and gas, but a very significant one on value-added tax (commonly referred to as VAT) and other taxes. Due to their complete foreign dependence and geographical position at the furthest point of Europe from the Middle East, Portugal also has one of the highest excluding-tax prices in Europe. All this contributes to the higher price Portugal (and Spain) have compared to Greece and France (Robson, 2020).

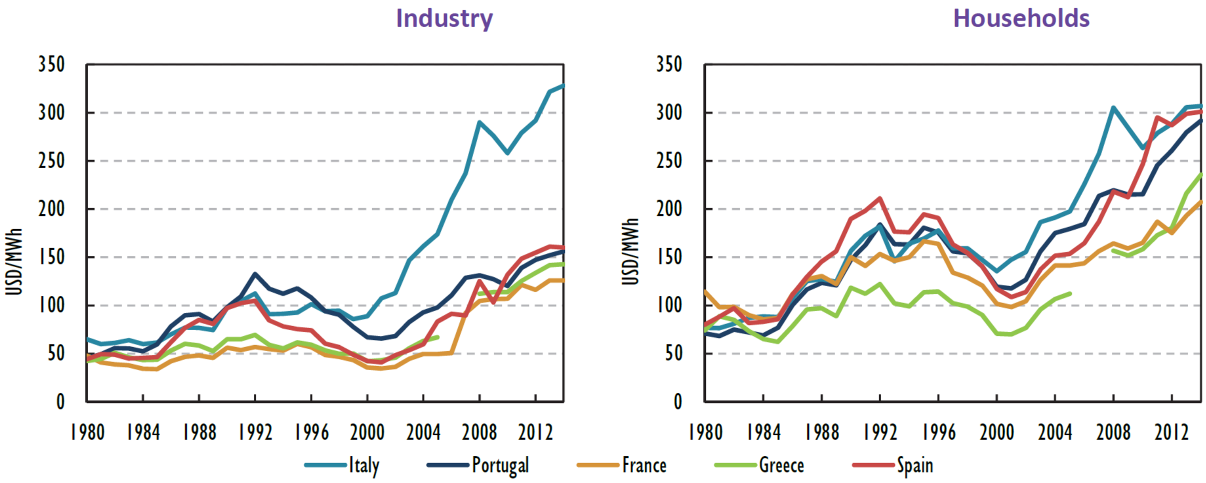

Figure 2.5: Electricity prices for the industry and household for several European countries. Source: IEA (2017).

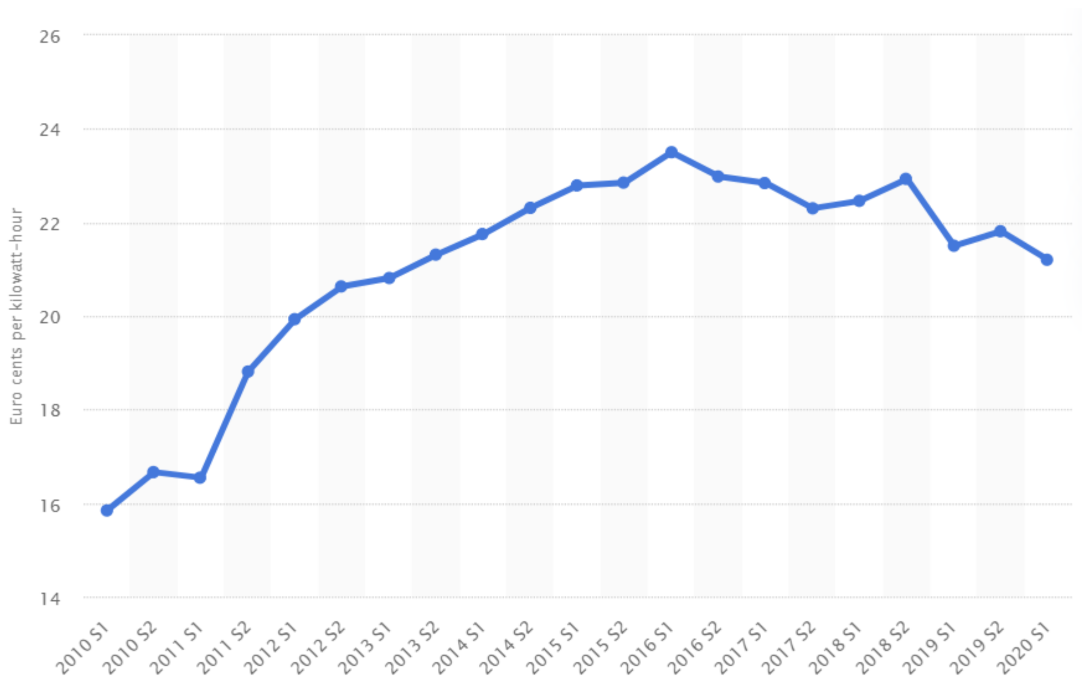

Figure 2.6: Electricity prices for households in Portugal 2010-2020, semi-annually. Source: Statista [2].

2.1.3 Exports/Imports

Portugal is a net importer of energy, as can be seen in Figure 2.7. Due to a lack of natural traditional resources (such as oil, gas or coal), renewables and (to some extent) biofuels and waste, are the only energy the country can be self-reliant on. Nuclear sources are also non-existent, one of the many reasons why this source has not been explored, although neighbouring country Spain has done so.

Figure 2.7: Energy imports and exports in Portugal. Source: IEA [1].

Besides the obvious environmental benefits renewable clean generation and storage brings, it is also very relevant on a sovereignty level that this transition occurs. Portugal, therefore, does not exist in a vacuum, the reason why it has integrated with Spain to create an Iberian wholesale market labelled Mercado Ibérico de Eletricidade (MIBEL), with further plans of integrating with France (IEA, 2017). This integration has been very beneficial for both countries as their geographies are extremely similar and prone to renewable generation due to the amount of irradiation comparing to the European average, as both are southern nations and therefore receive more Wh/m^2, making it fundamentally more efficient to construct solar power plants in these regions. Beyond the geographical reality, Portugal is in a different time zone than Spain, even though this is the only country Portugal shares a land border with. This allows for shared management of their grids from a demand perspective as when Spanish nationals wake up or come back home, the two major spikes on a daily consumption graph, Portuguese demand is still one hour away from its spikes. This shared market has increased the energy exports in recent years, although the value is still residual compared to the imports.

2.2 Setting

Now that the energy generation scenario is known, it stands to reason that the energy storage layout is detailed as well. Subsection 2.2.1 is meant to unfold how storage systems have been implemented at a global level for it to be possible to do a comparison to the Portuguese situation, in Subsection 2.2.2.

2.2.1 Worldwide

As has been stated, the transition to sustainable energy generation, storage and consumption are impossible without the parallel integration of storage systems, and many have already been installed. At a global level, the overall installed capacity is not only increasing but also accelerating, which creates an exponential, as can be seen below.

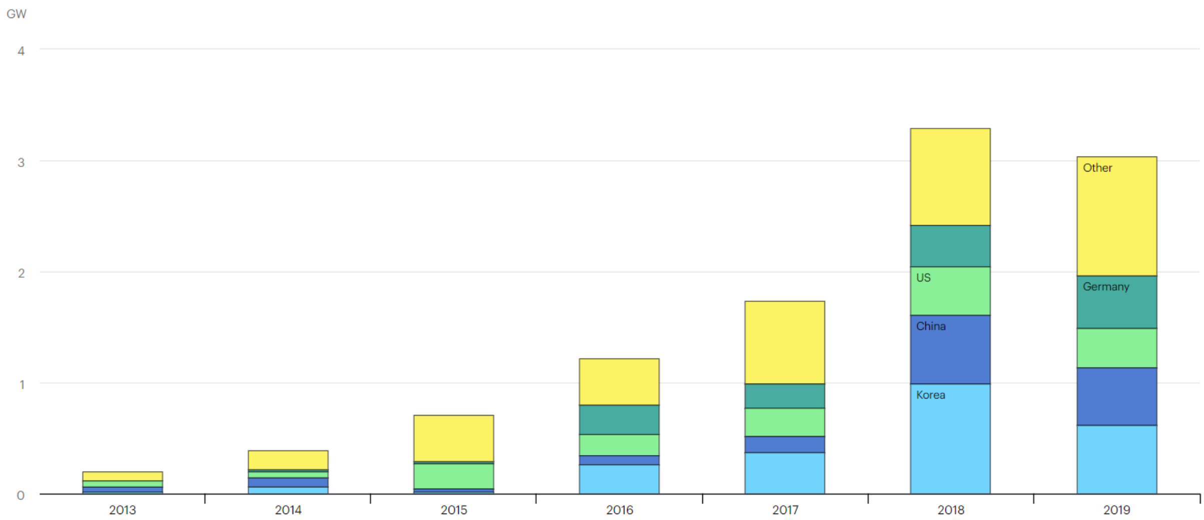

Figure 2.8: Annual energy storage deployment by country. Source: IEA (2020).

As would be expected, the largest and most developed economies on earth are leading the way either through selflessness in the fight against climate change or through pure strategic interest. Most developed nations are net importers of energy and of the four largest investors in the area, only the United States of America has recently become a net exporter of energy, which has and will continue to have plenty of global repercussions.

It is by no means a coincidence that the US, China and Germany are also some of the largest investors in renewable energy generation. Yet again, it becomes clear that both these subjects should not be viewed in a vacuum, they go hand in hand, mutually benefiting or damaging each other's growth.

2.2.2 Portugal

Portugal has for years implemented storage systems, although without much diversification. Let us now present some of the energy storage systems installed in Portugal, with the help of the Sandia National Laboratories database [3], which has almost the entire world's energy storage installations. Among others: Flores (Azores) PowerStore Flywheel Project, Graciosa (Azores) PowerStore Flywheel Project, Graciosa (Azores) Project (Lithium-ion), PVCROPS Évora Demonstration Flow Battery Project, Alto Rabagão Hydro Power Plant, Vilarinho Furnas Pumped Hydro Station, Aguieira Hydro Power Station, Torrão Pumped Storage Power Plant, Salamonde II Pumped Hydro Station, Alqueva Pumped Hydro Storage Power Plant, Frades I Pumped Hydro Station, Frades II Pumped Hydro Station, Baixo Sabor Montante

[3] https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/

Pumped Hydro Station, Baixo Sabor Jusante Pumped Hydro Station, Venda Nova III Pumped Hydro Station, Foz Tua Pumped Hydro Station (Ferrão et al., 2021).

A clear pattern has started to emerge as 99% of Portugal's storage capacity is from Pumped Hydro Stations. The country has several rivers and has invested in the control of its water flow. Mainland Portugal has created, with pros and cons, a very complete set of hydro plants that have reduced for quite some time interest in alternative storage options. There are so many hydro storage solutions that hydropower is itself considered an energy generation technology. The main Madeira island has also invested in hydropower as its geography allows it.

It may be relevant to point out that although hydroelectric generation is commonly referred to as an energy source, this dissertation is considering it as a storage solution as it fits into every possible definition of what a storage system is. It is only logical, natural and healthy that, eventually, a greater number of storage solutions will be universally considered a source, cementing and further highlighting the importance these technologies have.

In contrast, due to their geographic limitations, the Azores islands have had to become more creative and experimental in their search for grid autonomy and self-reliance, experimenting initially with two flywheels in two different islands. Even a Lithium-ion project has recently been installed in one of the flywheel islands.

The only exception to these major trends has been the installation of PVCROPS Évora Demonstration Flow Battery Project, a system that was implemented within a European project, which indicates that there is interest in the implementation of further storage systems, even in the mainland (Fialho, 2019).

2.3 Summary

In this chapter, it was possible to understand the background of the energy consumption and storage reality in Portugal over the last few decades, as well as understanding the near and long term future objectives of the nation. These macro forces have been the major contributors to the recent shifts in the energy consumption market shares and will continue to play a very significant role in the years to come. These trends will be taken into account in the upcoming Chapter 4 and Chapter 5.

Chapter 3

Literature review

Before the creation of the model, it is necessary to fully understand the energy storage market, its needs, and specificities. Therefore, the characterisation of the several sectors that make up the energy storage market will be done in Section 3.1, and in another section, the major actions/technologies currently available will be presented in Section 3.2. Section 3.1 is to have a listing in the form of several subsections to further contextualise the categories in analysis, as will the Section 3.2, but in this case, it will be a condensed description of the technologies chosen for evaluation.

3.1 Energy storage sectors

Essentially, two clients have an interest in acquiring energy storage solutions - grid providers and individuals.

It is considered that the purchase of a car, a truck or any other regular means of transportation can be loosely included in the individual clients grouping, as in the end, it will have to come from an individual or a company (which is a group of individuals) the decision to acquire the transport that happens to have a storage system integrated. The line gets blurry when individuals or companies decide to create their microgrids, becoming their grid provider even if only at times, but this will be accounted for.

Considering the general potential locations and applications of the electricity stored in the power system, we have: balancing storage, bulk storage, distributed storage, residential storage, thermal storage, commercial storage and the possible development of the vehicle to grid (V2G) capabilities (IRENA, 2017). It is now necessary to aggregate the service sector of the energy storage market according to this binary view over the value chain.

At the grid level, four sectors are commonly identified in the literature (Eyer & Corey, 2011; IRENA, 2017):

Sector 1 ELECTRIC SUPPLY/BULK ENERGY SERVICES;

Sector 2 ANCILLARY SERVICES;

Sector 3 GRID SYSTEM;

Sector 4 RENEWABLE INTEGRATION.

All these systems and services are located at the intersections between the locations where energy is produced and transmitted, and where energy stops being transmitted and finally starts being distributed at a local, more granular, level. First, ELECTRIC SUPPLY/BULK ENERGY SERVICES regard two of the main uses of battery storage: the control of the amount of energy available and the cost being paid for that energy by the end-user. Second, ANCILLARY SERVICES is a broad term encasing all coordination and scheduling services (load following, energy imbalance service, and control of transmission congestion), automatic generation control (load frequency control and the economic dispatch of plants), contractual agreements (loss compensation service), and support of system integrity and security (reactive power, or spinning and operating reserves). Third, the GRID SYSTEM envelopes services related to the transmission and distribution of energy. Fourth, and finally, RENEWABLE INTEGRATION covers all requirements by solar, wind and all other forms of renewable storage that, when connected to the grid, demand a balance of the output provided by these sources.

Of all these necessities and locations, what most differentiates the demand and supply is the time frame at which the energy is obtained and required, especially in a renewable sourced based world. Some of it can be used immediately while some other variable amount would have to be wasted if not required. Therefore a very significant rift occurs between short and long term energy storage.

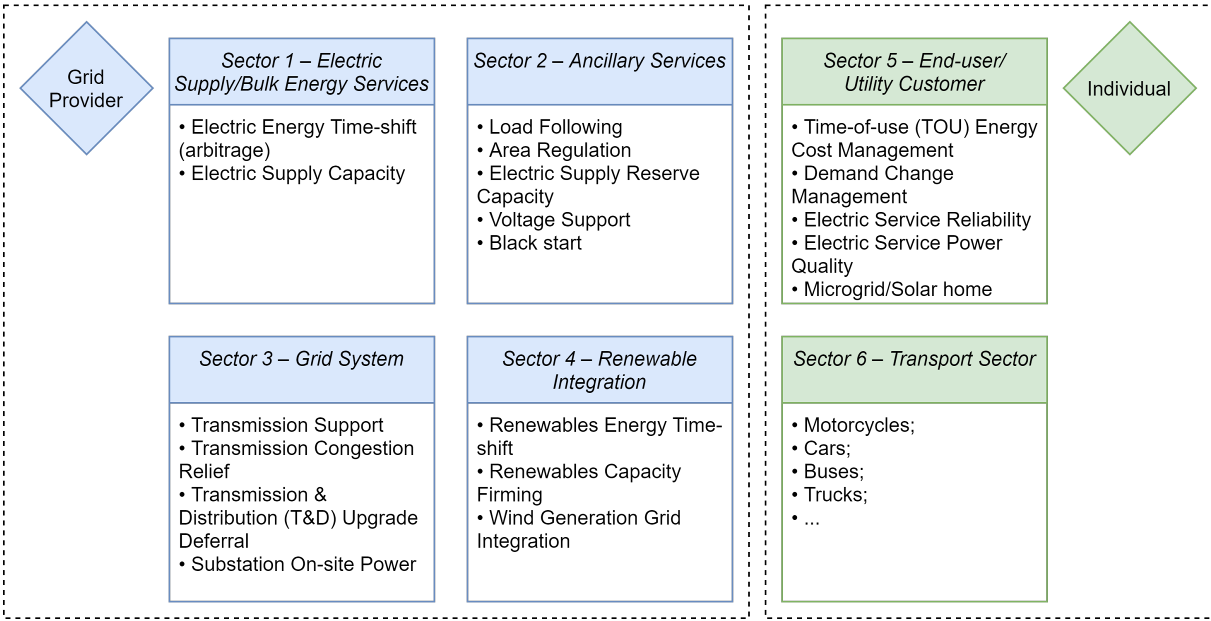

Figure 3.1: Macroscopic view of the energy storage market sectors.

At a more particular level, individuals relate to energy in two fundamental ways: at home/work or via transportation. Thus, two very distinct sectors emerge (Eyer & Corey, 2011; IRENA, 2017):

Sector 5 END-USER/UTILITY CUSTOMER;

Sector 6 TRANSPORT SECTOR.

The fifth sector allows businesses and homeowners to install their power generation solutions and/or implement in parallel energy storage solutions to control any number of variables, and the sixth encases every major means of transportation such as cars, buses, and trucks. The END-USER/UTILITY CUSTOMER sector implements storage solutions to decrease the energy bill paid to the utility company by buying energy from the grid only when power is cheaper, as well as to ensure the quality of the energy reaching the building to never experience a power surge or blackout. At some point, with enough energy generation and storage, a microgrid can be established, completely disconnecting a building from the grid.

A macroscopic analysis of the several sectors where energy storage solutions are required reveals a clear contrast between the grid provider and the individual scale, as is shown in Figure 3.1. If on the one hand the grid provider can be analysed as a sector divided by the time frame of storage, on the other hand, the individual's sectors are more specific in different ways. The END-USER/UTILITY CUSTOMER does not have the same space available as the grid provider, nor do they have the same energy requirements. The storage systems, besides the size, are required to have a much broader range of capabilities as not all kinds of speciality storage systems can be implemented in parallel. Finally, the TRANSPORT SECTOR has an even greater additional layer of constraints and requirements due to extreme spatial requirements, heat restrictions, toxicity hazards, performance demands and many more.

Therefore, it is proposed that four categories are chosen from the six market sectors:

Category 1 Grid Provider - Short Term Duration;

Category 2 Grid Provider - Long Term Duration;

Category 3 Individual - Microgrid;

Category 4 Individual - Mobility.

Now that the sectors have been rationally categorised, it is relevant to evaluate how meaningful each other is. Much like in Subsection 2.1.1, IEA's website on Portugal has revealed itself as a most useful source of up to date and relevant information.

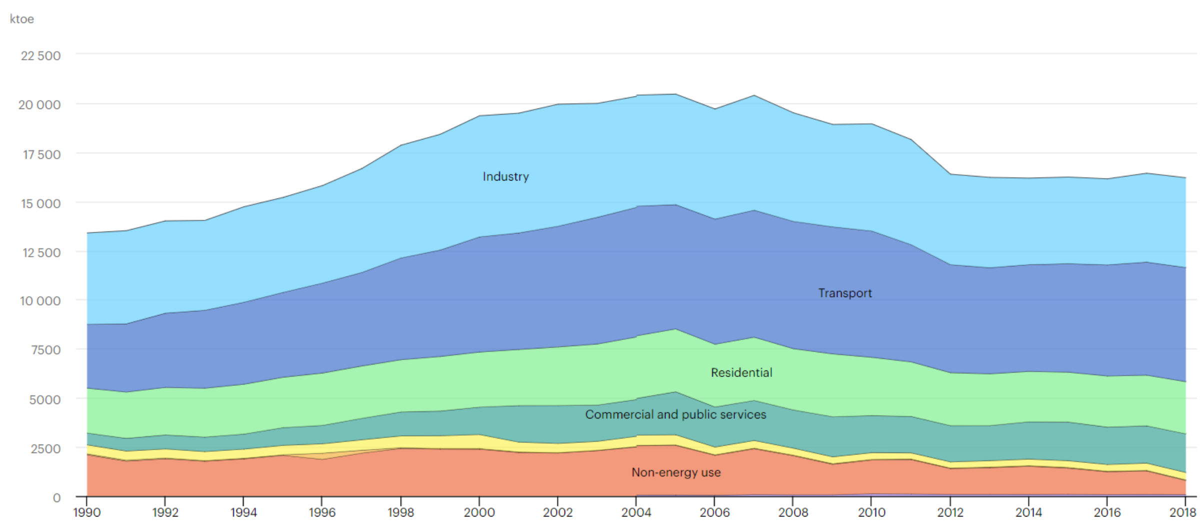

Figure 3.2: Aggregate total final consumption (TFC) by sector in Portugal. Source: IEA [1].

The industry and the transport sectors immediately stand out in Figure 3.2 as the two major sources of energy consumption. From the highs in 2005, Portugal has managed to lower, and stabilise, the consumption levels at around 16000 ktoe, or about 186 TWh, per year.

