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

André Pereira
andre.alves.pereira@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

November 2021

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 the 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

1. Introduction

With the realisation that all that is not renewable is going to run out at some point, renewable energy generation is inevitable. Although generation technologies are still in development, it has become common sense to believe in this transition. However, as renewable sources increase in significance, so will their problems. Therefore, it is only logical that storage systems must be implemented in parallel to account for this and it is precisely here an opportunity emerged to develop this project.

Several objectives were first put forward - the development of a deep understanding of the energy generation and storage state of affairs in Portugal; the recognition of the current capabilities and limitations of the available energy storage solutions on a technological level; analysis and understanding of the issue, identifying how it is a multi-criteria problem; identification of how the criteria interact with each other, requiring the use of the Choquet multiple criteria preference aggregation model; evaluation of each alternative according to the defined criteria; creation of a ranking of technologies according to the preferences of the decision-makers (DMs) for each category, and at a governmental level; study of the results and preferences of the choices performed by the DMs; and finally the conduction of robustness analysis to validate and further analyse the variability in the results, to explore future possibilities that may help make decisions in the present.

With all the objectives defined, it was then time to establish the eight methodological steps that would guide the project to fruition:

1. Identification of the monumental problem of managing the ever-changing electrical grid;

2. Description of the problem;

3. outline the importance of performing in-depth research of the sector, setting up the foundations of the dissertation;

4. Creation of a model for the issue;

5. Collection of data, to operationalise the criteria;

6. Implementation of the whole model, following the meetings with the DMs;

7. 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. At last, the final conjectures and conclusion of the project.

2. Knowledge gap

2.1. Sectors

Even though this project is focused on the energy storage sector, it can not be analysed without looking first at the energy supply. In Portugal, in the last few decades, natural gas has significantly increased in importance as well as renewables such as hydro, wind and solar, even though on a smaller scale. Oil, and especially coal, have entered a significant decline in the same period. It can be concluded therefore that Portugal has been moving in the right direction, although by essentially switching from oil and coal to natural gas. Nevertheless, it has been progressively investing in renewables. This leaves Portugal still quite far away from its 2030 (and 2050) clean energy goals and for this reason, it is worth looking in more detail at the renewable sources.

Regarding just renewables, it becomes clear that wind has been by far the most invested in technology since the turn of the century. Solar photovoltaics (solar PV) would be expected to be far more relevant, especially when new solar farms are constantly being inaugurated in Spain, but the technology has not yet taken off in the country. Meanwhile hydro appears to have peaked and remains somewhat stable. Geothermal has minuscule relevance overall, even though at a local level, especially in Portugal's smaller islands this apparent low energy output may be extremely significant. All in all, solar PV is expected to grow exponentially in the coming years, with increases whenever possible in wind, hydro and geothermal, although these three sources are far more geographically limited on a fundamental level.

The relationship between energy storage and renewable energy supply has already been established so it is no surprise to see that energy storage deployment has exponentially increased worldwide not just as a whole, but year on year. Yet again it is unsurprising to see the greatest investors in these technologies have been the fastest countries moving into a renewable long term future.

Regarding Portugal, and considering hydro rivals some other energy generation sources, it is obvious that this technology dominates the storage sector, making over 99% of the market. This does not leave a lot of room for other technologies, but flywheel and battery projects have been installed, especially in the Azores islands. Hydropower has dominated the segment, but in recent years the emergence of alternatives shows that this technology is not infinitely scalable.

Therefore, when looking at the energy storage market it is easy to identify that there are essentially two clients who have an interest in acquiring energy storage solutions - grid providers and individuals.

Four categories have been chosen. Category 1 will represent the grid providers needs on the short term duration, while Category 2 relates to the long term. Category 3 is intended to represent the microgrid alternative which is the possibility of any individual or company to install their energy generation and storage grid, making any building or area possibly autonomous. In the limit, if everyone wanted to, despite probably not making the most financial sense, they could become their microgrids, therefore, it is essential to consider. Finally, Category 4 is the Mobility sector which is a category all of its own. It is not very significant that all these categories are not equally relevant, at least from a consumption standpoint, or even that the lines between them may get blurry, as the DMs should be able to account for this.

2.2. Technologies

The following technologies are going to be taken into consideration - **Mechanical storage**: Pumping Hydro storage (PHS), Pumped Heat electrical storage (PHES), Adiabatic Compressed Air energy storage (ACAES), 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 batteries (VRF), 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, Sensible Thermal energy storage (STES), Phase Change Materials (PCM), Thermochemical storage (TCS).

