Possible scenarios for the electric system by 2050

Portugal case

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Abstract

Like many other institutions and companies, the European Commission and the EU member states resort to energetic models to support policy making and market design.

Energetic models are not carried out as a precise prediction exercise but as a means to outline possible scenarios and explore possible futures. This report aims to study possible solutions for the Portuguese electric system, with a carbon emission mitigation and an energetic dependency perspective in mind.

Considering security of supply, weighing together Portugal's current energetic dependency on fossil fuels, their future investment in renewable energy sources and the intermittency and irregular over and under renewable production, it is justifiable for Portugal to invest in storage technologies and/or other system adjustment mechanisms such as demand side management.

The most immediate storage solution for Portugal, as discussed extensively in many papers, news, and theses (for example [19], [21], [22]), is the electricity storage through pumped hydroelectricity.

In this work the main motivation is to find and compare to pumped hydroelectric storage other storage technologies, study their adoption conditions and impact in Portugal's electricity generation cost.

The selected energy storage systems were: pumped hydroelectric storage, lithium ion batteries and power-to-gas.

For all these storage systems was calculated and compared their impact on the electric energy generation cost, on the country's energetic dependency and on the emissions of CO_2.

It was also briefly discussed demand side management as a non-technological approach to reach the same emissions mitigation goal.

Pumped hydroelectric storage remains as a good storage solution however, in many aspects, a power-to-gas approach to the problem would overtake this first solution.

Within a P2G strategy were considered different scenarios which, depending on the desired outcome, presented different viable possible futures for the Portuguese electric system.

From an emissions mitigation and a renewable electricity point of view was concluded that Portugal is on the right track to achieve the desired goals.

Keywords: electric system, Pumped Hydroelectric Storage, Li-ion battery, Power-to-Gas, Demand Side Management, electricity generation cost

Resumo

Tal como muitas outras instituições e empresas, a Comissão Europeia e os estados membros da EU recorrem a modelos energéticos como forma de apoiar as políticas tomadas e a organização do mercado.

Os modelos energéticos não são realizados com um exercício de previsão, mas como um meio de delimitar possíveis cenários futuros. Esta dissertação tem como objectivo estudar possíveis soluções futuras para o sistema eléctrico português, tendo em mente tanto uma perspectiva de mitigação de emissões como uma perspectiva de dependência energética

Considerando a segurança da oferta de energia, juntando algumas variáveis como (1) a actual dependência em combustíveis fósseis, (2) o futuro investimento em fontes de energias renováveis e (3) a intermitência e sub e sobreprodução renovável em Portugal, justifica o investimento em tecnologias de armazenamento de energia e/ou outros mecanismos de ajuste do sistema tal como “demand side management”.

A solução de armazenamento mais imediata para Portugal tem sido, já extensivamente discutida ([19], [21], [22]), o armazenamento eléctrico em barragens com bombagem (reversíveis).

A principal motivação deste trabalho é encontrar e estudar as condições de implementação e o impacto no custo de geração de electricidade de outras tecnologias de armazenamento eléctrico quando comparadas com as barragens reversíveis.

As tecnologias de armazenamento selecionadas foram: barragens reversíveis, baterias de lítio e “power-to-gas”.

Para todos estes sistemas de armazenamento foi calculado e comparado tanto o seu impacto no custo de geração de electricidade como o impacto na dependência energética do país como também o impacto nas emissões de CO_2.

Foi também brevemente discutido “demand side management” como uma medida não tecnológica de atingir os mesmos objectivos em termos de atenuação de emissões.

As barragens reversíveis permanecem uma óptima solução para o país, no entanto em vários aspectos uma abordagem “power-to-gas” ultrapassou esta primeira solução.

Dentro da estratégia de P2G foram considerados vários cenários que, dependendo do resultado final pretendido, apresentavam diferentes futuros possíveis para o sistema eléctrico português.

De um ponto de vista de atenuação das emissões e electricidade renovável, concluiu-se que Portugal encontra-se no caminho certo para atingir os objectivos estabelecidos.