The transport sector has had a massive increase due to the number of cars on the roads as more and more people were able and managed to buy cars ever since Portugal joined the EU in 1986, although the financial crisis in the mid-2010s has managed to keep stable, much like what happened to the residential consumption. Non-energy uses have experienced a significant decline right about the same time, being overtaken by the ever-increasing commercial and public services sector. Agriculture/forestry, fishing and non-specified uses of energy have remained low or even negligible.

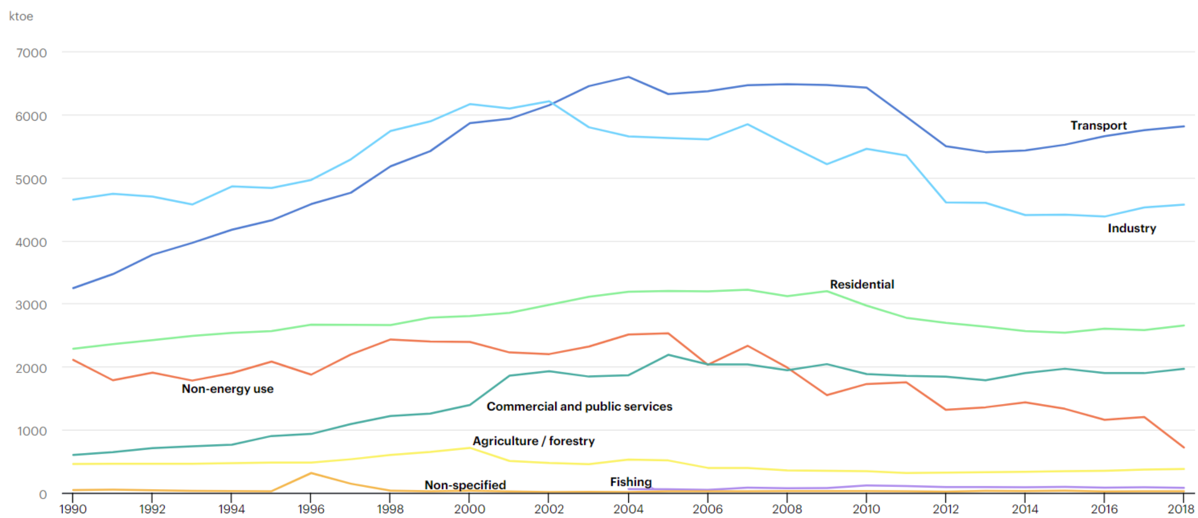

Figure 3.3: TFC individually by sector in Portugal. Source: IEA [1].

All these values must have had major shifts in 2020 onward, due to the COVID-19 pandemic. Residential consumption must have substantially increased, with a similar decline in the transport sector as people remained at home for significant parts of the year. This must have challenged not only the distribution networks of raw energy sources but also the grid, on a geographical level and on the inability of predicting demand, resulting from the never-seen lock-downs.

3.1.1 Category 1 - Short Term Grid

The grid provider has, unsurprisingly, not appeared in any of the previous graphs (Figure 3.2 and Figure 3.3), since the grid provider is not an end in itself. Certainly managing the grid requires a non-zero amount of energy, but it simply serves as an arbiter of who gets how much and when.

The grid provider has, at present, as one of its many responsibilities the prediction of demand. Although impossible in theory, as no one can predict when someone will turn on or switch off a light (or an entire building), studying the past and the cycles in human behaviour, working out averages or even creating neural networks that see patterns better than people ever could, provides the requirements to make it all work out (Rodrigues, Cardeira, & Calado, 2014).

Now, it is relevant to see how the power consumption shifts during the day in Figure 3.4.

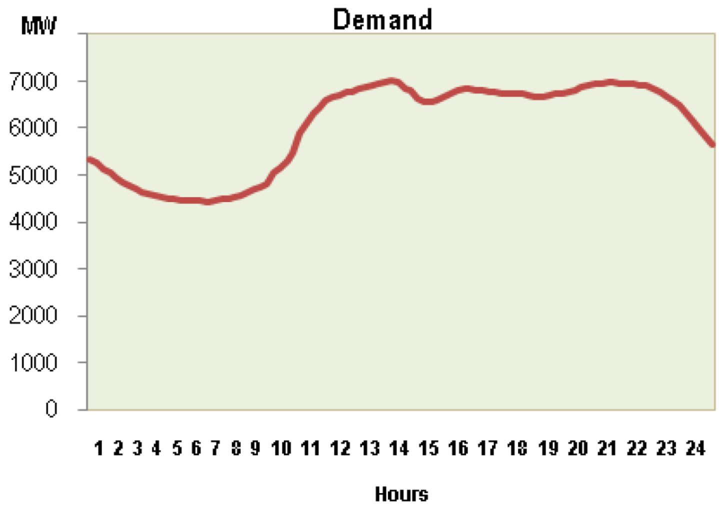

Figure 3.4: Hourly average power consumption in Portugal. Source: Camus et al. (2011).

Much time should not be spent discussing the y-axis, as this graph refers to averages taken from the four different seasons in 2008 and is here in a purely illustrative capacity. Very broadly speaking, two plateaus can be seen in the figure, one baseline around the 4000 MW that crosses the entire day, and a second baseline, much more variable, that delineates the maximum power required from the 11-hour mark to the 22-hour mark. It is possible to see how the demand significantly increases as people wake up, and decreases more smoothly as they go to sleep. This is the bulk of the problem grid providers face every day, demand that has to be met exactly as required, no more, no less, or outages begin to appear.

3.1.2 Category 2 - Long Term Grid

If energy generation and consumption change during the day, such a phenomenon also occurs on a broader scale. Due to irradiation changes, temperature and weather patterns vary leading to shifts in human behaviour such as activating heat or cold sources.

The variances in demand have to be accounted for and provided, creating a demand for energy storage that needs to be accessed on a much different time scale than that of the short term storage, which acts on an hourly timescale.

As can be seen in Figure 3.5, electricity consumption does change as was predictable. If the objective is to phase out non-renewable energy sources, an alternative to hydro and wind must be attained for the whole year and from year to year. Energy must therefore be stored from years with high availability to the ones that require the greater use of fossil fuels.

3.1.3 Category 3 - Microgrid

Picking up right where Subsection 3.1.1 left off, demand changes during the day and it is especially dependent on human behaviour and movement. Starting immediately with the example of the average household, it is clear to see how demand is not as linear as it may have appeared in Figure 3.4.

Figure 3.6 immediately shows the very distinct peaks in consumption a house has during the day.

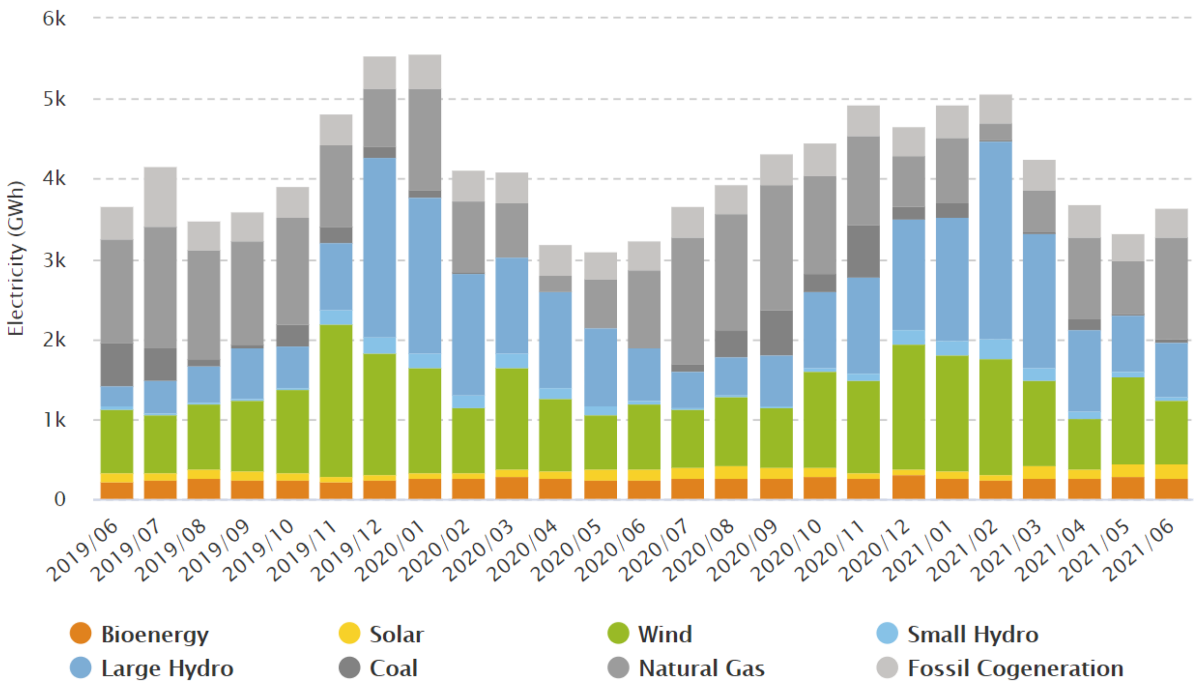

Figure 3.5: Electricity generation by source (June 2019 to June 2021). Source: APREN [3].

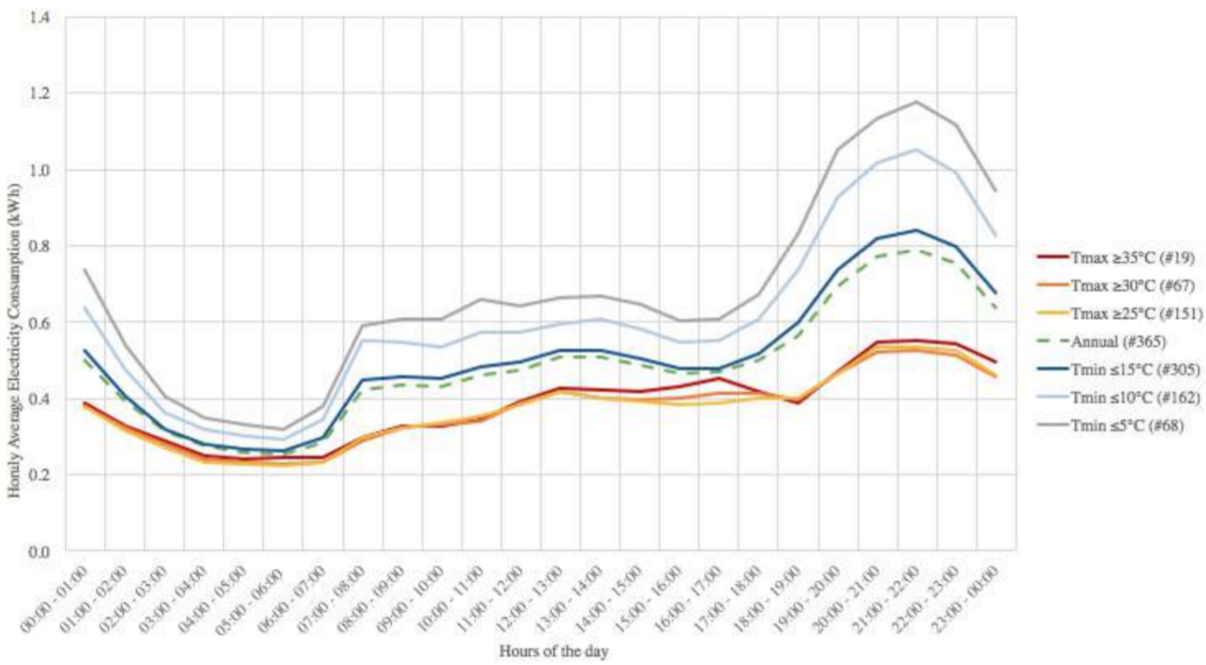

Figure 3.6: Hourly average power consumption in Portugal. Source: Gouveia (2017).

The work being referenced also clearly defines how these values change, depending on the outside temperature due to, especially, heating (Gouveia, 2017).

If the demand shifts from a house are so significant, it can be logically extrapolated that so too will the individual demands from the industry, transport and commercial sectors. Whereas the average household consumption peaks when people arrive home, with a significant increase, up to the daily baseline, as people wake up, the commercial and industrial sector should have a very significant high baseline during the normal working hours, so that the highs and lows conform to the expected average demand from Figure 3.4.

In conclusion, average demand is a very broad way to look at the shifting demand on a local level, as demand follows the movement of people. Knowing this, individuals and firms may decide to install some energy storage (and generation) solutions, creating their local grids. This in turn could potentially have major repercussions outside the local level as the average demand expected by the grid providers could be significantly altered, in time. It is now that one caveat must be added before the dissertation moves along as is - the grid provider is an essential service as long as millions or thousands of people rely on it. This is necessary to point out because in the advent of renewable energy, in symbiosis with energy storage, it does not need to be the case. In the limit, if everyone wanted to, they could become their microgrids and that is the reason why it is so important to consider this category. Although it may be refreshing for some to think of a self-reliant life, this must not need to be the ideal solution. Decentralised storage systems could work with the grid if the proposition was to be mutually beneficial.

3.1.4 Category 4 - Mobility

It has already become clear that energy is consumed essentially by people as they go about their day and that the transportation sector is one of the most energy-intensive sectors. Despite this and the fact that the average vehicle is an avid energy consumption machine, as of now cars, bikes, trucks and many more do not burden the electrical grid, or any kind of grid for that matter, besides the distribution network of fossil fuels. As everyone knows, this may be about to change. Currently, vehicles transport all kinds of fuels, and that may still be the case in the future, although energy sources like hydrogen can be transported in adapted gas grids.

Valley filling, peak shaving and load shifting are common demand response strategies, but if one adds the additional stress of an all-electric car sector to the equation, the situation becomes more challenging. According to INE/Pordata [1], there are slightly less than 7 million light vehicles on the road and there are slightly over 100 thousand heavy vehicles. If one assumes, for purely academic curiosity, that all light cars instantly change to electric ones, with an average capacity of 80 kWh considering the battery would be able to perform for 400 km and that the average car user drives for 9000 km during a full year, the additional strain on the electric grid would be of about 12.6 MW/year, for lightweight cars alone (ACP, 2018). This is not even taking into account the 10 to 15% energy loss in the charging process, depending on a large number of factors. It is a very rough estimate, but it is quite illustrative (Camus et al., 2011):

[1] https://www.pordata.pt/en/Portugal/Motor+vehicles+in+circulation+total+and+by+type+of+vehicle-3100

$$7000000 \times 9000\,[km] \times \frac{80\,[kWh]}{400\,[km]} \times 1.15 = 14.53\,TWh \quad (3.1)$$

Continuing with this supposition, it is worth acknowledging, that although it does not appear very significant in the overall consumption from Figure 3.2, it is worth contextualising in the electricity grid. As can be seen below in Figure 3.7, an increase of well over 12 TWh would require an increase of about 25% in electrical consumption. The grid has already doubled in energy transported in the last 3 decades, for this further scaling is far from impossible, nevertheless, it would require some improvements. A certain group of people may point to this increase in electricity consumption as a deciding factor that the bulk of the transportation sector can not transition to new forms of consumption, but it should be noted that all this electricity demand is already being consumed in extremely low-efficiency engines, therefore this is not a matter of lack of energy, it is a question of structural changes in how and where this energy is produced, distributed and consumed.

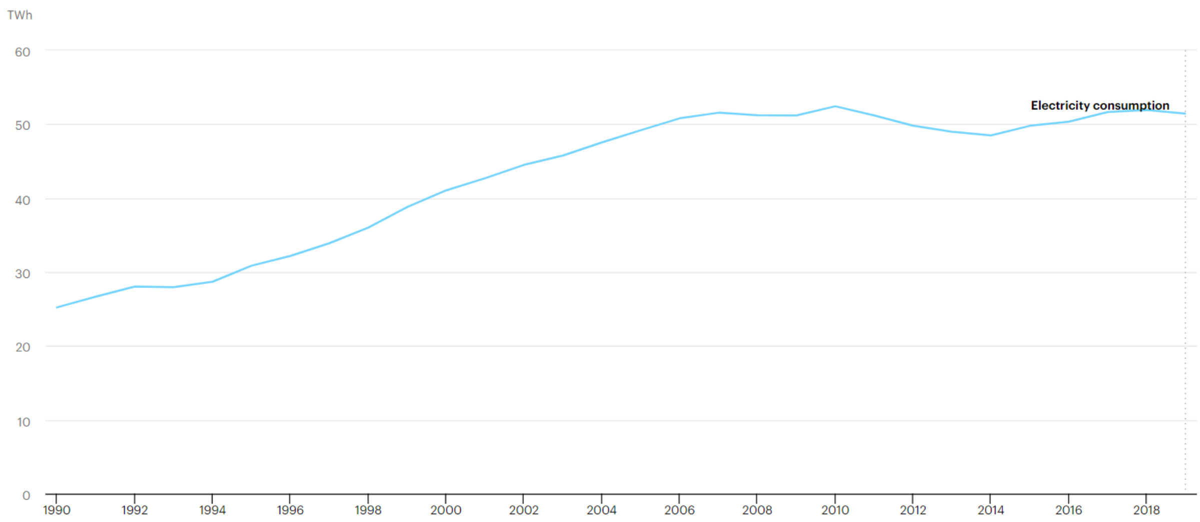

Figure 3.7: Electricity consumption in Portugal. Source: IEA [1].

It is now well established that the transportation sector's transition will imply a noteworthy amount of energy and structure reform, either electrical or through a hydrogen network. If it so happens to be hydrogen who wins, significant changes would be required in the infrastructure but would be business as usual for the consumers who would continue to go to a gas station. If it happens to be the electrical options, new challenges and opportunities emerge as can be seen in Figure 3.8.

According to the literature, 85% of electric car charging occurs when people get home. This would mean a quite non-optimal situation for the grid, but extremely convenient for the consumer, as can be seen in Figure 3.8. Besides the overwhelming demand spike, it would come at a time when the Sun, one of the potential major sources of renewable energy, was on its way out. This would potentially require a change in incentives. If one wants to create a much more linear demand, optimal for the grid, one should consider Figure 3.9.

Creating a more flexible pricing scheme, either through a fluid or intraday/off-hours tariff, should be enough to create these incentives that could very easily be programmed into the vehicles.

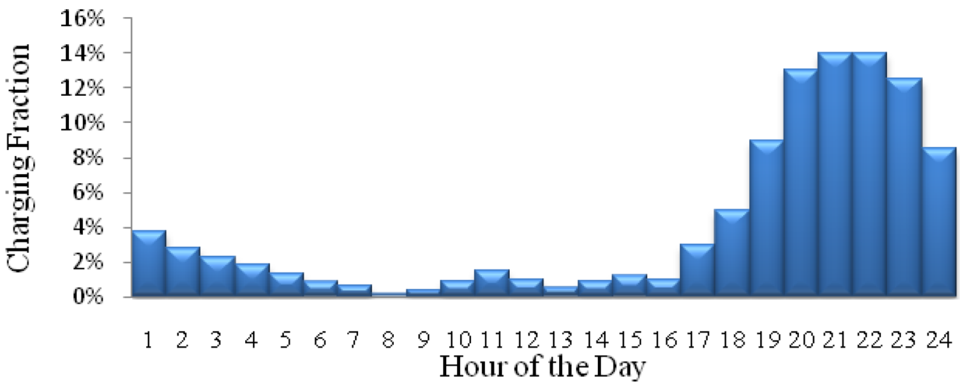

Figure 3.8: Expected charging profile for uncontrolled charging scenario. Source: Camus et al. (2011).

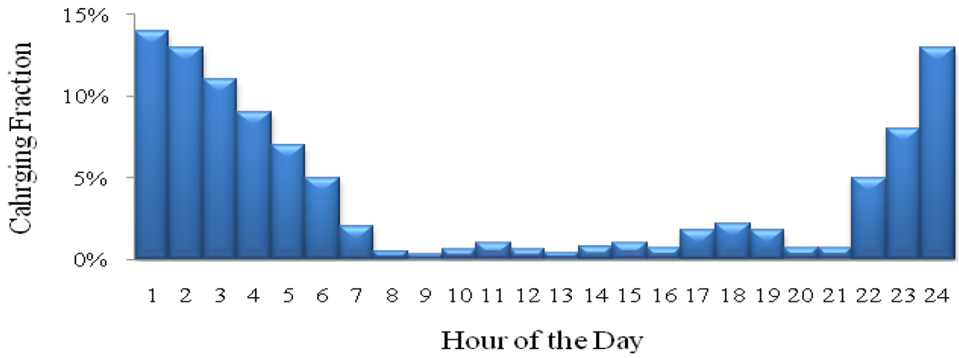

Figure 3.9: Expected charging profile for a smoothing off-peak charging scenario. Source: Camus et al. (2011).

One possible problem subsists, the fact that the Sun does not shine during the whole day. On that topic, some solutions are possible, either through the use of other forms of energy at specific times of the day, intraday incentives, among others. That would become a topic for the grid providers, or microgrid managers, to decide what best suits them.