All of them were introduced in greater detail in the dissertation, nevertheless, it is relevant to summarise the groups. Mechanical storage accumulates energy in kinetic and potential form; the extraction format usually uses the spinning of a turbine or motor. Electrical storage is the accumulation of energy in an electromagnetic field. Electrochemical storage is the batteries sector, with the basics for all of them being 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. In Chemical storage, 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. Thermal storage uses 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.

Each technology has been explained and characterised in much greater detail in the dissertation. Furthermore, it was decided to leave all the sources that were used to learn about the storage device as well as where the data was extracted from, in each technology's sub sub section.

Of all these options, Portugal has in essence only one implementation of storage systems - hydro - so the grid is in reality still being balanced by fossil fuels, although Portugal has heavily invested in renewable energy generation in the last few decades.

3. Methodology

3.1. Criteria

The aforementioned solutions have to be characterised in detail and ranked according to a set of criteria. Knowing that it is inadequate to consider dozens of criteria in a model, some of the many points of view taken into consideration had to be aggregated.

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 Capital expenditure (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.

3.2. Overview of the model

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 set of the categories. 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. It should be noted that usually, 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 mode, which considers 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 will be used. When all is said and done, a robustness analysis will be performed to validate the results.

3.2.1 Choquet integral

The Choquet integral is only one of many functions or methodologies to create rankings or value functions. Out of all the options available, the Choquet integral can account for positive or negative interactions between criteria, interactions that were considered to occur but only the DMs would be able to certify. The Choquet integral can be formulated as (Bottero, Ferretti, Figueira, Greco, & Roy, 2018):

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

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 $u_0(g_0(a_k)) = 0$.

3.2.2 Möbius transformation

The Möbius function of the Choquet integral can be formulated as (Pereira, Machete, Ferreira, & Marques, 2020):

$$\begin{aligned} C_\mu(a_k) = & \sum_{g_i \in G} m(g_i) u_i(g_i(a_k)) + \\ & + \sum_{g_i, g_j \in O} (m(g_i, g_j) * \\ & * \min\{u_i(g_i(a_k)), u_j(g_j(a_k))\}) \end{aligned} \tag{2}$$

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. 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.

3.3. Deck of Cards method

Finally in the methodology, the Deck of Cards is the methodology to create the value functions and compute the Möbius coefficients. It is rather easy to use with the DM simply ordering the criterion or levels from the least to the most important and the beginning to fill the spaces between the criteria with the number of cards they deem necessary to contrast the difference in weight.

All that is left is to define the ratio-z in the program and it outputs a normalised or non-normalised set of results for the weights.

4. Case study

4.1. Overview

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 [1] 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 cited in the technologies described in the dissertation.

4.2. Stakeholders and their representatives

Each category required an expert in the area to perform and expressed 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. Their decisions can be viewed in the dissertation document.

4.3. Database

The following tables are the result of the criteria choices and their performances as described in the literature.

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

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

Table 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

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 people currently experience 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 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 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

Table 2: Database for the criterion Physical Adequacy.

Alternatives	C1	C2	C3	C4
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

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.

4.4. Performance table

Below are the performances for each of the categories. Taking into consideration that most DMs identified interactions, the data featured on Table 4 incorporates all of the decisions. In the dissertation a comparison for every category was made with the results not accounting for the interactions to further validate the choices in the model.

5. Results and discussion

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-

Table 3: Database for the government criteria.

Alternatives	Grid Short Term Performance	Grid Long Term Performance	Microgrid Perfor-mance	Mobility Perfor-mance	Matu-rity	Environ-mental 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

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.

In the full project, a robustness analysis was performed following four relevant scenarios. The first scenario relates to the eventuality of all technologies achieving maximum performance in the distribution network in Category 4, where some chemical storage solutions manage to overcome the best performing electrochemical ones, but not by a wide margin. Scenario 2 analysis how well some of the technologies would perform if the estimated cost for 2030 was achieved, with some of them climbing up the ladder, as VRF becomes the most desirable tech-

Table 4: Performance for all Categories.