Palavras-chave: sistema eléctrico, barragens reversíveis, baterias de lítio, “Power-to-Gas”, “Demand Side Management”, custo de geração de electricidade

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List of abbreviations

€'18	Euro 2018 (monetary value)
APREN	Associação Portuguesa das Energias Renováveis
CF	Capacity Factor
CH_4	Methane
CO_2	Carbon Dioxide
DSM	Demand Side Management
EDPR	EDP (Energias de Portugal) Renewables
ENTSO	European Network of Transmission System Operators
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EU	European Union
GHG	Greenhouse Gas
GRHYD	Gestion des Réseaux par l'Hydrogène pour Décarboner les energies (grid management through the injection of hydrogen for energy decarbonization)
GWh	Giga Watt hour
H_2	Hydrogen
IEA	International Energy Agency
INEGI	Instituto Nacional de Ciências e Inovação de Engenharia Mecânica e Engenharia Industrial
IRENA	International Renewable Energy Agency
IoT	Internet of Things
ktoe	Kilo tonne of oil equivalent
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
Li-ion battery	Lithium-ion battery
MWh	Mega Watt hour
NG	Natural Gas
NGV	Natural Gas Vehicles
NREAP	National Renewable Energy Action Plan
n.d.	Non determined
PHS	Pumped Hydroelectric Storage
PV	Photovoltaic
P2G	Power-to-Gas
P2G w/ Dec	Power-to-Gas strategy with normal NG plants decommission
P2G w/ Dec 2040	Power-to-Gas strategy with delayed NG plants decommission, starting in 2040
P2G w/o Dec	Power-to-Gas strategy without NG plants decommission
RE	Renewable Energy
RES	Renewable Energy Sources
SWOT	Strengths Weaknesses Opportunities and Threats
toe	Tonne of Oil Equivalent
TYNDP	Ten Year Network Development Plan

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1. Introduction

1.1. Motivation and objectives

Europe is taking measures to (1) decrease carbon emissions, (2) increase the share of renewable energy in the energy supply mix and (3) increase energy efficiency. [7]

According to the International Renewable Energy Agency IRENA report (Global energy transformation: A roadmap to 2050 [38]), two main evolutions of the energy sector - increased use of renewable energy, combined with intensified electrification - could prove decisive for the world to meet key climate goals by 2050. Hence, increased renewable share and lower carbon emissions often come hand in hand with a higher share of electricity in the final energy demand.

To achieve such goals, several different strategies are being followed. Different strategies among the countries, and even within each country, but every time, though, increasing the production of electricity, especially from renewable sources- often less dispatchable and more intermittent than conventional thermal power generation processes-, gives rise to some obstacles, namely due to its often imbalance between supply and demand. Since electric energy cannot be stored, system balancing must always be ensured and is expensive. At any given time pace (e.g. 5 min, 15 min, 1 hour) the grid operators in charge of ensuring such balancing, will need to manage surplus or deficit between production and demand, using one of a few mechanisms available: (1) capacity mechanisms in which producers and users agree to either use or refrain from using their installed capacity (production or consumption); (2) transnational market mechanisms -, the electricity surplus is either sold to a neighbour country or (3) resort to balancing services provided to the grid operators by making use of storage capacity - the energy is then transformed into a different kind of energy and therefore stored.

Considering the goals mentioned above, most of the efforts and discussions are naturally focusing on the renewable energy industry. Because each country has very distinct environmental, economic and social conditions, in the end all the strategies become very different from country to country.

Like many other institutions and companies, the European Commission and the EU member states resort to energetic models to support policy making and market design.

Energy-modelling is the virtual or computerized simulation that focuses on energy consumption, utility bills and life cycle costs of various energy related items. It is also used to evaluate the payback of green energy solutions like solar panels and photovoltaics, wind turbines and high efficiency appliances. This simulation helps take any hard decision more easily and efficiently while saving both time and resources. [44]

These are not carried out as a precise prediction exercise but as a means to outline possible scenarios and explore possible futures, this report aims to study possible solutions for the Portuguese electric system, with a carbon emission mitigation and an energetic dependency perspective in mind.

Since they are based in many assumptions (technical, economic, policy, behaviour, etc.), energetic models include some level of uncertainty. It is also important to mention that the more options are considered, the more complex the analysis is.

Evaluation criteria are required to compare between scenarios as means to support investment or policy decisions.

Portugal has a good solar and wind exposure, which makes the installation of solar photovoltaic panels and wind turbines a viable solution. Also, Portuguese topography provides very good conditions for hydroelectric plants, as it has already been widely proven and has been done for decades and all over the country. However, all the renewable generation capacity installed, electricity generation is highly dependent on weather conditions which can vary yearly, seasonally, daily etc.