3.2 Actions/Technologies

In the previous section, several sectors of the energy storage market were identified and described. In this subsection, the technological solutions to solve those problems will be presented. Indeed, there is a vast set of options from which to choose as evaluated in the database of the European energy storage technologies and facilities [2]:

Mechanical storage:

– Pumping Hydro storage (PHS);

– Pumped Heat electrical storage (PHES);

– Adiabatic Compressed Air energy storage (ACAES);

[2] https://data.europa.eu/euodp/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities/resource/0b44e8b4-bd9c-417d-b736-f22439a5ae4d

- Compressed Air energy storage (CAES);
- Liquid Air energy storage (LAES);
- Flywheel;

Electrical storage:

- Superconducting Magnetic energy storage (SMES);
- Supercapacitor;

Electrochemical storage:

- Sodium Sulphur (NaS) batteries;
- Lead acid batteries;
- Sodium Nickel Chloride ($NaNiCl_2$) batteries;
- Lithium-ion (LiIon) batteries;
- Nickel-Cadmium (NiCd) batteries;
- Nickel-Metal Hydride (NiMH) batteries;
- Vanadium redox flow (VRF) batteries;
- Zinc Bromine redox flow (ZnBr RF) batteries;

Chemical storage:

- Power to Gas - Hydrogen (H_2);
- Power to Ammonia;
- Power to Methane;
- Power to Methanol;
- Power to Gasoline;

Thermal storage:

- Molten salts;
- Hot water;
- Phase Change Materials (PCM);
- Thermochemical storage (TCS).

Portugal has heavily invested in renewable energy in recent years, seizing the opportunities of its geography by creating several wind farms. Fossil fuel installations have even started to be decommissioned and made obsolete, in parallel to the creation of an incentive structure at the European Union and national levels towards the adoption of non-gas vehicles, most of which up until now have been electric vehicles (EVs).

Regarding storage solutions, as has been discussed, the whole mainland area of the country is essentially supported by mechanical storage via pumping water in dams. Besides dams, there are also a few experimental installations throughout the country, especially in the Azores, as seen in Subsection 2.2.2. In essence, however, the grid is still being managed by fossil fuels, such as natural gas and oil.

The following subsections are meant to briefly introduce several technologies regarding some of their most significant characteristics. It is intended to create a model in Chapter 4 that allows for a greater number of technologies to be easily incorporated in the evaluation process, making it independent of the options currently available. At the end of all these subsections, the sources for the understanding and all the data extracted and used in this dissertation will be cited.

3.2.1 Mechanical Storage

Every form of storage that accumulates energy in the kinetic and potential form is engulfed in this storage type. The extraction format usually uses the spinning of a turbine or motor.

3.2.1.1 Pumping Hydro storage

One of the most well known and ancient forms of energy storage, PHS uses the height differential of a water reserve to spin a turbine and thus, create energy. Due to its time in the market, the technology is as mature as it gets, with good efficiency and long storage and discharge duration, but very significant cost because of the size of the installations. Being available for so much time, it has proliferated across most nations with the capabilities and the natural and geographical resources to construct it. Major plans are still in development across the world, despite the damage it causes down and upstream, as nations try to control their water supply, which has created some friction among neighbouring countries, even within with dislocated communities, and significantly increase their energy generation/storage capabilities. Portugal has heavily invested in a similar technology for decades, through dams. The energy density is quite low, with the efficiency not stellar as well, but the degradation is low. Power can be outputted for several hours, although the charging and discharging may also take some time.

The database of the European energy storage technologies and facilities [3], the European Association for Storage of Energy [4] and the works of Rehman, Al-Hadhrami, and Alam (2015) and Khawaja, Alkhalidi, and Mansour (2019) were used to extract data regarding PHS and substantiate the knowledge on this technology.

3.2.1.2 Pumped Heat electrical storage

If PHS meant the physical pumping of water, PHES relates to pumping of the energy of gas up and down a typical Carnot cycle. Considering the charging phase, argon, or some other inert gas, starts at ambient pressure and temperature. As is expected from the typical Carnot cycle, the gas is then

[3] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[4] https://ease-storage.eu/energy-storage/technologies/

compressed and heated up. As it is heated, the gas rises moving into an intermediate store while cooling but maintaining pressure. The gas can now be expanded back to ambient pressure and starting from ambient temperature reaches as low as -160º C. It can now move into another intermediate store where the temperature rises back to ambient levels, just like at the beginning of the process. Discharging is a similar process that follows the opposite movement across the Carnot cycle. Several sections are therefore required, one cold and another hot storage with two intermediate storages and one expander and compressor that connect both storages with an additional motor/generator, where the energy is inserted or extracted from the system. Argon is a much better material than air for the increases and decreases in pressure and volume, as it is an inert monoatomic gas. This technology is still in early development, with some similar characteristics to PHS but results show a significantly higher energy density, lower costs and no significant environmental impact.

The database of the European energy storage technologies and facilities [5], the European Association for Storage of Energy [6] and the works of Smallbone, Jülch, Wardle, and Roskilly (2017), Roskosch and Atakan (2017) and Khawaja et al. (2019) were used to extract data regarding PHES and substantiate the knowledge on this technology.

3.2.1.3 Adiabatic Compressed Air energy storage

With a few operational installations between the US and the EU, a great amount of capacity has already been installed using the ACAES technology. In this process, the air is pumped into a compressor with the use of a motor and finally stored, similar but different from PHS. The heat is also stored in a separate chamber to make the process adiabatic, or rather as much as possible, to keep efficiency high. While discharging, the heat will then be used in the heat exchanger, with the air going through the turbine that will load a generator, extracting energy from the system. This technology has already been proven, although it is not as mature as PHS. Some reservoir alternatives are available, with very dissimilar costs.

The database of the European energy storage technologies and facilities [7], the European Association for Storage of Energy [8] and the works of Sabihuddin, Kiprakis, and Mueller (2015), Helsingen (2015), Zhou, Du, Lu, He, and Liu (2019) and Khawaja et al. (2019) were used to extract data regarding ACAES and substantiate the knowledge on this technology.

3.2.1.4 Compressed Air energy storage

CAES is a simpler variation on the ACAES process, with lower efficiencies, and cost, as the adiabatic process is not accomplished as the heat is not stored. The air is still inserted and compressed into the system, but before running through the turbine, it requires fuel in a combustion chamber, because the heat was not stored in a separate chamber.

[5] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[6] https://ease-storage.eu/energy-storage/technologies/

[7] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[8] https://ease-storage.eu/energy-storage/technologies/

The database of the European energy storage technologies and facilities [9], the European Association for Storage of Energy [10] and the works of Sabihuddin et al. (2015), Helsingen (2015), Budt, Wolf, Span, and Yan (2016) and Khawaja et al. (2019) were used to extract data regarding CAES and substantiate the knowledge on this technology.

3.2.1.5 Liquid Air energy storage

LAES is a greater variation on the ACAES process, storing the air in liquid form. As is said in the name, the air is liquefied before being stored, and after the compression. Extracting the liquid air from storage requires a pump and it is then evaporated, where cold air can be separately stored for a future liquefaction process, and then expanded, with the heat optionally stored from the compression process. This format is slightly more experimental than the two compressed air technologies.

For all these air technologies, efficiency is most significantly lost due to heat dissipation, making them lose a negligible amount of energy daily according to most sources, although others put out values around 10%.

The database of the European energy storage technologies and facilities [11], the European Association for Storage of Energy [12] and the works of Borri, Tafone, Romagnoli, and Comodi (2021) and Khawaja et al. (2019) were used to extract data regarding LAES and substantiate the knowledge on this technology.

3.2.1.6 Flywheel

Any technology's daily self-discharge value pales in comparison to the flywheel. The process is as simple as storing energy in the angular momentum of a spinning object/contraption, that naturally requires a rotor and housing for the equipment. Even though the technology is implemented mostly in an experimental way, storing energy in a rolling weight is fundamentally inefficient in the medium term. Nevertheless, it could fulfil quick loading and unloading functionalities, even though this is not the fastest response technology in the market. Despite having extremely high discharge rates, flywheels do have a surprisingly high cycle life, which nevertheless is unable to compensate for the high energy degradation of the devices. Two Azores islands have installed one flywheel each, experimentally.

The database of the European energy storage technologies and facilities [13] and the works of Sabihuddin et al. (2015), Cansiz (2018), Herbener (2011), Gao (2015), Aly, Kassem, Sayed, and Aboelhassan (2019), (Amiryar & Pullen, 2017) and Khawaja et al. (2019) were used to extract data regarding Flywheel and substantiate the knowledge on this technology.

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[9] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[10] https://ease-storage.eu/energy-storage/technologies/

[11] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[12] https://ease-storage.eu/energy-storage/technologies/

[13] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

3.2.2 Electrical storage

Electrical storage is the accumulation of energy in an electromagnetic field, with the two main examples being SMES and Supercapacitors.

3.2.2.1 Superconducting Magnetic energy storage

Once beyond the critical temperature, at cryogenic levels, SMES stores energy in the magnetic field, generated by a direct current in a superconducting coil. Energy can be extracted by discharging the coil, but the temperature must be kept below the critical level. This system is extremely fast and efficient, but maintaining the temperature level requires some energy. These devices tend to be quite small while having some energy density. The technology is also being experimented upon.

The database of the European energy storage technologies and facilities [14], the European Association for Storage of Energy [15] and the works of Cansiz (2018), Vulusala G and Madichetty (2018) and Khawaja et al. (2019) were used to extract data regarding SMES and substantiate the knowledge on this technology.

3.2.2.2 Supercapacitor

Essentially consists of two electrode walls, separated by a membrane permeable to ions. These ions are loaded and unloaded through voltage differentials across the gap. Additionally, a Helmholtz double layer is placed between the polarised electrode walls and the electrolyte with positively or negatively charged ions. Although the technology is still in development, it shows fast discharges and response time, as well as some energy loss daily and high efficiency, in contrast with its size, with the ability to potentially have an extremely high cycle life.

The database of the European energy storage technologies and facilities [16], the European Association for Storage of Energy [17] and the works of Cansiz (2018), Drew (2009), González, Goikolea, Barrena, and Mysyk (2016) and Khawaja et al. (2019) were used to extract data regarding Supercapacitor and substantiate the knowledge on this technology.

3.2.3 Electrochemical storage

A variety of technologies insert themselves in this big tent. Primary and secondary battery solutions are the two technology branches, that consist of storing energy in the active materials, converting them via an oxidation-reduction reaction to extract the electrical energy. Primary batteries, although very interesting on the statistical sheet, are one use only and for that reason can not be considered a long term solution for any of our categories. Secondary batteries can be recharged via an external electric source, although this process can not be performed *ad eternum*, therefore they will fill in the space

[14] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities
[15] https://ease-storage.eu/energy-storage/technologies/
[16] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities
[17] https://ease-storage.eu/energy-storage/technologies/

with their very wide range of options. The basic principle of operation for all these batteries is the same, electrochemical charge and discharge reactions are performed between a positive electrode - the anode - and a negative one - the cathode, with an intermediary medium either a membrane or an electrolyte. The fundamental difference from one battery to the next is the physical atoms and molecules that make up these three main components, or like it is usually referred to, the chemical composition.

3.2.3.1 Sodium Sulphur batteries

In the case of the NaS batteries, the chemical composition imposes a working temperature of over 300º C, to keep the electrodes melted. In this case, sulphur (S) makes the cathode, while sodium (Na) makes the anode. In the middle, there is a solid ceramic that allows positively charged ions to pass through and outside the battery independent heaters are required to keep the temperature. Efficiency is good, but energy is also needed to maintain the high temperature. The technology is widely available with good discharge duration and fast reaction, but improvements to the cycle life are still being tested. Currently, this battery type is only researched and used for grid systems even though it did start being researched for unsuccessful vehicle applications.

The database of the European energy storage technologies and facilities [18], the European Association for Storage of Energy [19] and the works of Sabihuddin et al. (2015), Holze (2009), Sudworth (1984) and Khawaja et al. (2019) were used to extract data regarding NaS and substantiate the knowledge on this technology.

3.2.3.2 Lead acid batteries

Knowing the process, now only an update on the chemicals is required. One of the electrodes is composed of lead dioxide (PbO_2) while the other electrode is made of lead (Pb). These two electrodes are submerged in an electrolyte of aqueous sulphuric acid. The battery does not have a long life duration due to the degradation of the components, but during its life, it can quickly react to stimulus, for up to several hours. Being a technology in use for many decades, it does have a low cost. Furthermore, improvements to the lack of energy density and capacity are in progress, while the degradation is also being addressed. Although this battery is used in cars, due to the less than desired energy density it can only be used in hybrid systems for the start-stop functionalities. Unless some unexpected breakthroughs are made, this chemistry will not be able to expand this use.

The database of the European energy storage technologies and facilities [20], the European Association for Storage of Energy [21] and the works of Sabihuddin et al. (2015), Garche, Moseley, and Karden (2015), Yang et al. (2017) and Khawaja et al. (2019) were used to extract data regarding Lead acid and substantiate the knowledge on this technology.

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[18] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[19] https://ease-storage.eu/energy-storage/technologies/

[20] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[21] https://ease-storage.eu/energy-storage/technologies/

3.2.3.3 Sodium Nickel Chloride batteries

Nickel makes the cathode, while sodium chloride makes the anode. Much like Subsection 3.2.3.1, this battery is also required to be kept at around 300º C, while also having a ceramic beta-alumina wall in the middle, able to allow the movement of ions but not of electrons. These batteries have been implemented in larger-scale projects only in the last several years, with plenty of improvements on all fronts, while currently being able to discharge for many hours, with fast reaction time. Efficiency is high as long as the battery can keep its internal temperature. The cycle life, while currently not very impressive, may be able to be significantly improved with the use of better materials still in development.

The database of the European energy storage technologies and facilities [22], the European Association for Storage of Energy [23] and the works of Sabihuddin et al. (2015), Longo, Antonucci, Cellura, and Ferraro (2014) and Manzoni (2015) were used to extract data regarding $NaNiCl_2$ and substantiate the knowledge on this technology.

3.2.3.4 Lithium-ion batteries

Yet again, this battery has a cathode and anode made of lithiated metal oxide and carbon materials or intercalation compounds, respectively. A porous polymeric material separates both electrodes while being immersed in a lithium salt electrolyte. The battery charges by ionising the lithium atoms in the cathode, moving toward the anode, where they recombine with an electron and deposit themselves in the carbon/intercalation layers. The process is easily logically reversed. These batteries can quickly respond to stimuli and perform at the maximum output for up to a few hours. The battery does not easily lose energy on its own, but like any battery, wear and tear eventually start to appear. It is not by accident that this is one of the most promising energy storage technologies, due to its high level of adaptability and use cases, these batteries are expected to significantly grow in volume, reducing costs. With better assembly and materials, further increases in energy density and cycle life are likely, even though current performance is already in great demand.

The database of the European energy storage technologies and facilities [24], the European Association for Storage of Energy [25] and the works of Sabihuddin et al. (2015), Bandhauer, Garimella, and Fuller (2011) and Khawaja et al. (2019) were used to extract data regarding LiIon and substantiate the knowledge on this technology.

3.2.3.5 Nickel-Cadmium batteries

New anode-cathode chemical composition is here proposed with nickel oxide-hydroxide making up the positive electrode, while the negative electrode is made of metallic cadmium. Both electrodes are separated by a membrane permeable to the electron and ion flow, being immersed in an aqueous potassium

[22] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[23] https://ease-storage.eu/energy-storage/technologies/

[24] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[25] https://ease-storage.eu/energy-storage/technologies/

hydroxide electrolyte. To charge and discharge the battery only water, and energy is required. NiCd batteries are highly regarded as reliable as the technology is completely matured, performing under harsh conditions and being able to protect other appliances from voltage disruption. While fast and able to discharge for up to a few hours, NiCd batteries are not very energy-dense and only last up to 5000 cycles or under two decades. Although cadmium is extremely toxic, the batteries can be collected and recycled causing no damage to the environment. This technology used to be much more prevalent, even in cars, but due to its high levels of toxicity, it has been somewhat fazed out.

The database of the European energy storage technologies and facilities [26], the European Association for Storage of Energy [27] and the works of Sabihuddin et al. (2015), McDowall (2008), Bernardes, Espinosa, and Tenório (2004) and Khawaja et al. (2019) were used to extract data regarding NiCd and substantiate the knowledge on this technology.

3.2.3.6 Nickel-Metal Hydride batteries

NiMH is a very similar battery compared to NiCd, having, therefore, similar applications, even though the chemistry is slightly different, only losing by a very thin margin in life duration, but managing to have a higher energy density. NiMH is by any other parameters equal to NiCd, making it unsurprising to know that for some time it was able to rival and replace NiCd batteries, although it now faces a similar disruption caused by LiIon.

The database of the European energy storage technologies and facilities [28], the European Association for Storage of Energy [29] and the works of Dhar et al. (1997) and Sabihuddin et al. (2015) were used to extract data regarding NiMH and substantiate the knowledge on this technology.

3.2.3.7 Vanadium redox flow batteries

Being the last of the electrical storage options, flow batteries had to be a bit different from the rest. Instead of one, this type of battery uses two different liquid electrolytes, separated by an ion-selective membrane. Unsurprisingly, one of the electrolyte tanks is positively charged, while the other is negatively charged. There is, albeit, one very significant characteristic that differentiates redox flow batteries - the interface is manageable. Besides this regulation, the pumps that take the electrolyte out of the tanks can also manage the flow. One can see how this battery type is easily scalable and does not lose energy while idle. The Vanadium battery has fast responses, discharges for some hours and has an average efficiency of about 70%. The technology has been tested, but still has a long road ahead, especially regarding cost and energy density. Recycling has also been evolving, but it is far from 100%. Regarding redox flow batteries as a whole, despite having somewhat low energy densities and slow electrical recharge rates, that require the replacement of the fluid in service stations, there is plenty of research to try to make them work in the automotive sector. Nevertheless, it is not currently possible,

[26] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[27] https://ease-storage.eu/energy-storage/technologies/

[28] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[29] https://ease-storage.eu/energy-storage/technologies/

and it may never happen due to the intrinsic limitations of the technology, much like what happened to the NaS battery, and for these reasons, it was not considered for the fourth category.

The database of the European energy storage technologies and facilities [30], the European Association for Storage of Energy [31] and the works of Sabihuddin et al. (2015), Mohamed, Sharkh, and Walsh (2009) and Cunha, Martins, Rodrigues, and Brito (2015) were used to extract data regarding VRF and substantiate the knowledge on this technology.

3.2.3.8 Zinc Bromine redox flow batteries

With the same architecture as the VRF batteries, even though the solutions are different, the fundamentals and specifications are not significantly dissimilar. ZnBr chemistry has the same reaction, power output and cost, with a larger gap in efficiency but the same average, although it is more energy-dense, it cannot cycle beyond 5000, compared to the over 10000 VRF is capable of. The lifespan, environmental impact and technological maturity are all very similar, as would be expected from a storage device parallel in all forms to its counterparts. Many other redox chemistries, and for that matter battery, are possible, but only these were chosen, following the data selected and available in the database that was set as the basis of this project.

The database of the European energy storage technologies and facilities [32], the European Association for Storage of Energy [33] and the works of Sabihuddin et al. (2015), Mohamed et al. (2009) and Weber et al. (2011) were used to extract data regarding ZnBr RF and substantiate the knowledge on this technology.

3.2.4 Chemical storage

In this case, energy is stored in a purely chemical compound. Energy is inserted and removed from the system by changing the structure or recombining the elements in a fluid.

3.2.4.1 Power to Gas - Hydrogen

The process of creating hydrogen is widely known and easily performed, even at a school level. All one has to do to create hydrogen is electrolysing water. This hydrogen can then be stored and re-electrified as needed with the addition of oxygen that is commonplace in the lower atmosphere of Earth. Chemical storage tends to be much more energy-dense than the technologies introduced up until now and H_2 is no exception, even though it does not reach the highs of the subsequent options. Even still, the process of creating and using H_2 as an energy source is quite inefficient and despite it having a good life duration and very low daily self-discharge, this is not the fastest reaction technology, nor is this the cheapest. What H_2 has significantly going for it is the long discharge duration and several use cases, as well

[30] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities
[31] https://ease-storage.eu/energy-storage/technologies/
[32] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities
[33] https://ease-storage.eu/energy-storage/technologies/

as a high interest from developed nations, expecting to significantly develop this option. H_2 has been used in the chemical industry (for example) for many years, with the most varied applications, created through the burning of fossil fuels. Many projects are being developed throughout Europe, the UK and the US to change this, by making energy generated in renewables immediately be converted into this long-duration energy source, and kick start a new format for the technology. Hydrogen can itself, or through the process of methanation, be transferred across the usual natural gas grids some countries already have in place, with the proper adaptations. Creating CH_4 through methanation or oxygen, that can be used in hospitals (high value) and many more, as a by-product from the electrolysis, it is easy to start to understand the appeal of hydrogen. Besides energy storage, this molecule is extremely well interconnected in the value-chain of many more products, which means value. It can also be created through the gasification of biomass, steam reforming, etc. The technology still has a long road ahead, but improvements in cost, efficiency and in energy input are in reach.

The database of the European energy storage technologies and facilities [34], the European Association for Storage of Energy [35] and the works of Gahleitner (2013) and Khawaja et al. (2019) were used to extract data regarding H_2 and substantiate the knowledge on this technology.