Alternatives	Category 1	Category 2	Category 3	Category 4	Category Government
PHS	56.8251	55.3478	0.0000	0.0000	47.0096
PHES	58.3422	56.1803	0.0000	0.0000	41.1581
ACAES	55.4989	54.6975	0.0000	0.0000	40.3486
CAES	57.3237	55.6546	0.0000	0.0000	41.2490
LAES	54.7816	54.5299	0.0000	0.0000	39.3657
Flywheel	58.3682	0.0000	61.5682	0.0000	37.4570
SMES	64.3782	0.0000	0.0000	0.0000	26.9668
Supercapacitor	62.8230	0.0000	0.0000	0.0000	20.0631
NaS	60.0484	40.3934	62.1000	0.0000	49.4990
Lead acid	64.9356	42.8166	63.5235	0.0000	52.0758
$NaNiCl_2$	64.4074	42.6455	63.3689	76.9453	73.4858
LiIon	65.7578	47.8197	71.1120	77.5154	77.7424
NiCd	64.8219	46.9989	70.8424	76.3750	79.6238
NiMH	63.3597	42.0122	63.0646	74.1887	75.4252
VRF	65.3607	56.4895	78.2584	0.0000	59.7051
ZnBr RF	63.9262	46.5470	70.5815	0.0000	53.6442
H_2	67.2597	81.0422	65.9017	65.8484	91.6163
Ammonia	61.5363	69.2397	58.2672	56.5491	80.5603
Methane	67.0612	78.0449	59.8814	63.8370	88.3954
Methanol	61.7392	69.5630	58.3244	56.6991	80.8068
Gasoline	64.6432	75.6546	58.5245	83.4721	93.3348
Molten salts	57.2498	46.4171	0.0000	0.0000	41.7275
Hot water	68.5449	58.1619	76.9823	0.0000	71.0290
PCM	38.6888	44.3165	71.2832	0.0000	51.9584
TCS	57.7495	54.5725	62.6025	0.0000	55.8132
Average	61.0172	55.4158	65.6580	70.1589	58.8024

nology in Category 3. In Scenario 3, the best-case scenario for all of the possible technologies that can improve in the Environmental Impact criterion was explored, with the conclusion being that this criterion, despite being quite talked about, will not be the deciding factor in technological adoption. Finally, Scenario 4 explored the possibility of any of the chemical storage solutions adapting the existing pipeline infrastructure from gas to their chemical requirements, where for the long term storage requirements it was found that importing these chemicals could be interesting.

6. Conclusions

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 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 the Methodology. Having the model finalised, it was then to the case study, in Section 4, 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.

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.

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 technology for this sector of the market.

References

Arambarri, J., Hayden, J., Elkurdy, M., Meyers, B., Hamatteh, Z. S. A., Abbassi, B., & Omar, W. (2019). Lithium ion car batteries: Present analysis and future predictions. *Environmental Engineering Research*, *24*(4), 699–710. doi: 10.4491/eer.2018.383

Bottero, M., Ferretti, V., Figueira, J. R., Greco, S., & Roy, B. (2018). On the Choquet multiple criteria preference aggregation model: Theoretical and practical insights from a real-world application. *European Journal of Operational Research*, *271*(1), 120–140. Retrieved from `https://doi.org/10.1016/j.ejor.2018.04.022` doi: 10.1016/j.ejor.2018.04.022

Crespo Del Granado, P., Pang, Z., & Wallace, S. W. (2016). Synergy of smart grids and hybrid distributed generation on the value of energy storage. *Applied Energy*, *170*, 476–488. Retrieved from `http://dx.doi.org/10.1016/j.apenergy.2016.01.095` doi: 10.1016/j.apenergy.2016.01.095

Gabrielli, P., Acquilino, A., Siri, S., Bracco, S., Sansavini, G., & Mazzotti, M. (2020). Optimization of low-carbon multi-energy systems with seasonal geothermal energy storage: The Anergy Grid of ETH Zurich. *Energy Conversion and Management: X*, *8*(July), 100052. Retrieved from `https://doi.org/10.1016/j.ecmx.2020.100052` doi: 10.1016/j.ecmx.2020.100052

Parra, D., Swierczynski, M., Stroe, D. I., Norman, S. A., Abdon, A., Worlitschek, J., ... Patel, M. K. (2017). An interdisciplinary review of energy storage for communities: Challenges and perspectives. *Renewable and Sustainable Energy Reviews*, *79*(March), 730–749. Retrieved from `http://dx.doi.org/10.1016/j.rser.2017.05.003` doi: 10.1016/j.rser.2017.05.003

Pellow, M. A., Emmott, C. J., Barnhart, C. J., & Benson, S. M. (2015). Hydrogen or batteries for grid storage? A net energy analysis. *Energy and Environmental Science*, *8*(7), 1938–1952. doi: 10.1039/c4ee04041d

Pereira, M. A., Machete, I. F., Ferreira, D. C., & Marques, R. C. (2020). Using multi-criteria decision analysis to rank European health systems: The Beveridgian financing case. *Socio-Economic Planning Sciences*, *72*(July), 100913. Retrieved from `https://doi.org/10.1016/j.seps.2020.100913` doi: 10.1016/j.seps.2020.100913

Shin-Ichi Inage. (2009). *Prospects for Large-Scale Energy Storage in Decarbonised Power Grids* (Tech. Rep.). International Energy Agency. Retrieved from `https://www.iea.org/reports/prospects-for-large-scale-energy-storage-in-decarbonised-power-grids`