Fossil fuels, however, do not present the same obstacle, since they can be used to generate electric energy whenever there is fuel and can be turned on whenever they are necessary. The main obstacle associated with fossil fuels for Portugal, besides being pollutant, lays in its importation. Portugal imports all the fossil fuels used in the country, causing a great energetic dependency towards the countries which export these fuels.

The 3 pillars of energy supply - vital for any country economic development and social stability - are security of supply, price competitiveness and - as already mentioned - alignment with climate policy. If we consider the first pillar, weighing together the country's energetic dependency on fossil fuels and the intermittency and irregularity over and under production of renewable energies, it is justifiable for Portugal to invest in development of storage technologies and/or other system adjustment mechanisms such as demand side management.

The most immediate storage solution for Portugal, as discussed extensively in many papers, news, and theses (for example [19], [21], [22]), is electricity storage through pumped hydroelectricity. By pumping back the water to the upper reservoir of a hydroelectric plant, it is possible to transform electricity into water that is then stored for future electric generation.

There are however, other storage technologies that can be explored. In this work, the main motivation is to find other storage technologies and compare them against pumped hydroelectric, studying their adoption conditions and impact in Portugal's electricity generation cost.

Two energy storage systems were selected to be compared against the pumped hydroelectric storage: batteries and power-to-gas.

A brief explanation is given below as for the reasons why each one of these three storage systems has been targeted in this study. Such reasons are further explained in Chapter 3.

Pumped hydroelectric storage was selected because it is economically viable and it's a technology already widely explored in Portugal through their 200 existing hydroelectric plants [23] since 1894 [22].

Batteries have been widely discussed and studied worldwide, in particular as components to electric mobility, microgrids and decentralized electricity generation such as individual homes, as part of ecodistricts and other forms of auto consumption. However, these are also being investigated for their potential to provide medium to large scale storage capacity and provide balancing services to the grid. As already mentioned, each country has their own environmental, economic and social characteristics, and a solution that works well in a country may not have the same outcome in a different country. The relative share of decentralized to centralized power generation varies significantly between countries (e.g. France with Nuclear Power ensuring all the baseload, relative to Denmark with a highly decentralized production, or Germany in which the energy transition named Energywende has been very dependent on citizen initiatives regarding local production plants), the relative share of intermittent to dispatchable power generation capacity, the different investment capacity, etc, can mean that even though battery storage is already technically and economically feasible in California (USA), it does not follow that it will be the same everywhere. This storage system is being implemented in other countries, and it may be a possible solution for Portugal. Regardless of their current high costs and its impact on the total electricity generation cost, the installation of batteries as a means to answer renewable generation intermittency is worth studying.

Power-to-gas is presented here as a new approach to the storage dilemma. Recently arrived at this discussion *arena*, this technology is not adequate for every country to adopt as a storage strategy. However, according to bibliography it is becoming consensual about the fact that in Europe, alongside the Nordic countries, Portugal has good conditions for its implementation [43]. This might even contribute for a future strategic decision of making the country become a hydrogen exporter.

For each of these storage systems, calculations will be done to determine its impact, both individual and comparative to one another, on the electric energy generation cost, as well as on the country's energetic dependency.

Finally, **in parallel to the comparison between different technological strategies applied to the same all-time rules' scheme**, it was considered relevant to invest some time looking at a totally different approach to achieve the goals of the energy transition.

There are two ways to look at the problem of balancing electricity supply and demand : either consider the "demand" as the target to reach, the objective to attain and manage the system and optimise its costs by acting on the production side - as proposed here on storage - or consider managing and optimising the system by acting on the demand side. This is called demand side management, – through an alternative path to changing energy generation technologies to keep responding to whatever the demand: what if Portugal forgets about the fossil generation and tries to stick only to the generation capacity from renewables? This would require an adaptation from both producers and consumers, the first ones determining the value of having some of their main clients not consuming during certain periods, and the latter accepting to be paid not to consume during some periods of time.

This solution, known as "demand side management" sets the controlling systems on the demand side rather than on the supply side. However, this "non-technological" strategy would require huge legislative changes. Just like the previous strategies, this one will be explained further in Chapter 3.