3.2.4.2 Power to Ammonia

Using regular air and water as sources, through air separation and an electrolyser unit, it is possible to get NH_3 and H_2. With these two molecules and a Haber Bosch NH_3 synthesis unit, the result is ammonia. This end-product can finally be used as a fuel instead of natural gas, moreover, ammonia does not release CO_2 when it is consumed. Almost all the processes have references at an industrial scale, but just like in Subsection 3.2.4.1 no full-scale plant has yet been built. In terms of specifications, all chemical storage options present in this project are similar, although ammonia has a greater energy density and lower cost, with slightly better efficiency. Unlike other technologies, ammonia has at times been used (and is currently partially used) as a fuel in the mobility sector, the reason for its choice as possible for the aforementioned sector.

The European Association for Storage of Energy [36] and the works of Yapicioglu and Dincer (2019) and Khawaja et al. (2019) were used to extract data regarding Ammonia and substantiate the knowledge on this technology.

3.2.4.3 Power to Methane

This process uses yet again H_2 by electrolysis, but now, to complete the methanation process and produce methane, CO_2 is required captured from flue gas via a post-combustion capture unit. Like all the other chemical storage options in the study, the objective is to fully integrate it into the renewable energy generation process, although no plants to scale have yet been built. Methane is highly energy-dense, with similar efficiencies, cost and long life duration when compared to AG. As of now, no chemical

[34] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities
[35] https://ease-storage.eu/energy-storage/technologies/
[36] https://ease-storage.eu/energy-storage/technologies/

storage options have been integrated into renewable generation, for they have only been used in the industry with the consumption of fossil fuels.

The European Association for Storage of Energy [37] and the works of Ghaib and Ben-Fares (2018) and Khawaja et al. (2019) were used to extract data regarding Methane and substantiate the knowledge on this technology.

3.2.4.4 Power to Methanol

Methanol can be produced with a very similar process to methane, it only requires the addition of a distillation unit that removes water from the methane solution. In terms of specifications, it is very similar to methane, although less energy-dense. The more energy-dense the product is, the less efficient it is.

The European Association for Storage of Energy [38] and the works of Heinzel and Barragán (1999) and Khawaja et al. (2019) were used to extract data regarding Methanol and substantiate the knowledge on this technology.

3.2.4.5 Power to Gasoline

While reviewing the literature on methanol it became evident that it was possible to get to gasoline (and LPG). It is worth pointing out that this process requires an additional many numbers of steps and production, hydration and fractioning units, but it is possible. One may think that if the objective is to transition the world to sustainable energy generation, storage and consumption, it seems counter-intuitive to measure up all the other options with gasoline, although the methanation process does consume CO_2. Still, there does not seem to be a better way to test these technologies head to head, with all of them having a similar footing.

In this case, it is relevant to understand how this can be performed. Starting from the distillation process, almost all the inefficiencies have already been performed in the electrolysis stage. Methanol is now required to go through a CAC gasoline production unit that creates water, that along with the one produced in the distillation unit can be used yet again as H_2 (after cleaning and a new electrolyser step) on the heavy fuel hydration unit. In this unit steam from the CAC gasoline production unit is inserted as it exchanges gas with the gasoline fractioning unit, where the raw products from the CAC unit have been added. From the fractioning unit, gasoline (and LPG) can be extracted. Just like with methanol, of course, the more energy-dense the end product is, the less efficient the process is, therefore a balance has to be reached. In the end, gasoline is extremely energy-dense, but all these processes add up the cost. None of these processes has been tested at scale.

The European Association for Storage of Energy [39] and the works of Khawaja et al. (2019) were used to extract data regarding Gasoline and substantiate the knowledge on this technology.

[37] https://ease-storage.eu/energy-storage/technologies/
[38] https://ease-storage.eu/energy-storage/technologies/
[39] https://ease-storage.eu/energy-storage/technologies/

3.2.5 Thermal storage

Using the elevation or lowering of the energy state of atoms and molecules, large amounts of energy can be stored in these levels, with a varied set of processes. There are three ways with which thermal energy can be stored. Sensible heat storage (SHS) is the most intuitive, simply increasing or decreasing the temperature of a material, either liquid or solid. Latent heat storage (LHS) uses phase-changing materials (PCM). Thermochemical storage (TCS) stores and releases energy in chemical reactions.

3.2.5.1 Molten Salts

Using the capabilities of certain salts to absorb energy from the heat at high temperatures, these can retain energy long enough to convert water into steam at a later time, producing energy through a turbine. Due to the high temperatures, it can reach, the technology can absorb large quantities of energy, although the degradation is not negligible, due to heat losses. The reaction is of the order of minutes. The salts can output energy for several hours and the technology has already been integrated a great number of times along with a large array of fields of solar generation. The technology is intimately connected to large solar concentration plants and the fact that a non-negligible amount of energy lost daily can be minimised at times enables it to be, under certain conditions, storage for renewable energy in the medium to long term.

The database of the European energy storage technologies and facilities [40], the European Association for Storage of Energy [41] and the works of Sabihuddin et al. (2015), IEA-ETSAP and IRENA (2013), Gibb et al. (2018), Patel, Pavlík, and Boča (2017) and Khawaja et al. (2019) were used to extract data regarding Molten Salts and substantiate the knowledge on this technology.

3.2.5.2 Hot Water

Water, inside a tank, is heated. This technology is as easy as that. Its simplicity translates to pricing on the unit level. If a hot water grid was to be created at the house or local level, if it does not exist, it would require very significant costs. The technology is highly mature, not particularly energy-dense or efficient, but better performances can be achieved with scale. The discharge can last over one hour, with a reaction of the order of seconds and a high technological life duration. Much like so many other technologies, it can be heated with fossil fuels, but it is already commonplace for this technology to be integrated with solar. With the appropriate tank insulation, the water temperature can be kept high for somewhat long periods. For greater efficiency in residential buildings, hot water storage installations can be inserted inside of an insulated space heating tank, providing not only hot water but also hot air to the building.

The European Association for Storage of Energy [42] and the works of Sabihuddin et al. (2015), IEA-ETSAP and IRENA (2013), Enescu, Chicco, Porumb, and Seritan (2020), Gibb et al. (2018) and

[40] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[41] https://ease-storage.eu/energy-storage/technologies/

[42] https://ease-storage.eu/energy-storage/technologies/

Pomianowski, Johra, Marszal-Pomianowska, and Zhang (2020) were used to extract data regarding Hot Water and substantiate the knowledge on this technology.

3.2.5.3 Phase-Change Materials

It is widely known that, for example, water needs energy not only to transition from 0 to 100º C but also to transition phases from solid to liquid (and gas). This is of course not exclusive to water and other materials do it better, or worse, depending on the view. PCM can store energy in a denser way for large quantities of time. These materials can even be integrated into the construction process creating fewer energy-demanding houses by passively storing and releasing energy. The technology has been in the market for some time, although improvements to the materials are being studied. The cost is tremendous, with average energy density. Power can be outputted for very large amounts of time.

The database of the European energy storage technologies and facilities [43] and the works of Sabihuddin et al. (2015), IEA-ETSAP and IRENA (2013), Enescu et al. (2020), Giovannelli and Bashir (2017), Sharif et al. (2015) and Khawaja et al. (2019) were used to extract data regarding PCM and substantiate the knowledge on this technology.

3.2.5.4 Thermochemical Storage

Involves a reversible exothermal (or endothermal) chemical reaction, having even higher energy densities than the rest of the thermal storage alternatives. Heat may be applied to a molecule, decomposing it. When required, the resulting products of the separation recombine and expel the energy used in the first place. The technology is still quite experimental and prices can be high, but far from the €/kW ranges of the PCM technology with higher energy density. It can be also be used integrated with solar energy generation.

The database of the European energy storage technologies and facilities [44] and the works of Sabihuddin et al. (2015), IEA-ETSAP and IRENA (2013), Kalaiselvam and Parameshwaran (2014), Yan, Wang, Lai, and Lai (2021), Abedin and Rosen (2011) and Khawaja et al. (2019) were used to extract data regarding TCS and substantiate the knowledge on this technology.

3.3 Summary

In this chapter, the energy scenario has been fully characterised in its two mains branches - the sectors and technologies - allowing for the appropriate methodology choices in Chapter 4. The most relevant criteria to evaluate and rank the technologies that were established in this chapter will now be selected in Subsection 4.2.1.

[43] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

[44] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

Chapter 4

Methodology

Section 4.1 is meant to establish the fundamentals of MCDA, initiating the discussion of what methods best suit the problem at hand. This discussion is to be followed by how the model is being planned in Section 4.2, and with the knowledge acquired in the previous sections, further decisions can be made. Section 4.3 will explain all methods to be used as well as explain how they will be implemented and adapted to the issue.

4.1 Introduction to MCDA

This section is meant to introduce and put forward a great number of MCDA concepts, explaining in greater detail what MCDA even is and what methodologies from this vast toolbox could be applied to this take on energy storage. Knowing that this dissertation merges energy and multiple-criteria decision making, it is worth explaining what greater concepts the former represents.

It has already been established that this project involves a great number of variables and that it will be very challenging, if not impossible, to optimise for all that is required. It is, therefore, necessary to create a system that can select, according to certain preferences, how available solutions perform according to what is being asked of them as a whole.

In broad terms, we can imagine the typical example where cost and performance are trying to be optimised at the same time. These two criteria are regularly in conflict as the cheapest option is usually not the best. If this were to happen, an option would dominate all the others and leave no room for preference or competition, as that one action would be chosen under all different scenarios. This unclear and non-domination scenario appears in the most varied moments in life, either in a company that is looking to buy new equipment, a hospital that whats to become more efficient, a person that is looking to choose a new phone or even in our personal lives.

Not only performance and cost, continuing with the example, have to be taken into account, but also the preferences on somebodies part on how to balance the two. Different people may want to minimise cost, others may want to maximise performance independent from cost and others may even try to buy the best “value for money” option, whatever that equilibrium may mean to them. Something as easy as buying a phone has already become trickier than a simple two-dimensional problem because of each person's value function, but this is far from the greatest challenges MCDA is applied to.

If all these previous statements have been slowly extracted from common knowledge the next will also be - hardly ever can performance be measured in one dimension. Size, speed, appearance and many more are all criteria that quickly add up, creating a multi-dimensional problem. It is now necessary not only to evaluate cost and performance, as well as consider the balance between both of them but also characterise performance (and cost) in all of their dimensions.

Now that the vast variety of criteria that exist in almost every problem has been introduced, it is high time that the concepts of point of view (PoV) and fundamental point of view (FPoV) get introduced and differentiated. Therefore, a PoV is the explicitation of a value that the actors/decision-makers consider relevant to the evaluation of the options. On top of a PoV is the FPoV which is an end in itself, reflecting a fundamental value. It could be a common end for which several elementary points of view contribute to and must respect several conditions, such as being (Keeney, 1997):

Essential FPoVs, are required to represent a fundamentally interesting characteristic that has consequences in the final decision;

Controllable They must also represent consequences to that final decision that are only influenced by the alternatives in the context;

Complete Overall, they must sum up to evaluate all fundamental aspects of the alternatives being considered;

Measurable Criteria must of course have clearly stated objectives and a measurement scale to describe up to which level they are achieved;

Operational It has to be possible to aggregate and analyse the information that refers to the FPoVs;

Decomposable To allow for the analysis of each FPoV on its own;

Non-redundant If a characteristic was to be counted for twice, its weight would be twice what it is, so each PoV must not be related to two FPoVs;

Concise Even though a topic may have infinite evaluation dimensions, the number of FPoVs must be limited for only the relevant parameters to be considered;

Understandable Each must further the understanding and ease the communication in the decision-making process.

Let us also take into consideration that criteria come in all formats, where some may evaluate things as exact as the size of a house ($143.7m^2$) and others have to evaluate, for example, customer satisfaction (high, low), creating as abstract concepts as good and bad can be.

For this reason, criteria can be categorised according to three dimensions (Costa & Beinat, 2005):

– Relationship to the criterion;

– Reading representation;

– Continuity and finitude.

In each of these dimensions, several types of descriptors can be assigned. For the relationship to the criterion dimension, there are 3 types of descriptors:

Direct or natural Naturally relate to the FPoV. Directly reflect effects;

Indirect or proxy Indicate causes more than effects;

Constructed Describe characteristics underlying the FPoV.

For the reading representation dimension there are 3 types of descriptors:

Qualitative Use of numbers;

Quantitative Use of semantic expressions and numbers;

Pictorial Use of visual representations.

For the continuity and finitude dimension there are 2 types of descriptors:

Continuous Represented by a continuous function;

Discrete Represented by a finite set of impact levels.

Finally, the importance of planning and methods has been put forward. PoVs have to be thought of and organised in what is called a value tree. This concept is meant to visually and intuitively arrange all the PoV, making it easy to spot inconsistencies, unbalances and a lack or excess of FPoVs (Pereira, Machete, Ferreira, & Marques, 2020). This dissertation's value tree can be seen in Figure 4.3. There are two essential ways to construct a value tree (Costa & Beinat, 2005):

Top-down Disaggregating PoVs;

Bottom-up Aggregating PoVs.

No one way is fundamentally better than the other and in this dissertation, the bottom-up approach was chosen, to more clearly consider all possible dimensions energy storage solutions can be evaluated in.

It is undoubtedly relevant to structure and solve problems, of any importance, involving multiple criteria, therefore, plenty of tools and methods have been created to evaluate the alternatives, for example: Elimination and Choice Expressing Reality (ELECTRE), Preference Ranking Organisation Method for Enrichment of Evaluations (PROMETHEE), Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), Multiple Attribute Utility Theory (MAUT), Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS), Data Envelopment Analysis (DEA), Goal Programming, Utilités Additives (UTA), Maximax, Maximin (Ishizaka & Nemery, 2013).

EVAMIX, ARGUS, COMET, IDRA, Lexicographic, MAVT, MAPPAC, VIKOR, DEMATEL, REMBRANDT, MELCHIOR, NAIADE, ORESTE, PACMAN, PAMSSEM, PRAGMA, QUALIFLEX, REGIME, STACTIC, Simple, among others, are only some of the countless number of methodologies available. With so many options available, some differentiation must exist between them. There is therefore value in organising the most relevant of these methods, according to what problems, approaches, models and methods they are meant to be used in. Besides all these methods, there are also plenty of programs created for the use of these methods (Belton & Stewart, 2002).

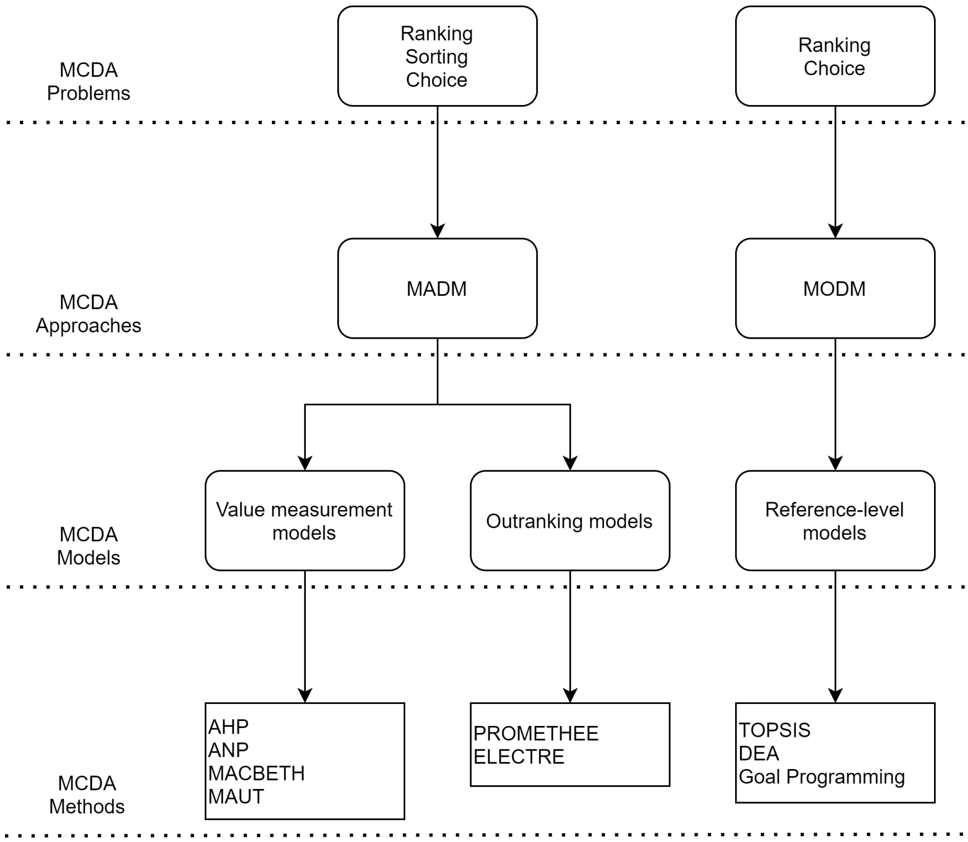

Figure 4.1: Classification of MCDA problems.

In regards to the types of problems, there are three types (Greco, Ehrgott, & Figueira, 2016):

Sorting Problem The actions will be allocated to a group, which will, in turn, be ranked between each other;

Choice Problem The subset of actions considered best are selected;

Ranking Problem Each action is to be hierarchically ordered.

Below, Figure 4.2 makes these descriptions all the more intuitive.

There are two fundamental MCDA approaches - multi-attribute decision making (MADM) and multi-objective decision making (MODM). Their definitions easily relate to their name, while MADM is meant to be used on problems with discrete decision spaces, MODM optimises at the same time for several competing objectives.

With respect to MCDA models, three types emerge (Belton & Stewart, 2002):

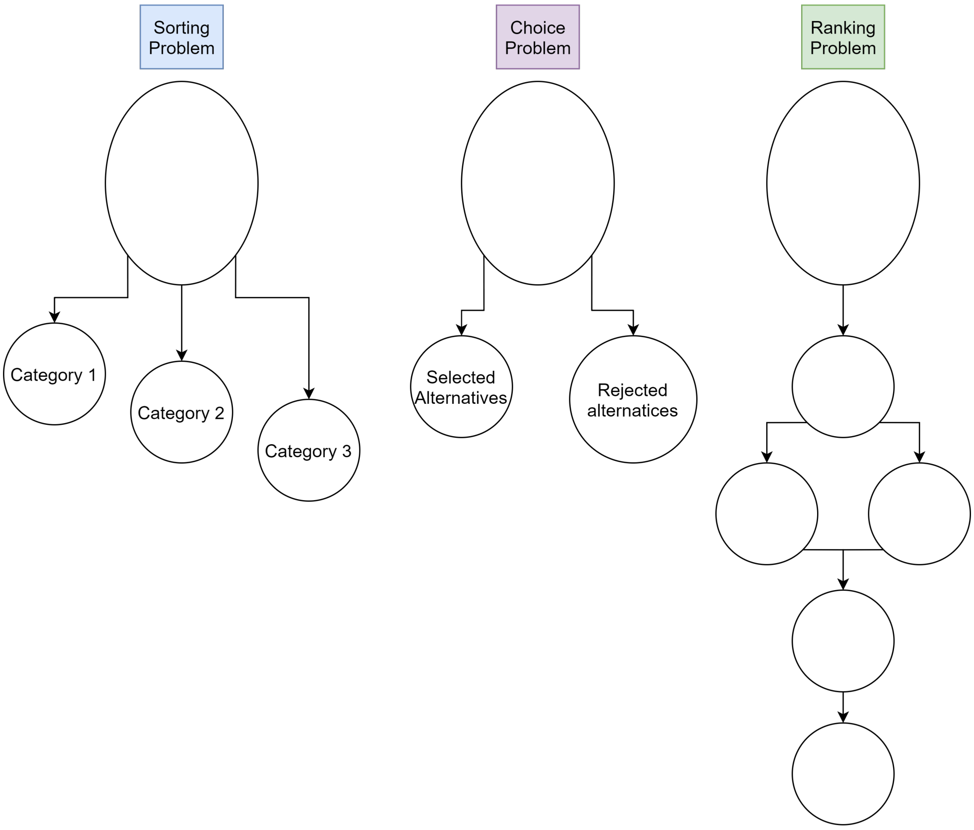

Figure 4.2: Types of MCDA problems.

Outranking models This segment of models create a pairwise comparison, to reflect the extent up to which one criterion is preferred over the other. The scores are then aggregated so that preference for one alternative over another is established.

Value measurement models These models reflect the preference for each alternative through a numerical score. Each alternative is first ranked to each criterion and then given a global score. These models involve a trade-off between the good and bad scores where the scores represent the preference from one decision option to another.

Reference-level models In these models a satisfaction level is established for each criterion. The model then seeks the alternative that best achieves these levels.

Besides methods for the evaluation of each alternative, it may also be necessary to evaluate the criteria between each other and the levels of performance in each criterion, creating the ratio and interval scales. Most methods can create their scales, but some very specific mathematical formulas require a complementary procedure and for this other methods have been created, such as the Deck of Cards, that was chosen for this project.

Now it is worth iterating that like a phone or a car, different MCDA methods may be more or less appropriate for a particular problem. This dissertation is space and time-limited and for that reason, not all methods can be explained in full detail. Those who are chosen will therefore be described in full theoretical detail and explained why they were chosen.

In conclusion, this dissertation has up until now been preparing for the structuring of the problem that will be concluded in the next section. The value measurement tasks, responsible for the creation of the weights for the criteria and among themselves can only be achieved in the Chapter 5, as well as the aggregation of the model, that will be chosen and justified in the coming sections.

4.2 Energy storage using MCDA

This section is meant to explain how this take on the energy storage sector can be integrated into the MCDA area of research now that some are already known about this area of research, enabling us to proceed from where Chapter 3 left off, laying out the several criteria chosen to be featured in the model, in Subsection 4.2.1, as well as make the full overview on the model to be applied on the energy storage issue, in Subsection 4.2.2.

4.2.1 Criteria

The first thing one takes into consideration is that it is inadequate to consider dozens of criteria in a model, as was explained previously. For that matter, the aggregation of PoVs has to be performed to reduce the overall number, creating then a set of the most meaningful values and performances when comparing technologies (Greco et al., 2016).

Let us now consider the countless miscellaneous PoVs an energy storage action could be evaluated by: Energy Density, Round-trip Efficiency, Conversion Efficiency, Cycle Life, Life Duration, Daily Self-discharge, Storage discharge duration at full power, Reaction Time, Charge Rate, Capital Expenditure, Distribution Network, Energy Capacity, Power Installed Capacity, Working Temperature, Storage System Footprint and Space Requirements, Modularity, Grid Short Term Performance, Grid Long Term Performance, Microgrid Performance, Mobility Performance, Maturity, Environmental Impact, By-products. Arranging the several PoVs in an FPoV tree, the result can be seen in Figure 4.3.

The aforementioned solutions, in Section 3.2 have to be characterised in detail and ranked according to a set of criteria. Table 4.1 presents the criteria that will be used in this dissertation, some information coming from the previously stated EU Open Data database, whereas many complementary data comes from numerous other sources (Eyer & Corey, 2011; IRENA, 2017; European Commission, 2020; International Energy Agency, 2020; Motyk et al., 2018).

The full list of criteria will be divided into two different stages of the dissertation as in fact, a significant number of criteria concern technical issues valued by the clients who will end up buying the solutions, whereas other criteria are intended to be taken into account by the government. Due to the government's broader time horizon and priorities, environmental and social responsibilities have to be taken into consideration. The first set of criteria allows for the creation of a ranking that both companies and individuals want to acquire, leaving broader incentives and future technology investments in the hands of organisations who in effect want to consider these issues.

The significance of most of these criteria is quite self-explanatory through their names, but some may

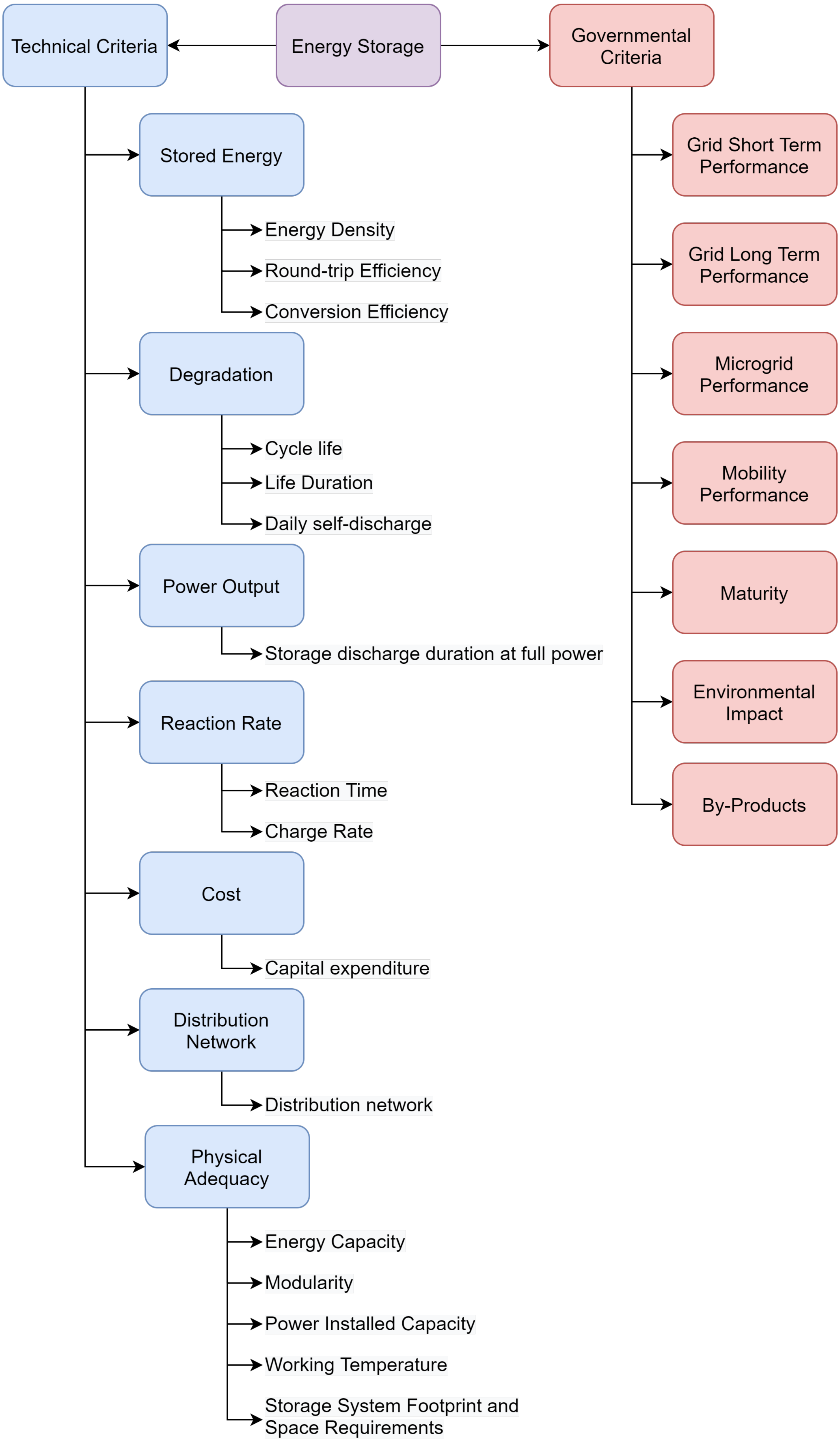

Figure 4.3: Value tree.

Table 4.1: Criteria and corresponding descriptions.

Criteria	Relation with the FPoV	Data type	Mathematical representation	Description
Stored Energy	Constructed	Quantitative	Continuous	Measure the amount of energy stored, discounting efficiency losses.
Degradation	Constructed	Qualitative	Discrete	Duration up to which the energy can be properly stored.
Power Output	Constructed	Qualitative	Discrete	Duration of the power output at full power.
Reaction Rate	Constructed	Qualitative	Discrete	Speed at which the storage can respond to the shifts in demand, either in or out.
Cost	Direct	Quantitative	Continuous	Capital expenditure in the project.
Distribution Network	Constructed	Qualitative	Discrete	Adaptations required to the energy distribution grid.
Physical Adequacy	Constructed	Qualitative	Discrete	Account for a number of physical limitations that exclude the use of a particular technology in a category.
Grid Short Term Performance	Constructed	Quantitative	Continuous	Output from Category 1.
Grid Long Term Performance	Constructed	Quantitative	Continuous	Output from Category 2.
Microgrid Performance	Constructed	Quantitative	Continuous	Output from Category 3.
Mobility Performance	Constructed	Quantitative	Continuous	Output from Category 4.
Maturity	Constructed	Qualitative	Discrete	Stage of development of a technology.
Environmental Impact	Constructed	Qualitative	Discrete	Measure for the environmental impact of a technology.
By-products	Constructed	Qualitative	Discrete	Resulting or inherent derivative that can add value for other purposes.

require further explanation, as well as the reasoning behind the aggregation of several of the PoVs one unified criterion.

Let us start with the technical criteria, to be considered on the first meetings on the category's level:

FPoV 1 Stored Energy - g_1. Energy/Power density has been paired up via multiplication with Round-trip Efficiency, which works as a discount coefficient on the overall performance in the Stored Energy criterion. An exact number can be used in this criteria, using the average of the efficiencies with the value up to which the energy density can achieve in Wh/kg. The objective will be to maximise the value. Conversion Efficiency could not be accounted for as it was considered a prior inefficiency, not an inefficiency inherent to the use of the installation, as well as the poor information relating to the increasingly complex and experimental at times process.

FPoV 2 Degradation - g_2. The Degradation of a device can essentially be measured by taking into account the Life Duration and Cycle Life of the installation, as well as its ability to hold the energy it receives, with the Daily Self-discharge. Technologies have been given the rating of low, average and high degradation considering these three parameters. The less degradation the system has, the better.

FPoV 3 Power Output - g_3. The storage discharge duration at full power will be considered in the Power Output criteria, but due to the lack of precision in the data, most of the time only having available the order of magnitude in time during which the technology can perform, it has been decided to use a triple ranking of low, average and high duration output, considering that the longer in time technology can discharge, the better.

FPoV 4 Reaction Rate - g_4. Is the result of the amalgamation of the reaction time and charge rate of technology. These two parameters reflect how fast the device can adapt to the shifting demands from outside, as well as its ability to recharge, which is an outside demand. Three levels can be identified when looking at the data, as there are technologies with fast reaction and charge, slower reaction but still fast charge and slower reaction and slow charge. These 3 levels will be expressed as fast, average and slow, respectively. The faster the overall reaction rate is, the better.

FPoV 5 Cost - g_5. Is as easy as considering the overall Capex performed on the project, being possible through the use of the average Capex. The lower the capital expenditure, the better.

FPoV 6 Distribution Network - g_6. Independent on a purely installation-specific manner, the Distribution network criteria is intended to take into consideration the necessary infrastructure changes to incorporate such technology. Some technologies may only require the extension of power cables, corresponding to an Excellent (E) level, to account for that device, while others may require small adaptations, Good (G), to the energy infrastructure, or even very significant investments in the overall extension and improvement of the grid, to account for a high level of adaptations, Bad (B). For those technologies that may require the complete overhaul, Non-existent (N) or the creation of an entirely new grid, a special ranking has been created.

FPoV 7 Physical Adequacy - g_7. Is the binary criterion that considers a plenitude of factors, such as Working Temperature, Storage System Footprint and Space Requirements, Modularity and overall Energy/Power Capacity, that will prevent a technology such as Pumping Hydro from being considered fit to use in a car. This criterion is not to be taken as the aforementioned criteria in the model, as its intent is simply to allow or prevent certain technologies from being ranked in categories where they do not fit.

And now for the criteria intended to be taken into consideration by the government:

FPoV 8, 9, 10, 11 Performances - g_8, g_9, g_{10}, g_{11}. No higher-level judgement can be made without taking into consideration the performances of the technologies and preferences of each Category's DMs. For this reason, each result from each previous Category is incorporated into the new decision-making process, allowing for the measure up of each Category between one another, as well as accounting for inevitable interactions between themselves. The overall numeric result for every category is normalised with 0, meaning the normalisation is performed between the maximum performance and 0, in order not to unfairly evaluate the lowest-performing technology (and all others) that is physically adequate as an inadequate alternative, and to still properly differentiate between the options available, while creating a 0 to 100 scale, easily interpreted by a DM.

FPoV 12 Maturity - g_{12}. Is intended to evaluate the stage of development at which the technology currently is. The higher the value (3), the more mature and fully optimised the technology is; the lower the value (1), the more uncertain and experimental the installation are. Several intermediary stages are also taken into consideration. Level 1 represents a purely experimental technology that is only now being tested. Level 1.5 represents a technology that has evolved into second-generation installations, while level 2 only considers technology that is somewhat widely implemented while having a long road ahead in terms of evolution. Level 2.5 technology are further ahead on this development road map, with inevitable less upgrade margin, yet with less uncertainty, while level 3 is reserved for fully developed and mature technologies.

FPoV 13 Environmental Impact - g_{13}. Is a very subjective criterion as the DMs will be asked to rank four possible impact levels: no impact/neutral or recyclable (N/R), disruptive to the habitat, toxic or harmful to global warming because of the way they are powered or the end-products of its use (GW). One should consider that GW is toxic and disrupts habitats, while toxic elements also disrupt habitats but may not significantly enhance global warning, nevertheless, the DMs will have the freedom to chose the ranking of the levels. The technologies have already been awarded their respective impact level.

FPoV 14 By-products - g_{14}. Many of the technologies being evaluated can serve more purposes than storing energy. Either on a smaller scale or at an industrial one, the content of the devices or some of the resulting by-products coming off the charge/discharge process can add value beyond the storage of energy. Without taking into consideration this criterion, a variable portion of the *de* *facto* value of technology would have been completely disregarded, which could in practice make the difference between choosing one storage device over another.

Criteria such as Degradation and Distribution Network do not share the same data certainty as Stored Energy and Cost, but they can be evaluated on a numerical scale, even if the criteria are qualitative.

Even though criteria with direct relation to the FPoV are preferred, constructed criteria had to be taken into consideration because so many PoVs had to be aggregated. The complexity of the energy storage market requires the use of this type of criteria, or else the FPoV would be much more plentiful, which is strongly discouraged in the literature as stated, or some would not have been taken into consideration.

Let us take into consideration other MCDA research, applying several other methods, done in the energy storage market such as Barin, Canha, Da Rosa Abaide, and Magnago (2009), Oberschmidt (2010), Cowan, Daim, and Anderson (2010), Barin et al. (2011), Krüger (2012), Daim, Li, Kim, and Simms (2012), Raza, Janajreh, and Ghenai (2014), Walker, Mukherjee, Fowler, and Elkamel (2016), Wei, Hou, Qin, Yuan, and Yan (2016), Vo, Xia, Rogan, Wall, and Murphy (2017), Baumann, Peters, Weil, and Grunwald (2017), Ren (2018), Ren and Ren (2018), Murrant and Radcliffe (2018) and van de Kaa, Fens, and Rezaei (2019). All these research projects had plenty of overlap regarding the use of the same criteria with the current dissertation (Cost, Efficiency, Maturity, Cycles, Lifetime, etc), nevertheless, most of them had to manage without several of the criteria others chose to consider. If for some this was manageable because the research was done on a more specific and constrained environment, for more ample projects such an approach may not be desirable. As an alternative, other research has been done trying to aggregate these criteria in broader groups, allowing for the consideration of a wider variety of criteria and information. Such an approach was attempted in Baumann, Weil, Peters, Chibeles-Martins, and Moniz (2019), trying to review applications on the grid level, leading the researcher to aggregate the criteria on 4 groups - Social, Economic, Technological and Environmental. In this dissertation, a more intelligible and comprehensive approach was chosen, nevertheless, with constructed criteria.

While looking into the literature and reading the aforementioned papers, as well as many others, it was made clear the unprecedented application of MCDA in the study of the energy storage topic in Portugal. Furthermore, never has the Choquet Integral method been applied to the subject on a global scale.

4.2.2 Overview of the model

The project can be easily understood from start to finish by looking at Figure 4.4. Using the table of performances, created according to the values of the available actions in line with the set of criteria previously defined, the DMs are provided with the necessary information to evaluate the problem in two different stages. In the first stage, a set of criteria will be used to create value functions for each sector. In the second stage, the second set of criteria, with the additional input of the value functions already calculated on the last step, will result in the creation of a ranking for all the alternatives.

Examples of the use of MCDA in the energy sector are abundant, among which we highlight applications using the ELECTRE TRI method (see, e.g., Cabeça, Henriques, Figueira, and Silva (2021))

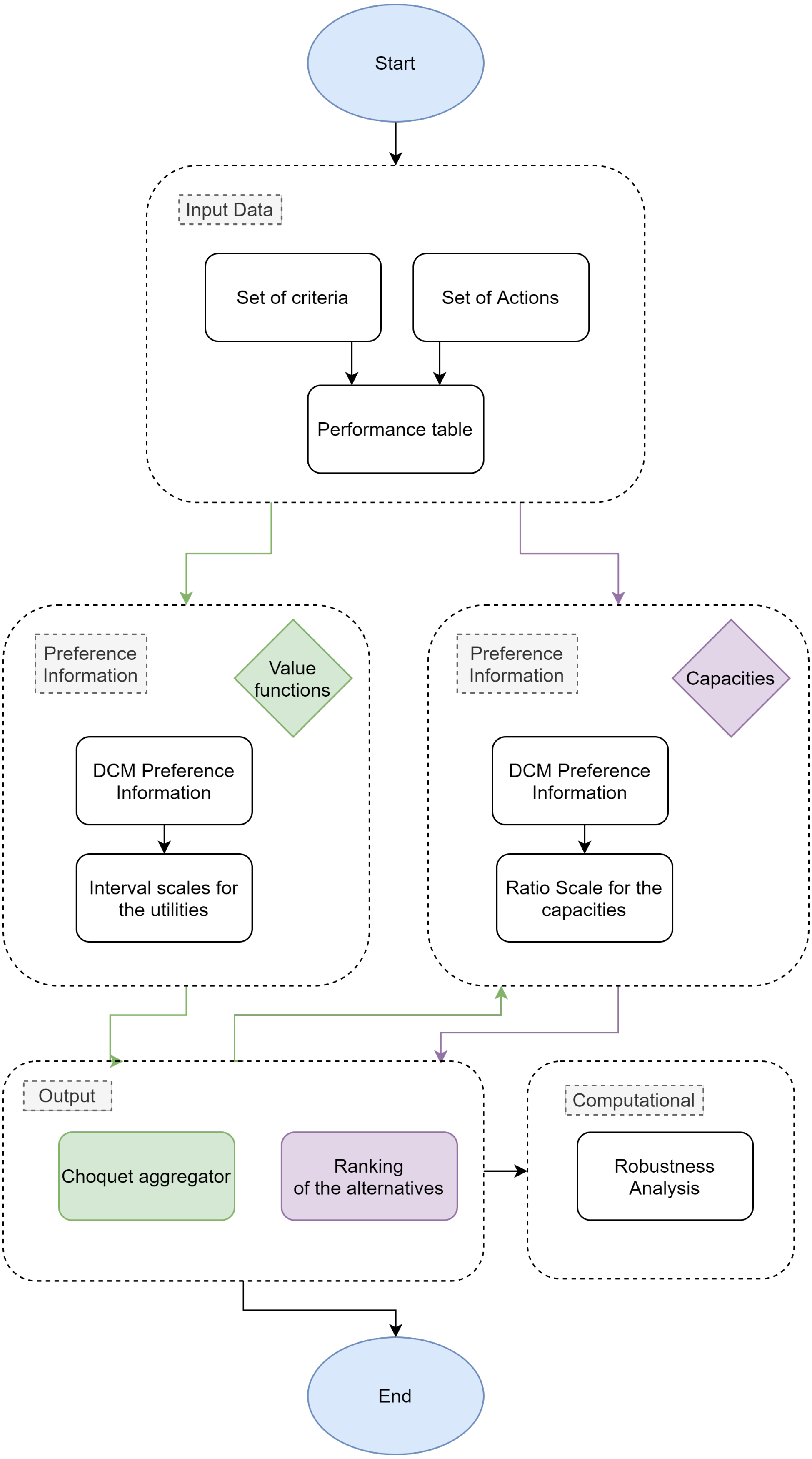

Figure 4.4: Flowchart of the project's methodology.

although it will not be the chosen method in this project, since it does not consider relevant synergies and redundancies between the selected criteria.

It is only the responsibility of the DMs to evaluate if the criteria interact with each other, but it is inevitable to conclude that the criteria Cost and Distribution network interact with synergy, as both relate to costs and as an aggregate, although independent, create the real overall cost of investment of a new installation. Other interactions can be thought of in the government section of the project where, for example, Grid Short Term Performance and Mobility Performance have a synergy effect, as vehicle to grid (V2G) systems begin to be rolled by major vehicle producing companies. Only the DMs can make a final decision if these, and other, interactions occur, but the model has been chosen with these presuppositions.

With all the required data duly collected, it is then possible to clearly define the work ahead. Each sector will be characterised according to its needs, thus developing a set of criteria that allows the evaluation of each technological solution. Each solution corresponds to a decision alternative that, ultimately, will be chosen if its performance in the selected criteria dominates the remaining solutions. It should be noted that this type of model considers that the criteria are independent. In reality, some criteria interact with each other. For this reason, it is necessary to use the Choquet multiple criteria preference aggregation model in its modified version to use the Möbius coefficients, which consider the synergies and redundancies that may exist between them.

It is also necessary to use an auxiliary method to convert the performance of the criteria into a utility-scale and to calculate the Möbius coefficient for each criterion and interaction. For that, the Deck of Cards method (Corrente, Figueira, & Greco, 2020) will be used. Having defined the model for each major sector of the energy storage market, it will be important to develop a broader model for strategic energy public policy. This model was idealised considering the government as the main DM.

If it is important to choose the best technological solution for each sector, at the governmental level, other factors must be considered beforehand, such as political criteria, among others. Using the same method, a new ranking will be built for a subject where transparency and clarity are desirable, and where we can understand where large funds should or could be invested.

4.3 Methodology choice

Now that the methodology is finally chosen, it will be explained in detail the theory behind these mathematical instruments in Subsection 4.3.1, Subsection 4.3.2, Subsection 4.3.3 and Subsection 4.3.4, with a final explanation on how in practice they will be used in the project in Subsection 4.3.5.