As said before, there is no right solution, but rather a mix of solutions depending on the required outcome and existing constraints. Therefore, the goal of this work is to provide the required information, both technical and economical, for any decision maker to use and support his decision regarding the energy path to a carbon neutral country.

1.2. Structure of the dissertation

This report is divided into seven chapters. Chapter 1 describes the motivation and objective that led to the topic.

In Chapter 2, the European energetic goals will be explained, focusing on the Portuguese ones - the goals set by the European Commission and EU member states regarding energy mix and carbon emissions for 2030, 2040 and 2050, and the current status regarding progress to achieve said goals.

Chapter 3 presents and explains the selected four strategies to achieve the goals shown in Chapter 2. The strategies are presented as follow:

1. Storage through pumped hydroelectric
2. Storage through lithium-ion batteries
3. Power-to-gas
4. Demand side management.

Chapter 4 had the data used, as well as the methodology used to calculate the impact of each strategy on the final electricity generation cost.

The obtained results from this last chapter are presented and discussed in Chapter 5.

Afterwards, in Chapter 6, all the obtained results from the different strategies are compared to allow decision makers on energetic strategies to make informed and fact-based decisions, according to different desired outcomes.

Finally, in Chapter 7, conclusions are presented.

All references to literature used in this work will be found afterwards, as well as an annex considered relevant.

2. Energy transition goals and tracking progress

In our society, there is a need to create rules and laws so that things can work in a fair and efficient way. Therefore, in general, the whole electric energy system is regulated.

Other than laws there are also goals towards a more renewable energy mix, as well as a reduction of the greenhouse gas emissions (GHG), and an increase of the electricity use in the total energy consumption. These goals are generalized and applied worldwide, mainly through the Kyoto's protocol and Paris agreement, but then the specific goals are defined more locally. The European Union creates its own goals, which require the commitment of all countries in the EU, meaning that each country must then create its own goals for both energy mix and emissions mitigation.

The European Union's targets for 2020 are the following: [7]

- Reduce greenhouse gas (GHG) emissions by at least 20% (from 1990 levels)
- Increase the share of renewable energy to at least 20% of consumption
- Achieve energy savings of 20% or more

Given the environmental conditions in Portugal, it was possible for the country to draw goals that would over compensate the European ones: [8];[12]

- Ensure that 31% of the gross final energy consumption will be derived from renewable energy sources (RES) (60% of electricity produced, and 10% of the energy consumption in the road transport sector)
- Increase to 10% the electrical interconnections with Europe
- Increase the country's energy independence to around 74%
- Reduce the balance of energy imports by 25%
- Consolidate the industrial cluster associated with wind energy and to create new clusters associated with new technologies in the RE sector
- Reduce 18% to 23% the GHG emissions, compared to the 2005 values

Aiming at 31% of RES in the final energy consumption by 2020, in 2015 Portugal had already reached an amazing 28%. One year later, that share rose 0,5%, which means that by the end of 2016 Portugal had already achieved 92% of the target. [9]

The European Parliament, however, is constantly setting new and more ambitious goals for the future. So far, they established the goals for 2030 and are adjusting the goals for 2050.

EU targets for 2030 are: [10]

- 40% cut in GHG emissions compared to 1990 levels
- At least 27% share of RE consumption
- Improvement in energy efficiency at EU level of at least 27% (compared to projections), to be reviewed by 2020 (with an EU level of 30% in mind)

- Support the completion of the internal energy market by achieving the existing electricity interconnection target of 10% by 2020, with the objective of reaching 15% by 2030

Once again, the 2030 targets for Portugal are slightly different: [12]

- Ensure that 40% of the gross final energy consumption will be derived from RES
- Reduce 30% to 40% the GHG emissions compared to the 2005 values
- Increase to 15% the electrical interconnections with Europe

For 2050, the European Commission developed a long-term strategy instead of specific targets, as it did for previous years. The purpose of this strategy is to create a vision and sense of direction, plan for it, and inspire as well as enable stakeholders, researchers, entrepreneurs and citizens alike to develop new and innovative industries, businesses and associated jobs. The long-term strategy also seeks to ensure that the modernization of our economy is socially fair and enhances the competitiveness of EU economy and industry on global markets, securing high-quality jobs and sustainable growth in Europe, while also helping address other environmental challenges, such as air quality or biodiversity loss. [14]

This strategy, presented on November 28th, 2018, shows how Europe can lead the way to climate neutrality by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research – while ensuring social fairness for a just transition.