4.3.1 Fuzzy measurements

Of all the options available, fuzzy measures and integrals must be further explained.

Fuzzy is not a method in itself, it is an umbrella of methods such as the Choquet integral - for cardinal evaluation - and the Sugeno integral - for ordinal evaluation. The fuzzy measure is:

1. $\emptyset \in \mathcal{C} \Rightarrow g(\emptyset) = 0$;

2. $E \subseteq F \Rightarrow g(E) \leq g(F)$.

where $\mathcal{C}$ is a class of subsets of the universe of discourse $\mathbf{X}$ and E, F $\in \mathcal{C}$. The function $g : \mathcal{C} \rightarrow \mathbb{R}$. Considering $E, F \in \mathcal{C}$, the characteristics of the fuzzy measure are the following:

Additive if $E \cap F = \emptyset$, then $g(E \cup F) = g(E) + g(F)$;

Supermodular because $g(E \cup F) + g(E \cap F) \geq g(E) + g(F)$;

Submodular because $g(E \cup F) + g(E \cap F) \leq g(E) + g(F)$;

Superadditive if$E \cap F = \emptyset$, then $g(E \cup F) \geq g(E) + g(F)$;

Subadditive if $E \cap F = \emptyset$, then $g(E \cup F) \leq g(E) + g(F)$;

Symmetric if $|E|= |F|$ then $g(E) = g(F)$;

Boolean because $g(E) = 0$ or $g(E) = 1g(E) = 1$.

This is a mere theoretical introduction to the concept of a Choquet integral, which will be explained next.

4.3.2 Choquet integral

The Choquet integral is only one of many functions/methodologies to create rankings or value functions (Greco et al., 2016). It comes from the definition of a fuzzy measurement, as in fact, the Choquet integral is a fuzzy integral. Out of all the options available, the Choquet integral can account for positive or negative interactions between criteria, thus allowing for the creation of a much more accurate method of analysis for a problem where criteria do have synergies or redundancies (Wątróbski, Jankowski, Ziemba, Karczmarczyk, & Zioło, 2019). These interactions between criteria will be decided and pondered by each DM. Although the Choquet function is the necessary instrument to use on this issue, it does demand the subtraction of each utility by its previous entry. Hence, the Choquet integral can be formulated as (Bottero, Ferretti, Figueira, Greco, & Roy, 2018):

$$C_\mu(a_k) = \sum_{i=1}^{n} \left(u_i(g_i(a_k)) - u_{i-1}(g_{i-1}(a_k))\right) \mu(G_i) \tag{4.1}$$

where C_μ represents the value provided by the Choquet integral, μ the Choquet capacity, a_k the alternative being considered, i represent the indices of each criteria, g the indicator being summoned, u the utility of that specific indicator, and G_i the set of criteria. It is also necessary to order the utility of each criteria for each alternative from the least to the highest value, such that $u_1(g_1(a_k)) \leqslant ... \leqslant u_i(g_i(a_k)) \leqslant ... \leqslant u_n(g_n(a_k))$, and $G_i = g_i, ..., g_n$ for $i = 1, ..., n$, with $u_0(g_0(a_k)) = 0$.

Now that some of the nomenclature is properly understood, two properties can be outlined, considering the set of criteria G and that a capacity is a set function $\mu : 2^G \rightarrow [0, 1]$ on the power set 2^G:

i. Boundaries: $\mu(\emptyset) = 0$ and $\mu(G) = 1$;

ii. Monotonicity: $\forall S \subseteq T \subseteq G : \mu(S) \leqslant \mu(T)$.

By translating the mathematics using words, it is possible to verify that the Choquet integral involves a sum over all the criteria being considered. Furthermore, it uses the capacities μ to compute an overall weight of each subset of the criteria set. It is easily understood that considering two criteria with no interaction, there shall be no additional capacity value to the sum of both individual capacities.

If, on the one hand, the interaction of the criteria increases the overall value of the capacity for both criteria, it is only natural for the overall capacity value to be greater than the value of the sum of both individual criteria without interaction. The value of the interaction is to be decided by the DM. On the other hand, the same is applied where the interaction of both criteria decreases the value of the overall capacity by outputting a result below the overall capacity without interactions.

Moreover, for each entry in this summation, the utility of alternative k for the criteria i is being subtracted by the utility of the previous criteria for the same alternative, multiplied by the Choquet capacity for the alternative k of the criteria set. The constant reordering and lack of clarity that this mathematical formulation can be easily avoided by the use of a similar and equivalent form.

It may be useful to clearly define how the synergies and redundancies will be accounted for in the integral:

– $\mu(g_i, g_j) > \mu(g_i) + \mu(g_j)$: there exists a synergy interaction between the criteria, therefore the overall utility will be greater;

– $\mu(g_i, g_j) = \mu(g_i) + \mu(g_j)$: there exists no interaction between the criteria;

– $\mu(g_i, g_j) < \mu(g_i) + \mu(g_j)$: there exists a redundancy interaction between the criteria, therefore the overall utility will be reduced.

4.3.3 Möbius transformation

Much like any other function transformation in mathematics, the Möbius transformation results in the same values as the original Choquet function, but now through a rather significantly more simplified form. As mentioned previously, the Choquet function is not the easiest function to compute or explain to a DM, leading to the choice of the Möbius function that simplifies the calculations by simply adding the minimum value for the utility of both criteria for the same actions, multiplied by the Möbius coefficient of the pair of criteria, to the utility of the criteria being considered multiplied by its Möbius coefficient. The Möbius function of the Choquet integral can be formulated as (Pereira, Figueira, & Marques, 2020):

$$C_\mu(a_k) = \sum_{g_i \in G} m(g_i) u_i(g_i(a_k)) + \sum_{g_i, g_j \in O} m(g_i, g_j) \min\{u_i(g_i(a_k)), u_j(g_j(a_k))\} \tag{4.2}$$

Fundamentally, this definition is in every way similar to the one formulated in the previous subsection, with the addition of the Möbius coefficients m. These coefficients are equivalent to the capacity of each criteria, to be defined by the decision maker.

A similar set of properties can be defined for this transformation as:

i'. Boundaries: $m(\emptyset) = 0$ and $\sum_{T \subseteq G} m(T) = 1$;

ii'. Monotonicity: $\forall i \in G$ and $\forall R \subseteq G : m(g_i) + \sum_{T \subseteq R} m(T \cup g_i) \geqslant 0$;

With all these new it is still worth considering the fuzzy measure is additive given R parallel another subset S, then $\mu(R \cup S) = \mu(R) + \mu(S)$ if $R \cap S = \emptyset$.

This redefinition of the properties has been possible, given the capacities μ on the power set 2^G, can now be defined with the Möbius representation function being formulated as $m : 2^G \to \mathbb{R}^n$ for all $S \subseteq G$, then:

$$\mu(S) = \sum_{T \subseteq S} m(T), \tag{4.3}$$

This can in turn give:

$$m(S) = \sum_{T \subseteq S} (-1)^{|S-T|} \mu(T), \tag{4.4}$$

Creating the concept of a polynomial fuzzy measure, with the idea of a k-order fuzzy measure, an additive linear representation can be formulated as $f(a_k) = \sum_{i=1}^{n} u_i(g_i(a_k))\omega_i$, where ω is a weighting vector, solving the problem of a decision maker having to evaluate 2^n coefficients. This is turn requires the following definitions. With $i \in G$:

$$\mu(g_i) = m(g_i) \tag{4.5}$$

Now considering two indicators $g_i, g_j \subseteq G$:

$$\mu(g_i, g_j) = m(g_i) + m(g_j) + m(g_i, g_j) \tag{4.6}$$

Finally, we must consider a set $S \subseteq N$, with $|S| \geqslant 2$ where:

$$\mu(S) = \sum_{g_i \in S} m(g_i) + \sum_{g_i, g_j \subseteq S \; g_i, g_j \in O} m(g_i, g_j) \tag{4.7}$$

$$\mu(G) = \sum_{g_i \in G} m(g_i) + \sum_{g_i, g_j \in O} m(g_i, g_j) = 1, \tag{4.8}$$

Considering these, it is only now possible, but one must also consider the conditions by which the Möbius coefficients must abide by:

$$
\begin{cases}
m(\emptyset) = 0 \\
\sum_{g_i \in G} m(g_i) + \sum_{g_i, g_j \subseteq G} m(g_i, g_j) = 1 \\
m(g_i) \geqslant 0, & \forall g_i \in G \\
m(g_i) + \sum_{j \in O} m(g_i, g_j) \geqslant 0, & \forall g_i \in G, \forall O \subseteq G \setminus g_i.
\end{cases}
\tag{4.9}
$$

In other words, these conditions are the so-called 2-order fuzzy measure conditions that allow for the required criteria interaction, without an increase to the computational and mathematical demands (Marichal & Roubens, 2000).

4.3.4 Deck of Cards method

Despite already knowing the method used to calculate the ranking for each sector, it is yet unknown the methodology to create the value functions and compute the Möbius coefficients that these functions require. For that, the Deck of Cards method will be used. This methodology has been developed in recent years and essentially requires the DMs to position blank cards between the cards representing each criterion (Corrente et al., 2020). This method will be used in two particular situations. On the one hand, the weight of each criterion must be ascertained. Thus, DMs will rank every criterion. Then, any number of cards will be positioned between the criteria or a group of criteria with equal importance, creating a buffer of value that allows for fine-tuning of the real importance difference between each criterion. A similar methodology will be followed when ranking each action. The value of each technology will already be known by the DM, thus allowing for a proper ranking to be created, with adequate value differences between each action.

Figure 4.5: Deck of Cards example. Source: DecSpace [1].

The Deck of Cards method is better understood via the creation of an example. Let us imagine the case shown in Figure 4.5, created on the website http://decspace.sysresearch.org/, where four criteria have been created. These criteria were first ordered by the DMs, that decided that Criterion 1 was the most important, Criterion 2 and 3 deserved the same weight, and criterion 4 was the least important. In a very visual and intuitive way, two white cards were placed between criterion 1 and 2/3, whereas only one was placed between Criteria 2 and 3 and Criterion 4, all according to the decisions of hypothetical DMs.

Besides this, all that is left in terms of model inputs are the determination of ratio-z, the definition of the number of decimal places to which to approximate to (maximum of 2), and the desired weight type of the criteria to output (normalised, non-normalised, or both).

4.3.5 Methodology implementation

This subsection discusses how the different methods which were previously chosen will work together. The approach by which the methods will be presented is the logical order in which they will be used. By the end of this section, it will be clear how every result is calculated.

The Deck of Cards method will be implemented in two different situations:

– Creation of the interval scales that will allocate the utility values to the alternatives;

– Creation of the ratio scale that will assign values to the Choquet capacities and Möbius Coefficients;

Now that it is known what the Deck of Cards is used for, let us walk through how this process will be performed along with the DMs for the calculation of the Choquet capacities (μ) and the Möbius Coefficient capacities (m):

1. The experts for each of the three categories, one meeting for each group, will be provided with the technical criteria cards (from Stored Energy down to Distribution Network) and their respective interactions (to be decided by the DMs), all of them will from now on be called projects:

$$P = p_1, p_2, ..., p_k, ..., p_t \tag{4.10}$$

   where

$$t = n + |O| \tag{4.11}$$

2. Each group will now be asked to rank this first set of cards, from the least to the most preferred project $R_1, ..., R_h, ..., R_v$. It may happen that two or more objects will be perceived with the same value, a situation that will have no consequence as both (or more) cards will simply be placed on the same value slot;

3. A second set of blank cards will then be provided, under the name e_h, with which the DMs can now define the distance between each position by the placement of these white cards;

4. The DMs must define the value of the ratio z, which represents the amount of times the most preferred criterion is to the least appreciated one;

5. Considering r_h representative of projects in the equivalence class R_h, for $h = 1, ..., v$, the value $w(r_1) = l$ is attributed to the project r_1, considering none of the projects have null utility;

6. From now on, calculations can start to be performed, starting with the unit value

$$\alpha = \frac{l(z-1)}{s} \tag{4.12}$$

$$s = \sum_{h=1}^{v-1}(e_h + 1) \tag{4.13}$$

7. Moving up the project chain, $w(r_h)$, for $h = 2, ..., v$, is calculated using

$$w(r_h) = l + \alpha\left(\sum_{j=1}^{h-1}(e_h + 1)\right) \tag{4.14}$$

8. Each project's value can now be calculated, $w(p_k) = w(r_h)$, for all $p_k \in R_h$ with $h = 1, ..., v$, as well as their modified values

$$\overline{w}(p_k) = \begin{cases} w(p_k) \text{ if } k = i \in G \\ w(p_k) - w(p_i) - w(p_j) \text{ if } p_k = p_{ij}, \text{ for } i, j \in O \text{ and } k \geqslant n+1 \end{cases}$$

9. The Möbius coefficients can now be finally calculated with

$$m_k = \frac{\overline{w}(p_k)}{\sum_{j=1}^{t}\overline{w}(p_j)} \tag{4.15}$$

as well as the Choquet capacities

$$\mu_k = \frac{w(p_k)}{\sum_{j=1}^{t}\overline{w}(p_j)} \tag{4.16}$$

These 9 steps illustrate how the creation of the ratio scales that provide the capacities and a similar process is performed for the interval scales, described below to calculate the utilities:

1. Instead of criteria, the experts will now be provided with a set of levels (l_k) for each criterion i, that will have to be ordered from the least to the most preferred level, $\prec$ meaning strictly less preferred than the next:

$$l_1 \prec l_2 \prec ... \prec l_k \prec ... \prec l_t \tag{4.17}$$

2. Two reference utility levels are usually defined, the maximum $u(l_q) = 1$ and the minimum $u(l_p) = 0$. If more levels are to be defined, they should be evaluated consecutively;

3. The decision makers must now realise that they can define the distance between each position by the placement of the white cards, here designated as e_k, creating an order like such:

$$l_1 e_1 ... l_p e_p l_{p+1} e_{p+1} ... l_k e_k l_{k+1} ... l_{q-1} e_{q-1} l_q ... l_{t-1} e_{t-1} l_t \tag{4.18}$$

4. The utility per unit can now be calculated just by considering the minimum and maximum levels:

$$\mu\alpha = \frac{u(l_q) - u(l_p)}{h} \tag{4.19}$$

with

$$h = \sum_{x=p}^{q-1} (e_{x+1}) \tag{4.20}$$

5. The utility of each level can now also be calculated:

$$u(l_k) = \begin{cases} u(l_p) - \alpha \left(\sum_{j=k}^{p-1} e_j + 1 \right), & \text{for } k = 1, ..., p-1 \\ u(l_p) + \alpha \left(\sum_{j=p}^{k-1} e_j + 1 \right), & \text{for } k = p+1, ..., q-1, ..., q+1, ...t \end{cases}$$

It is quite obvious to understand how these steps will be applied in the subsequent meeting with the government DMs. In this meeting, the same 9+5 step procedures will be applied, but now to the criteria from Grid Short Term Performance down to By-products.

Furthermore, considering most criteria are constructed and have their interval scale, one simply needs to use the levels already defined by the criterion. Although the most prevalent type of criteria is discrete, for Stored Energy, Cost and the Performances it is necessary to establish some equidistant discrete levels that were decided to be 0%, 25%, 50%, 75% and 100%, from the worst-performing to the best performing technology.

4.4 Summary

In the end, if all the information is valid, the program will output a table with values for the weights of each criterion. All in all, the energy storage method is now finally complete and fully operational.

Besides the obvious criteria differences, different levels will be defined on a criterion by criteria basis, to be decided on the chapter 5.

Chapter 5

Case study

The preparation described in the previous chapters has led up to here, where results will be obtained. To start, the DMs will be introduced in section 5.1, followed by the data they will have to decide upon. The resulting performance table will appear in Section 5.2, followed by the analysis and discussion of the results in Section 5.3. After the results of the standard model are made, the robustness analysis will be performed in Section 5.4 following four relevant scenarios.

5.1 Stakeholders and their representatives

Each category required an expert in the area to perform and express the preferences of the sector when analysing the storage market for their specific needs. The Categories Short Term Grid and Long Term Grid preferences have been performed by Engineer André Pina, an Associate Director at Energias de Portugal (EDP); the Category Microgrid preferences have been performed by Professor Filipe Soares, a researcher on the subject at Instituto de Engenharia de Sistemas e Computadores - Tecnologia e Ciência (INESC-TEC); the Category Mobility preferences were performed by Professor Patrícia Batista, a researcher on the subject at Center for Innovation, Technology and Policy Research (IN+); and finally, the Government preferences were performed by Jerónimo Cunha, an advisor to the Deputy Minister and Secretary of State of Energy at Ministry of Environment and Climate Action, and David Oliveira, a technical specialist at the Secretary of State for Energy.

This wide range of experts, with rich and diversified backgrounds, assured the necessary technical knowledge for the completion of the decision-making process as well as the decentralisation of the decision-making power.

5.2 Data and sample

It was decided that the use of a single database was the ideal way to obtain some data integrity and for that reason it was utilised the database of the European energy storage technologies and facilities [1],

[1] https://data.europa.eu/euodp/en/data/dataset/database-of-the-european-energy-storage-technologies-and-facilities

as well as its sources. Despite there being plenty of technologies and PoVs, many of the entries were blank, which had to be completed in some cases or even whole criteria with the use of a plentitude of studies. For example, the Environmental Impact criteria performances were fully evaluated with the use of a single paper (Khawaja et al., 2019). Many other smaller and trickier gaps of knowledge had to be plugged with a plentitude of already cited studies at an almost individual level, already having been cited in Section 3.2.

5.2.1 Database

The result of the data collection can be seen below on Table 5.1, first on the technical criteria database, to be used on the meetings regarding the four categories, and then on the government criteria, to be used on the meeting with the government DMs, as well as on the intermediary table of physical adequacy, not to be used in the meetings but essential to the project.

Table 5.1: Database for the technical criteria.

Alternatives	Stored Energy (Wh/kg)	Degradation	Power Output	Reaction Rate	Cost (€/kW)	Distribution Network
PHS	2.325	Low	Average	Slow	1000	Excellent
PHES	21.8	Low	Average	Slow	350	Excellent
ACAES	42	Low	Average	Slow	1600	Excellent
CAES	33	Low	Average	Slow	800	Excellent
LAES	198	Low	Average	Slow	2000	Excellent
Flywheel	47.5	High	Low	Average	1250	Excellent
SMES	96.5	Average	Low	Fast	1350	Excellent
Supercapacitor	47.5	Average	Low	Fast	2000	Excellent
NaS	154.5	High	Average	Average	2500	Excellent
Lead acid	28	High	Average	Average	300	Excellent
$NaNiCl_2$	108	High	Average	Average	575	E/G
LiIon	282	Average	Average	Average	725	E/G
NiCD	45.5	Average	Average	Average	1000	E/G
NiMH	52	High	Average	Average	1000	E/G
VRF	35	Low	Average	Average	1400	Excellent
ZnBr RF	63	Average	Average	Average	1400	Excellent
H_2	9134.1	Low	High	Slow/Average	3500	E/N
Ammonia	2730	Low	High	Slow/Average	2400	E/N
Methane	7019.5	Low	High	Slow/Average	2400	E/N
Methanol	2887.5	Low	High	Slow/Average	2400	E/N
Gasoline	6211.5	Low	High	Slow/Average	3000	E/N
Molten salts	48	Average	Average	Slow	200	Excellent
Hot water	21	Low	Average	Average	5.05	Excellent
PCM	123.8	Average	High	Slow	10250	Excellent
TCS	218.8	Average	High	Slow	2000	Excellent

From $NaNiCl_2$ down to NiMH two values for the distribution network have to be considered in the context of Category 1/2 and Category 3, as on the two first categories no significant adaptations have to be performed, but on the mobility sector, the same can not be said. Though electricity is pretty much omnipresent, charging stations are still necessary for some situations.

Different levels can be attained by several technologies, especially the chemical options, regarding the Distribution Network criterion depending on how the technology is being planned to be connected to the grid, either electrically with self-generation or adapting existing pipelines, importing the new materials. This will be studied in the analysis of the results.

Moving onto the Reaction Rate, the chemical storage solutions present two distinct charge/discharge situations. When applied to the grid they should be analysed as any other normal and lengthy chemical rearrangement of particles, but the *de facto* experience of utilising such a service will not involve the reversion of the chemical compounds. What happens is the normal charge of fluid any person currently experiences with gas. Therefore, the process will be quite short.

Physical Adequacy is a somewhat trickier criterion and for that reason it deserves its own space, in Table 5.2. As was mentioned, this is a criterion introduced in order for technologies, as good as they may be, not to be considered in nonsensical situations, or applications that have not or will not occur.

Finally, for the government criteria, here is Table 5.3.

The performances will only be presented in the next subsection, but in the mean time the values that came out of the preferences of the decision makers and the previous two tables have already been normalised with zero for the purposes of this table. All other three criteria have already been explained and the results are quite straight forward now.

Different levels can also be attained by many technologies regarding the Environmental Impact criterion depending on how the energy that powers the storage is being generated. This will be studied in the analysis of the results on how they would change depending on this.

The Category Importance values will be given by the rankings obtained in the first three meetings with the DMs.

5.2.2 Meetings with the decision makers

Knowing in advance what was required from the DMs, an as brief as possible explanation and contextualisation to the project was provided to all the DMs. The decisions were made fully aware of their role on the overall project as well as their degrees of freedom in regards to their options within the meeting.

The first objective on each of the meetings was the realisation of the interactions between each criteria.

For Category 1 and 2, no interactions were identified. For Category 3 interactions between Stored Energy and Cost, as well as Stored Energy and Power Output were identified. For Category 4 interactions between Cost and Distribution Network, Stored Energy and Cost, Degradation and Reaction Rate and finally between Degradation and Power Output were identified. For the government criteria, interactions between Grid Short Term Performance and Grid Long Term Performance, Grid Short Term Performance and Maturity, Grid Long Term Performance and Maturity, Grid Long Term Performance and By-products, Mobility Performance and Maturity and finally Mobility Performance and Environmental

Table 5.2: Database for the Physical Adequacy criterion.

Alternatives	**Category 1**	**Category 2**	**Category 3**	**Category 4**
PHS	1	1	0	0
PHES	1	1	0	0
ACAES	1	1	0	0
CAES	1	1	0	0
LAES	1	1	0	0
Flywheel	1	0	1	0
SMES	1	0	0	0
Supercapacitor	1	0	0	0
NaS	1	1	1	0
Lead acid	1	1	1	0
$NaNiCl_2$	1	1	1	1
LiIon	1	1	1	1
NiCd	1	1	1	1
NiMH	1	1	1	1
VRF	1	1	1	0
ZnBr RF	1	1	1	0
H_2	1	1	1	1
Ammonia	1	1	1	1
Methane	1	1	1	1
Methanol	1	1	1	1
Gasoline	1	1	1	1
Molten salts	1	1	0	0
Hot water	1	1	1	0
PCM	1	1	1	0
TCS	1	1	1	0

Table 5.3: Database for the government criteria.

Alternatives	Grid Short Term Performance	Grid Long Term Performance	Microgrid Performance	Mobility Performance	Maturity	Environmental Impact	By-products
PHS	0.8290	0.6620	0.0000	0.0000	3	Habitat	Water
PHES	0.8512	0.6720	0.0000	0.0000	1	GW	Comp Air
ACAES	0.8097	0.6542	0.0000	0.0000	2	GW	Comp Air
CAES	0.8363	0.6657	0.0000	0.0000	2	GW	Comp Air
LAES	0.7992	0.6522	0.0000	0.0000	1.5	GW	Liquid Air
Flywheel	0.8515	0.0000	0.7867	0.0000	1.5	N/R	Nothing
SMES	0.9392	0.0000	0.0000	0.0000	1.5	N/R	Nothing
Supercapacitor	0.9165	0.0000	0.0000	0.0000	1.5	Toxic	Nothing
NaS	0.8760	0.4831	0.7935	0.0000	2.5	Toxic	Nothing
Lead acid	0.9473	0.5121	0.8117	0.0000	2.5	Toxic	Nothing
$NaNiCl_2$	0.9396	0.5101	0.8097	0.9218	2	Toxic	Nothing
LiIon	0.9593	0.5720	0.9087	0.9286	2	Toxic	Nothing
NiCd	0.9457	0.5622	0.9052	0.9150	3	N/R	Nothing
NiMH	0.9244	0.5025	0.8059	0.8888	3	N/R	Nothing
VRF	0.9535	0.6757	1.0000	0.0000	2	Toxic	Nothing
ZnBr RF	0.9326	0.5567	0.9019	0.0000	2	Toxic	Nothing
H_2	0.9813	1.0000	0.8464	0.7889	1	GW	Chemicals
Ammonia	0.8978	0.8121	0.7209	0.6775	1	GW	Chemicals
Methane	0.9784	0.9335	0.7652	0.7648	1	GW	Chemicals
Methanol	0.9007	0.8320	0.7453	0.6793	1	GW	Chemicals
Gasoline	0.9431	0.9137	0.7607	1.0000	1	GW	Chemicals
Molten salts	0.8352	0.5144	0.0000	0.0000	2.5	Toxic	Radiated Heat
Hot water	1.0000	0.6928	0.9753	0.0000	3	N/R	Hot Water
PCM	0.5644	0.6795	0.8165	0.0000	2.5	Toxic	Radiated Heat
TCS	0.8425	0.5324	0.9141	0.0000	1	Toxic	Radiated Heat

Impact were identified by the DMs.

From the moment of the whole list of criteria and interactions was complete, the decision makers proceeded to rank all these items, use the blank cards between the levels and evaluate the ratio-z of the ranking. The following the result from those choices.

Table 5.4: Ranking of criteria and interactions by meeting.

Levels + Ratio-z	**Category 1**	**Category 2**	**Category 3**	**Category 4**	**Government**
1st	g_4; g_5	g_2; g_3	$\{g_5, g_6\}$	$\{g_5, g_6\}$	$\{g_8, g_9\}$
Cards	0	0	0	0	0
2nd	g_3; g_6	g_1	$\{g_1, g_5\}$; $\{g_3, g_5\}$	$\{g_1, g_5\}$	$\{g_9, g_{12}\}$
Cards	0	0	0	0	1
3rd	g_1	g_5; g_6	g_5; g_6	g_5	$\{g_9, g_{14}\}$
Cards	0	0	0	0	0
4th	g_2	g_4	g_2	$\{g_2, g_4\}$	g_9
Cards	-	-	1	0	0
5th	-	-	g_1	g_4; g_6	$\{g_{11}, g_{13}\}$
Cards	-	-	0	1	0
6th	-	-	g_3; g_4	g_1	$\{g_{11}, g_{12}\}$
Cards	-	-	-	0	0
7th	-	-	-	$\{g_2, g_3\}$	g_{11}
Cards	-	-	-	0	0
8th	-	-	-	g_2; g_3	$\{g_8, g_{12}\}$
Cards	-	-	-	-	0
9th	-	-	-	-	g_8
Cards	-	-	-	-	0
10th	-	-	-	-	g_{10}
Cards	-	-	-	-	0
11th	-	-	-	-	g_{12}
Cards	-	-	-	-	0
12th	-	-	-	-	g_{13}
Cards	-	-	-	-	0
13th	-	-	-	-	g_{14}
Ratio-z	4	4	2	3	10

Most DMs identified plenty of interactions between the criteria, thus justifying the previous decision to use this specific MCDA method. Apart from the interactions, some white cards were placed to further differentiate between the importance of criteria, except for the DM who was responsible for Categories 1 and 2, who beyond not using any white cards did not as well identify any interaction, which is acceptable.

In the second stage of every meeting, the DMs simply had to rank the levels of every criterion and place white cards wherever they saw fit. It is useful to systematically present every level of every criterion in their natural and most common form. For the technical criteria the levels are the following, in decreasing order of value:

Table 5.5: Ranking levels for each technical criteria.

Levels	Stored Energy	Degradation	Power Output	Reaction Rate	Cost	Distribution Network
1st	9134.1	1	1	1	0	Excellent
2nd	6850.6	Low	High	Fast	2562.5	Good
3rd	4567.0	Average	Average	Average	5125.0	Bad
4th	2283.5	High	Low	Slow	7687.5	Non-existent
5th	0	0	0	0	10250.0	-

All the decision makers identified the previous order of the levels, the only difference where the white cards some placed, or did not. Such decisions where the following:

Category 1:

- 1 white card between levels Slow and Average on the Reaction Rate criterion;

Category 2:

- 1 white card between levels Average and Low on the Degradation criterion;
- 1 white card between levels Average and High on the Power Output criterion;

Category 3:

- 1 white card between levels Low and Average on the Power Output criterion;
- 1 white card between levels Slow and Average on the Reaction Rate criterion;

Category 4:

- 2 white cards between levels 0 and 1772.25 on the Stored Energy criterion;
- 1 white card between levels 0 and High on the Degradation criterion;
- 1 white card between levels Slow and Average on the Reaction Rate criterion;
- 2 white cards between levels 7687.5 and 10250 on the Cost criterion;
- 2 white cards between levels Non-existent and Bad on the Distribution Network criterion;
- 1 white card between levels Bad and Good on the Distribution Network criterion;

For the government criteria, as only one meeting was performed, information is more easily convened through a table with the levels, as well as the white cards, in decreasing order of value:

Table 5.6: Ranking levels for each government criteria.

Levels	Grid Short Term Performance	Grid Long Term Performance	Microgrid Perfor-mance	Mobility Perfor-mance	Matu-rity	Environ-mental Impact	By-products
1st	100	100	100	100	3	Neutral	Chemicals
Cards	0	0	0	0	0	0	1
2nd	75	75	75	75	2.5	Habitats	Radiated Heat
Cards	0	0	0	0	0	0	0
3rd	50	50	50	50	2	Toxic	Hot Water
Cards	0	0	0	0	0	0	0
4th	25	25	25	25	1.5	GW	Comp Air
Cards	0	0	0	0	0	-	0
5th	0	0	0	0	1	-	Liquid Air
Cards	-	-	-	-	-	-	1
6th	-	-	-	-	-	-	Water
Cards	-	-	-	-	-	-	0
7th	-	-	-	-	-	-	Nothing

5.2.3 Performance table

Now that all the decisions have been made, it is just a matter of making the calculations on Excel and out come the results. Below are the performances for each of the categories. All tables have the performance with and without considering the interactions to realise how much different the results would have been, with that difference being evaluated in percentage form on the right-side column.

Table 5.7 presents the data for Category 1, the Short Term Grid Performance. All technologies were evaluated in this category, as all can contribute in one way or another, better or worse, to this sector. The DM decided that no interactions occurred, which does not invalidate the methodology. It is a simple choice to opt-out of an additional degree of freedom.

Table 5.8 covers the performance on Category 2, the Long Term Grid Performance, where a few of the technologies chosen could not be options in essentially due to their high self-discharge rates and low capacities. As the decision maker was the same, no interactions where identified and there is naturally no difference in performance.

Moving on to Table 5.9, more technologies had to be removed, essentially because of the industrial size inherent to most of them, as well as the type of applications currently available or planned to be installed.

Table 5.10 has the performances for the Mobility sector, where only some technologies apply to. This category has the most physically demanding limitations in size and density, among others, therefore it is no surprise it is here most technologies have to be cut out.

Finally, aggregating all others and the decision makers preferences is Table 5.11. Much can be said and extrapolated from all these tables and has been done in the next subsection.

Table 5.7: Performance in Category 1.

Alternatives	Without Interactions	With Interactions	Difference (%)
PHS	56.8251	56.8251	0.00
PHES	58.3422	58.3422	0.00
ACAES	55.4989	55.4989	0.00
CAES	57.3237	57.3237	0.00
LAES	54.7816	54.7816	0.00
Flywheel	58.3682	58.3682	0.00
SMES	64.3782	64.3782	0.00
Supercapacitor	62.8230	62.8230	0.00
NaS	60.0484	60.0484	0.00
Lead acid	64.9356	64.9356	0.00
$NaNiCl_2$	64.4074	64.4074	0.00
LiIon	65.7578	65.7578	0.00
NiCd	64.8219	64.8219	0.00
NiMH	63.3597	63.3597	0.00
VRF	65.3607	65.3607	0.00
ZnBr RF	63.9262	63.9262	0.00
H_2	67.2597	67.2597	0.00
Ammonia	61.5363	61.5363	0.00
Methane	67.0612	67.0612	0.00
Methanol	61.7392	61.7392	0.00
Gasoline	64.6432	64.6432	0.00
Molten salts	57.2498	57.2498	0.00
Hot water	68.5449	68.5449	0.00
PCM	38.6888	38.6888	0.00
TCS	57.7495	57.7495	0.00
Average	61.0172	61.0172	0.00

Table 5.8: Performance in Category 2.

Alternatives	Without Interactions	With Interactions	Difference (%)
PHS	55.3478	55.3478	0.00
PHES	56.1803	56.1803	0.00
ACAES	54.6975	54.6975	0.00
CAES	55.6546	55.6546	0.00
LAES	54.5299	54.5299	0.00
Flywheel	0.0000	0.0000	0.00
SMES	0.0000	0.0000	0.00
Supercapacitor	0.0000	0.0000	0.00
NaS	40.3934	40.3934	0.00
Lead acid	42.8166	42.8166	0.00
$NaNiCl_2$	42.6455	42.6455	0.00
LiIon	47.8197	47.8197	0.00
NiCd	46.9989	46.9989	0.00
NiMH	42.0122	42.0122	0.00
VRF	56.4895	56.4895	0.00
ZnBr RF	46.5470	46.5470	0.00
H_2	81.0422	81.0442	0.00
Ammonia	69.2397	69.2397	0.00
Methane	78.0449	78.0449	0.00
Methanol	69.5630	69.5630	0.00
Gasoline	75.6546	75.6546	0.00
Molten salts	46.4171	46.4171	0.00
Hot water	58.1619	58.1619	0.00
PCM	44.3165	44.3165	0.00
TCS	54.5725	54.5725	0.00
Average	55.4158	55.4158	0.00

Table 5.9: Performance in Category 3.

Alternatives	Without Interactions	With Interactions	Difference (%)
PHS	0.0000	0.0000	0.00
PHES	0.0000	0.0000	0.00
ACAES	0.0000	0.0000	0.00
CAES	0.0000	0.0000	0.00
LAES	0.0000	0.0000	0.00
Flywheel	53.9004	61.5682	14.23
SMES	0.0000	0.0000	0.00
Supercapacitor	0.0000	0.0000	0.00
NaS	56.5228	62.1000	9.87
Lead acid	60.7954	63.5235	4.49
$NaNiCl_2$	60.3639	63.3689	4.98
LiIon	65.0187	71.1120	9.37
NiCd	64.0812	70.8424	10.55
NiMH	59.4099	63.0646	6.15
VRF	67.8764	78.2584	15.30
ZnBr RF	63.2955	70.5815	11.51
H_2	54.8659	65.9017	20.11
Ammonia	46.8622	58.2672	24.34
Methane	53.7218	59.8814	11.47
Methanol	47.1141	58.3244	23.79
Gasoline	51.2092	58.5245	14.28
Molten salts	0.0000	0.0000	0.00
Hot water	63.7978	76.9823	20.67
PCM	42.8945	71.2832	66.18
TCS	59.8273	62.6025	4.64
Average	57.1504	65.6580	16.00

Table 5.10: Performance in Category 4.

Alternatives	Without Interactions	With Interactions	Difference (%)
PHS	0.0000	0.0000	0.00
PHES	0.0000	0.0000	0.00
ACAES	0.0000	0.0000	0.00
CAES	0.0000	0.0000	0.00
LAES	0.0000	0.0000	0.00
Flywheel	0.0000	0.0000	0.00
SMES	0.0000	0.0000	0.00
Supercapacitor	0.0000	0.0000	0.00
NaS	0.0000	0.0000	0.00
Lead acid	0.0000	0.0000	0.00
$NaNiCl_2$	60.2165	76.9453	27.78
LiIon	62.0563	77.5154	24.91
NiCd	59.9381	76.3750	27.42
NiMH	57.9594	74.1887	28.00
VRF	0.0000	0.0000	0.00
ZnBr RF	0.0000	0.0000	0.00
H_2	53.4756	65.8484	23.14
Ammonia	48.7815	56.5491	15.92
Methane	53.4776	63.8370	19.37
Methanol	48.9539	56.6991	15.82
Gasoline	71.0890	83.4721	17.42
Molten salts	0.0000	0.0000	0.00
Hot water	0.0000	0.0000	0.00
PCM	0.0000	0.0000	0.00
TCS	0.0000	0.0000	0.00
Average	57.3275	70.1589	22.20

Table 5.11: Performance in Category Government.

Alternatives	Without Interactions	With Interactions	Difference (%)
PHS	46.2594	47.0096	1.62
PHES	35.6697	41.1581	15.39
ACAES	38.2640	40.3486	5.45
CAES	39.0144	41.2490	5.73
LAES	35.6543	39.3657	10.41
Flywheel	30.5546	37.4570	22.59
SMES	22.3768	26.9668	20.51
Supercapacitor	16.9950	20.0631	18.05
NaS	46.7886	49.4990	5.79
Lead acid	48.9643	52.0758	6.35
$NaNiCl_2$	65.8155	73.4858	11.65
LiIon	69.3958	77.7424	12.03
NiCd	79.2266	79.6238	0.50
NiMH	75.2505	75.4252	0.23
VRF	52.7054	59.7051	13.28
ZnBr RF	47.4769	53.6442	12.99
H_2	76.9261	91.6163	19.10
Ammonia	67.5711	80.5603	19.22
Methane	74.2855	88.3954	18.99
Methanol	67.7855	80.8068	19.21
Gasoline	77.9714	93.3348	19.70
Molten salts	41.9917	41.7275	-0.63
Hot water	67.0748	71.0290	5.90
PCM	48.1885	51.9584	7.82
TCS	47.2689	55.8132	18.08
Average	52.7790	58.8024	11.65

5.3 Results and discussion

For starters, the short term performance table presents the most balanced and even overall performances among all technologies. Hot Water, H_2 and Methane have the best performances by a very close margin with all other technologies, except for PCM which is severely penalised due to its significantly higher cost. Since short term grid requirements are still so broad, there is no single standout performer. On a first look, there seems to be room for all technologies, except for those that break the bank.

On the Long Term Performance table, chemical storage is by far the selected type of storage. Batteries in general and even mechanical or thermal storage are unable to compete in terms of the preferred performance. Among themselves, H_2, Methane and Gasoline are the standout achievers.

Moving onto the Microgrid, interactions have been chosen and they are proven to have a tremendous effect. TCS jumps from one of the lowest-performing technologies to one of the best. VRF keeps being the best performing technology, closely followed by Hot Water. Most other available technologies have somewhat average performances, except for the chemical storage options, certainly hampered by the difficult implementation of distribution networks and the cost associated with them. From these low performing options, H_2 stands out because of the exceptional energy density capabilities.

Regarding the Mobility performance table, the Distribution Network appears to be the most fundamental criterion. Gasoline is the best performer, not only because of its great attributes but essentially due to the infrastructure our world currently runs on. All the initial capital costs have been made for many decades, therefore it would always come as a massive advantage that all this was already put in place. Batteries do seem to be a very satisfying option, from which LiIon stands out by a thin margin. Nevertheless, every single detail matters and it does make sense as this is one of the most prevalent technologies in the sector. Other chemical storage technologies seem to lag because the distribution network takes such a significant upfront cost, even hindering their future perspectives. The interactions performed by the DM have had a massive impact, positively, on how batteries are perceived. With an above 25% upgrade in performance, these have risen from average-performing alternatives to some of the best, only surpassed by Gasoline, thus proving the importance of the consideration of this in the model.

Now, regarding the government category performances, all past performances are accounted for. It is precisely because all previous categories are accounted for that Physical Adequacy is such an important criterion. Most batteries and chemical storage solutions are the best performers here as they have been building up overall value because they can be applied in so many situations. It is therefore fair that this adaptability is rewarded when figuring out which technologies to back and invest in. On the other hand, SMES and Supercapacitors are severely handicapped for their limited applications regarding the objects at study in this project. Mechanical storage solutions have also not performed sufficiently well, as did the thermal storage solutions, with the faint exception of hot water that, throughout the project presented itself as a viable solution. It is still worth understanding that the interactions perceived by the DMs catapulted the performances of the chemical storage solutions from behind the value of the best performing batteries to reasonably more. Chemical storage is undoubtedly valuable, with several batteries in second place having well and truly showed their application potential.

Before looking into the results of the project, it is worth analysing first the preferences of the DMs.

Regarding the ordering of the levels for the technical criteria, nothing more should be added than that the choices were all logical, intuitive and simple, which can be seen by the fact that all of them chose the same order. Only the DM for Category 4 identified a substantial amount of cards as well as interactions, creating a significant differentiation between them. Completing this lack of differentiation is the fact that, because of the abundance of criteria and interaction, only the government DMs chose a higher number for the ratio-z.

Cost is almost universally picked as the most relevant criteria, except for Category 2, being surpassed by Degradation and Power Output. Besides Cost, which even has an exception, it is interesting to realise that the diversity of needs is not reflected in the diversity of preferred choices. About three technologies are always among the most desirable for all situations, having their lead only at times and at most disputed by two others.

Besides the preferences of the DMs, attention must shift now to the results. These show that in general the performance is directly related to the type of storage the technology is from. Certainly due to similarities between each other. From there, what can be perceived is that the type of storage is, most of the time first selected, followed by the technology itself.

Knowing this, it is apparent the importance of investing, maturing and creating the infrastructure for chemical storage systems, nevertheless, it is also noteworthy that there is no end all be all technology solutions. No solution solves every problem in perfection, therefore it is expected that a mix of technologies will be used (Spataru, Kok, Barrett, & Sweetnam, 2015).

It is also apparent why so much buzz has been created around chemical storage solutions, as they do appear to be useful in several situations. Regarding batteries, what has been said gains even greater relevance as there are so many storage types. Infrastructure does not seem to be such a problem as electricity is always electricity across the whole process. Since infrastructure is more malleable, the chemistry of the battery can be much more easily switched and hand-picked for the project at hand. With this information, it is no surprise that in the future, a much greater number of chemistries will be added to the database that would be able to easily incorporate them and evaluate them.

Regarding the short term grid applications, a wide range of solutions will be picked for specific purposes, as there is no singular great performer. For long term storage purposes, chemical storage systems are the best alternatives and, once ready, will play a role in the area. Overall, these results are substantiated by several pieces of literature that have expected or proposed chemical storage solutions, LiIon, SMES and PHS to be part of the energy storage mix (Shin-Ichi Inage, 2009; Pellow, Emmott, Barnhart, & Benson, 2015). Pumped hydro storage has not had the best of results in the current model, in contrast to what the IEA study suggests. Nevertheless, the study is considering technology with a variation, adjustable-speed pumped hydro storage, and dams are such a widespread technology in Portugal, as well as the knowledge that has been built up over the years, it is reasonably expected that similar systems could be implemented in Portugal simply because of the availability of existing resources.

For microgrid purposes, batteries, from which Redox Flow present themselves as a great solution (for any scale), Hot Water, LiIon and Thermochemical Storage will all be part of the conversation when choosing the best solutions for the specific purpose of a house, business or industrial complex. All of these technologies are either already in use for several years now, or are being planned and constructed (Crespo Del Granado, Pang, & Wallace, 2016; Gabrielli et al., 2020). Electrochemical storage has revolutionised this sector, creating a wider range of options for everyday people to adopt electricity specific storage options, the reason why there are plenty of companies cropping up, even a couple of automotive ones, selling electrochemical storage solutions to the average consumer. Thermochemical has the added value of radiated heat, for it has been more widely adopted by the industry.

Parra et al. (2017) also indicates LiIon and Nickel based batteries as some of the best options as short to medium term grid solutions, with RF as some the best options for medium-term requirements, indicating yet again why this technology had its best performance for the Microgrid Category, where more versatile devices are selected. Thermal storage is also expected to increase in deployments, for increasingly longer storage duration for the microgrid.

Regarding the mobility sector, gasoline has the greatest advantage that will be diluted with time, which is infrastructure. Other chemical storage solutions will require heavy capital investments to compete, an opportunity that could be time-limited, or already have passed, as several battery solutions, among which LiIon stands out, are already able to perform at a high level for the requirements. According to Arambarri et al. (2019), battery storage solutions will have fast-paced innovation in the coming years, as well as recycling and reusing at the end of life process. These evolutions in the ecosystems will be essential for the wider adoption of these systems, in line with what the current model has indicated.

Looking at the whole problem from the perspective of a political DM, chemical storages solutions do seem like the overall best performers and a great contender for higher levels of investment and development, nevertheless, due to the very significant capital costs, they did only shine on one category, long term storage. For this reason, the results require a good level of analysis, not just the mere interpretation that because of the performance in the last category, these technologies were the fundamental answer for all other purposes.

It is worth taking a closer look at LiIon and NiCd. While the first technology over-performs the latter in every technical category, in the government category an inversion occurs, due to the Maturity and Environmental Impact criteria. This is a perfect example of why the data needs to be analysed in greater depth as choosing one over the other would be in some sense looking at the rearview mirror. LiIon is the best technology of the two, being chosen by most clients over NiCd. What it does not have is a fully matured development cycle and at scale recycling systems.

5.4 Robustness analysis

In this section, four scenarios will be further studied to understand the potential value of some or all of the technologies in relevant frameworks, as well as to understand the sensitivity of the model in regards to the variance in the input values. Subsection 5.4.1 will concern only with Category 4, while Subsection 5.4.2 only with the Environmental Impact criterion, having an impact only on the Government Category. In contrast, Subsection 5.4.3 deals only with Cost, altering the performance of some technologies in every category, while Subsection 5.4.4 covers the Distribution Network criteria in the two first categories.

5.4.1 SCENARIO 1: Perfect mobility infrastructure

One of the most relevant scenarios to analyse is, with all other variables remaining the same, what would the performances of a perfect distribution network for all technologies look like.

Two caveats must be added: the chemical storage technologies are gaining the most advantage here and these options would also not reach the same level of availability as it would only be possible to charge in service stations, not at home or while parking. Taking this into considerations, it is still worth looking at the performances on Table 5.12.

Table 5.12: Performance in Category Mobility for scenario 1.

Alternatives	Without Interactions	With Interactions	Difference (%)
$NaNiCl_2$	63.5498	81.3214	27.96
LiIon	65.3896	82.6550	26.40
NiCd	63.2714	82.1721	29.87
NiMH	61.2927	79.9858	30.50
H_2	73.4756	89.1782	21.37
Ammonia	68.7815	77.4611	12.62
Methane	73.4776	84.7490	15.34
Methanol	68.9539	77.6110	12.55
Gasoline	71.0890	83.4721	17.42
Average	67.6979	82.0673	21.56

First of all, interactions play once again a massive role in all technologies. Looking at the results, the overall performances are much more balanced, being the difference from the best to the worst-performing technology only about 13% of the value of H_2. NiCd and LiIon are still the best performers in the electrochemical storage type, but this time it is slightly overcome by Gasoline, Methane, and a bit more by H_2.

One may look at the results and conclude this immediately justifies every and all investment to reach the promised future of the chemical devices, nevertheless one has to reconsider the caveats and contextualise the results. To reach this somewhat parity in performance, one would need to invest very significant amounts of capital, arguably higher for the chemical options than the electrical ones, that in turn would never reach the level of ubiquity of electricity.

The conundrum is now apparent: would it be worth all the extra investment? This project does not have in its scope the objective of answering such large and important questions, but the data, according to this model, DM preferences and database has been made available, indicating that the difference would not be very significant.

5.4.2 SCENARIO 2: Future Costs

When considering technologies, especially technologies to bet on, it is worth considering their evolution curve depending on incoming improvements research may offer.

Cost has been chosen almost universally as the most relevant technical criteria, therefore it is worth analysing what would happen to the performance of some technologies if their costs were to decrease. Fortunately, the database serving as the basis for this project had a column for the expected Capex estimated for 2030. Unfortunately, only 9 of the technologies were in luck to have received values for this entry. Furthermore, in the lack of good fortune, the data available was in €/kWh, rather than the €/kW that all technologies had been evaluated by. Nevertheless, if one was to consider that these two metrics correlate with each technology, then the fact that there is an average Capex for these same technologies would allow for the calculation of improved cost. Even with the limitations of the data available, it is worth understanding how the conclusions could change, given these advancements. Table 5.13 has the numbers used for the calculation of the expected 2030 €/kW, while Table 5.14 has the resulting performances of these values, only for the interactions.

Table 5.13: Data for Cost for scenario 2.

Alternatives	Average Capex in 2016 (€/kWh)	Capex Estimated for 2030 (€/kWh)	Change in %	Cost (€/kW)	Capex Estimated for 2030 (€/kW)
PHS	19	19	0	1000	1000.00
CAES	47	40	-14.89	800	680.85
Flywheel	2750	1750	-36.36	1250	795.45
NaS	330	143	-56.67	2500	1083.33
Lead Acid	220	110	-50.00	300	150.00
$NaNiCl_2$	350	143	-59.14	575	234.93
LiIon	520	200	-61.54	725	278.85
VRF	300	100	-66.67	1400	466.67
ZnBr RF	800	275	-65.64	1400	481.25
Average	-	-	-45.66	-	-

The improvements in cost are very significant, being on the average of about 50%. It is evidently, and as stated an estimation, but one that could have a very significant impact on the projects' results.

Unsurprisingly, PHS has no price enhancement. It already is a well-established technology in which no significant improvements are expected. All other are not fully matured.

First of all, such a significant change especially for the electrochemical storage devices does not represent a change as significant as could be expected in the overall performance of the devices. This

Table 5.14: Performance in all categories for scenario 2.

Alternatives	Category 1	Category 2	Category 3	Category 4	Category Government
PHS	56.8251	55.3478	0.0000	0.0000	47.0096
CAES	57.5972	55.7999	0.0000	0.0000	41.3847
Flywheel	59.4116	0.0000	61.8718	0.0000	37.7067
NaS	63.3004	42.1210	63.0462	0.0000	51.1606
Lead Acid	65.2800	42.9996	63.6237	0.0000	51.1630
$NaNiCl_2$	65.1880	43.0602	63.5960	79.8303	74.8199
LiIon	66.7819	48.3638	71.4100	81.3004	79.5113
VRF	67.5032	57.6277	78.8819	0.0000	60.7683
ZnBr RF	66.0352	47.6674	71.1952	0.0000	54.7008

may indicate a lack of sensitivity and differentiation on the lower-cost alternatives, due to the lack of white cards placed by the DMs. Nevertheless, these changes do exert some influence, as LiIon and VRF close the gap on Category 1 on the front runners. In Category 3, VRF even becomes the most desirable technology, while on Category 4 $NaNiCl_2$ and LiIon become very close to reaching parity with Gasoline. At the governmental level LiIon, just with cost reductions, is at 0.0026% from becoming the most desirable electrochemical storage device, even if no improvements to recycling and maturity are made.

In conclusion, besides any limitations that will be explored on Section 6.3, if the technologies fulfil their expected potential by 2030, different decisions at that time might have to be made at several sectors of the market. This does indicate that, when deciding on what technologies to bet on at the present, one has to consider the, ever so difficult and subjective to predict, evolution of the alternatives, even when analysing the present data.

5.4.3 SCENARIO 3: Best Environmental Impact

Considering that nowadays the environmental impact is such a relevant criterion on the agenda it would be ideal that the technologies meant to help transition the world to sustainable energy were themselves not damaging to the ecosystem. In this subsection, the best possible performances in the Environmental Impact criteria will be considered, all other performances remaining the same, even though these decisions would incur several meaningful externalities, at least in cost.

To achieve such a performance it will be given to the purely toxic technologies the value of reusable, considering these devices could be entirely recycled, as so many others already are.

For the ones that require, as of today, the charging via petroleum derivatives to charge, will be given the value of no impact, considering these technologies would be powered by renewable energy.

For the ones that, all things considered, still have a sizeable impact on the habitat, no better ranking than this can be given. Table 5.15 shows the performance on the criteria and the impact on the end result.

Table 5.15: Performance in Category Government for scenario 3.

Alternatives	Performance in g_{13}	Without Interactions	With Interactions	Difference (%)
PHS	Habitat	46.2594	47.0096	1.62
PHES	N/R	42.4020	49.7943	17.43
ACAES	N/R	44.9963	48.9847	8.86
CAES	N/R	45.7467	49.8851	9.05
LAES	N/R	42.3866	48.0018	13.25
Flywheel	N/R	30.5546	37.4570	22.59
SMES	N/R	22.3768	26.9668	20.51
Supercapacitor	N/R	22.0443	26.5402	20.40
NaS	N/R	51.8379	55.9761	7.98
Lead Acid	N/R	54.0136	58.5529	8.40
$NaNiCl_2$	N/R	70.8648	78.7247	11.09
LiIon	N/R	74.4451	82.9687	11.45
NiCd	N/R	79.2266	79.6238	0.50
NiMH	N/R	75.2505	75.4252	0.23
VRF	N/R	57.7546	66.1822	14.59
ZnBr RF	N/R	52.5262	60.1213	14.46
H_2	GW	76.9261	91.6163	19.10
Ammonia	GW	67.5711	80.5603	19.22
Methane	GW	74.2855	88.3954	18.99
Methanol	GW	67.7855	80.8068	19.21
Gasoline	GW	77.9714	93.3348	19.70
Molten Salts	N/R	47.0409	46.4490	2.47
Hot Water	N/R	67.0748	70.1055	5.90
PCM	N/R	53.2378	61.5756	9.76
TCS	N/R	52.3182	59.5457	19.06
Average	-	55.8759	62.6755	12.63

Before starting the analysis, it is worth stating that PHS had to keep its habitat disruption level because, even with the best of efforts, it can not be avoided. Besides PHS, all others can eventually be recycled or powered in some other way, except for all the chemical storage technologies. These devices will ultimately lead to global warming, as the chemicals themselves or their by-products. Even water vapour causes global warming, therefore, it must be accounted for (Held & Soden, 2000).

When considering that the criterion was in part eliminated and that the overall results showed no significant change, one can conclude that the Environmental Impact criterion has little impact on the overall performance of the technologies.

Knowing this, chemical storage devices are still by far the best choice but now by a thinner margin to the electrochemical storages options. Beyond these highlights not much standouts out regarding other technologies.

On the one hand, improvements to the Environmental Impact of the storage technologies are positive, especially to those who require a recycling process at the end of their usable life and those that are powered by fossil fuels, as of now. On the other hand, these improvements do not seem essential to their adoption.

5.4.4 SCENARIO 4: Pipelines

Up to now, all technologies have been considered to be generated at a certain location in Portugal and connected electrically to the grid. As a final scenario to take into consideration, it could be relevant to analyse how significantly the performances would be impacted if the chemical storage devices were imported using the existing infrastructure for gas, instead of the one produced in Portugal.

As the infrastructure is to be adapted, the performance in the Distribution Network criteria will be assigned the value Bad, as it would require significant adaptations, but it is not non-existent.

As the DM for Categories 1 and 2 identified no interactions, it is redundant to present the same information twice. Furthermore, only H_2 and Methane have been seriously considered for these adaptations, besides being part of the only technology type that performed well on both categories, which is in line with what has been found in the project as these two are by some margin the best performing technologies in the chemical storage type across all categories (Adam, Heunemann, von dem Bussche, Engelshove, & Thiemann, 2020). Table 5.16 shows the results for the first two categories, while Table 5.17 has the information for the Government category.

Table 5.16: Performance in Categories 1 and 2 for scenario 4.

Alternatives	Category 1 - Before	Category 1 - After	Category 2 - Before	Category 2 - After
H_2	67.2597	55.4950	81.0442	72.7109
Methane	67.0612	55.2965	78.0449	69.7116

Table 5.17: Performance in the Government category for scenario 4.

Alternatives	Before	After Without Interactions	After With Interactions	After - Difference (%)
H_2	91.6163	73.2239	87.8449	19.97
Methane	88.3954	70.5030	84.4449	19.77

Imported H_2 and Methane via existing gas pipelines are still two very well-performing technologies in the end. The overall decrease has not been very significant, allowing them to maintain their level of interest. The same can be said for Category 2 where the chemical solutions were by far the most appealing. The chemical technologies would have to be severely penalised for any other technology to start being considered at the same level. Regarding Category 1, the same can not be said as the tremendous competitiveness in this category does not allow any margin for less desirable performances.

In conclusion, the model indicates that for short term energy needs, it would make sense to have the generation of the chemicals in the country, while for longer-term storage requirements this self-generation could be complemented in international markets, which seems to be sustained by logic.

Before ending, let us try to fit the pieces together on what the future, according to the suggestions of the model could look like. In a renewable future when Portugal and the World were to have a significant amount of energy produced by solar, the winter months would be energy poor. To compensate for this lack of power one would have to store very significant amounts of energy from the sunny summer months, or store less energy and import some other percentage from sunnier locations of the globe during this period. As luck would have it, northern Africa has some of the countries with higher levels of solar irradiation, as these countries are closer to the equator. Furthermore, these regions have plenty of unused space due to the Sahara desert. Solar energy farms producing H_2/Methane and sending it through pipelines into Europe may be the answer to some of the continents future energy demands. Finally, not by luck but by design, the existing gas pipelines connecting Portugal to Spain and the rest of the continent originate in northern Africa, for further partnerships and international co-operations between the continents is to be expected (van Wijk & Wouters, 2020).

5.5 Summary

In this chapter, the data was finally analysed and the results calculated. For this to be possible, the data had to be translated into a numerical performance format. Stored Energy and Cost, as well as all the Performances coming out of the first four categories, had to be normalised. Beyond that, all values received the performance recognised to them by the DMs. After the utilities had been found, results could be reached by incorporating the ranking and interactions. All came together in the end, the results had been reached and with that verdicts were possible. Other than the already performed data and robustness analysis, further conclusions regarding the achievements, recommendations, limitations and future developments on the topic are presented.

Chapter 6

Conclusions and future remarks

6.1 Achievements

The main objective of this dissertation was to evaluate a wide range of technologies in different scenarios, with a combination of interactive variables that integrated the preference of several DMs, to create a clearer picture of their worth in the future of the energy storage market.

As far as could be searched at the time of writing this dissertation, the use of the Choquet integral methodology had never applied anywhere, and more specifically in Portugal, a multicriteria decision-making project had never been done, this being to the energy storage sector and with the scope and objectives of this project.

To achieve this outcome, a lengthy literature review was performed in Chapter 3 to attain a profound and complete knowledge of the technologies available and problem at hand, as a basis for the construction of the model utilising the Choquet multi-criteria preference aggregation model developed by Bottero *et al.* (2018), as detailed in Chapter 4. Having the model finalised, it was then to the case study, in Chapter 5, where five different categories were confirmed and assessed with the cooperation of the DMs. Further, a robustness analysis was performed while studying how the technologies would perform in different scenarios beyond the base case.

Comparing the results obtained with the literature it was then possible to establish their validity, as well as those of the choices made when constructing the model. This in turn sets up the model as a reasonable and well-founded alternative to the evaluation of technologies, indicating a new way in which to perform decision-making choices in the energy storage sector.

In the end, a review of all the objectives must be performed to assess whether they have been successfully achieved. Therefore:

– A deep understanding of the energy generation and storage state of affairs in Portugal has been developed;

– The current capabilities and limitations of the available energy storage solutions on a technological level have been recognised;

– The multi-criteria problem has been verified and analysed;

– The criteria interactions have been recognised by the DMs, with clear impacts to the performances of the alternatives, justifying the use of the Choquet multiple criteria preference aggregation model;

– Each alternative has been evaluated according to the defined criteria;

– Several rankings of technologies have been created according to the preferences of the DMs for each category, and at a governmental level;

– The results and preferences of the choices performed by the DMs have been analysed;

– The robustness analysis has been performed, with relevant data being brought forward to the current decision-making processes.

6.2 Recommendations

The most fundamental recommendation is that further technological development in the energy storage sector is desirable. Nevertheless, current options are already quite reasonable and can perform at an appropriate level, the reason for which most of them can be perceived as real alternatives in the present.

Moving on to more specific recommendations, two energy storage types appear to be the overall future winners in almost every sector of the market, electrochemical batteries and chemical storage, with hot water being a very interesting alternative. Therefore, it is of no surprise that investing in infrastructure capable of accommodating and anticipating the advent of these technologies, Portugal would place itself at the forefront of innovation.

Regarding the short term grid storage, there is no clear cut recommendation to be made. Knowing that Portugal already has so many dams, adaptations could be performed to allow for this process to occur in a given number of them, utilising and optimising the existing resources. Further solutions emerge when looking at other categories.

In terms of long term storage, chemical storage is the clear cut winner, where H_2 is certain to play a role.

Furthermore, when looking into the microgrid category electrochemical batteries, such as Redox Flow and Lithium-ion stand out, as well as Hot Water. The creation of microgrids could be incentivized, creating not only self-sustaining localities connected to the already subsidised self-generation of power, but also dispersing the capital investments done to create several potentially unnecessary power plants.

Investment in these two previous categories may help not only themselves but also the short term grid balance, creating a bundle of options to be used as necessary in conjunction among themselves.

Finally, the mobility sector is somewhat contentious because any of the solutions will involve some necessary infrastructure investments. What needs to be considered is the cost-benefit analysis. Chemical storage devices do not seem to be worth the tremendous amounts of money for a potentially more limited distribution network as several batteries can and will perform at a very satisfying level.

Beyond the technical categories, H_2 and other derivatives did emerge as the most appealing political investment since it can perform so well in several categories, but can also be applied in several other relevant industries due to its chemical properties. What can be concluded from the project is that these are promising technologies, but others will be necessary, especially at the consumer level.

To recommend Power to x is not a particularly controversial statement, as is also the recommendation of electrochemical devices such as Lithium-ion batteries. Other multicriteria decision-making projects, applied to the energy storage market, have reached similar conclusions regarding some of the best performing technologies this dissertation has highlighted (Raza et al., 2014; Baumann et al., 2019).

6.3 Limitations

The most pressing issue with the project is that the cost values for some chemical storage devices, beyond H_2, provided by the database used in this dissertation are not coherent. What is meant by this is that it is hard to understand how a more complex process, whether Methane or Methanol which use the same electrolysis process H_2 does, can have lower cost values than the simpler chemical.

This brings into question the need to create and keep a database up to date with several predetermined criteria because it is so hard to come up with an extensive and complete dataset from which unequivocal conclusions can be extrapolated.

Not trying to put into question the decisions of the DMs, it can be at times, difficult to properly establish the intended differentiation in value between criteria and their levels, as this project DMs were at times reluctant to use more white cards and provide higher values for the ratio-z.

The final limitation has been somewhat self-imposed from the offset, as this project is not to be perceived as to give the unquestionable best alternative in every category for every single implementation situation.

6.4 Future work

Following what has just been said, the creation of a complete and universally accepted database is the first order of business. Information is unnecessarily dispersed and at some points contradictory, which are more than enough reasons, not only for academia but also for clear and more transparent decision making processes.

Beyond the database, more granular and specific work could and should be done at a regional and local level, allowing for a greater and clearer decision making process for the public to understand. The same methodology could be easily applied to individual projects, granting a much better adjustment of performance to the real and concrete applications.

It may also be worth differentiate to a higher level the short term grid storage category to a small and high scale, to get a better sense of the high and low performing technologies in this sector of the market.

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