The road to a climate neutral economy would require joint action in seven strategic areas: [14]

(i) Energy efficiency

(ii) Deployment of renewables

(iii) Clean, safe and connected mobility

(iv) Competitive industry and circular economy

(v) Infrastructure and interconnections

(vi) Bio-economy and natural carbon sinks

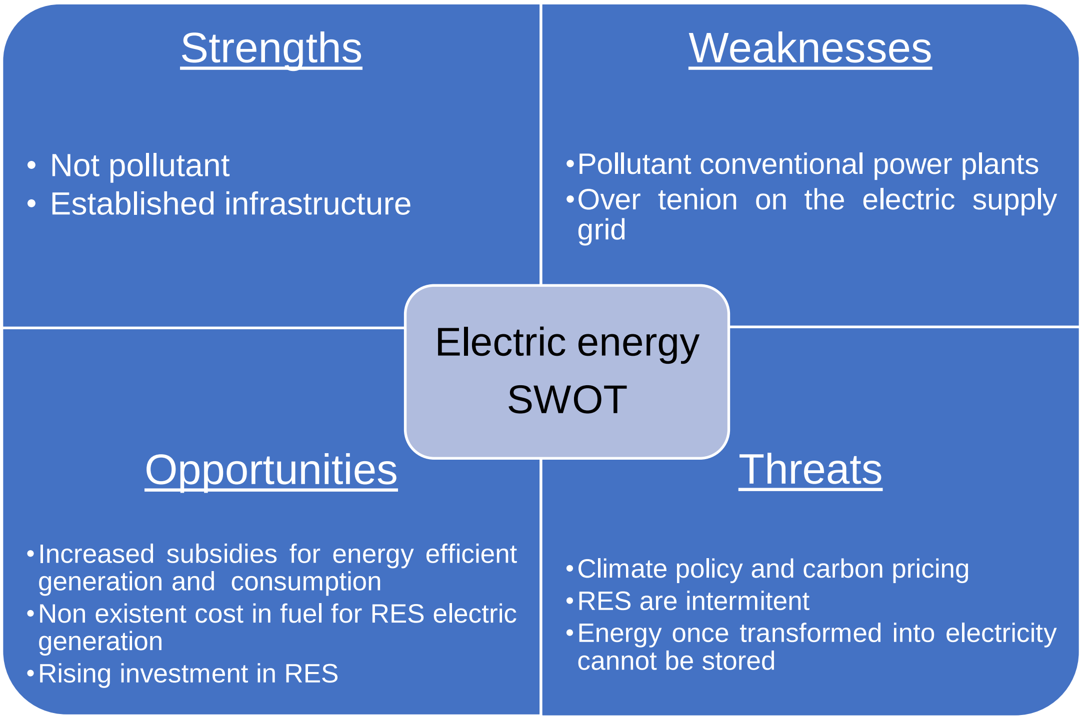
(vii) Carbon capture and storage to address remaining emissions

Never forgetting that the main goal is to have a climate change mitigation, assuring the security of energy supply and its price competitiveness, it is wanted, worldwide, that the share of renewable energy sources in electric energy increases, as well as the share of electric energy in the total energy consumption.

Electricity has its strength and weaknesses, which can open the door to new possible strategies to optimize the electric energy sector.

Some of the strengths electric energy presents is the fact that once the primary energy is transformed into electricity, this one does not have emissions, and is not pollutant. There has also been a great investment, worldwide, in renewable energy sources (RES) for electricity generation, since the electric grid can aggregate electric energy from different sources.

On the other hand, electricity production is still highly depend on the conventional energy sources, that are pollutant, and our society is as well greatly dependent on electric energy for everyday functions which paves the way to a huge problem if anything is to happen to it. While on the subject, it is important to mention that, when the grid has many and different energy sources contributing to energy supply, it can get overwhelmed and over tensioned, which can be dangerous. [16], [17]



Electric energy SWOT

Strengths

- Not pollutant
- Established infrastructure

Weaknesses

- Pollutant conventional power plants
- Over tenion on the electric supply grid

Opportunities

- Increased subsidies for energy efficient generation and consumption
- Non existent cost in fuel for RES electric generation
- Rising investment in RES

Threats

- Climate policy and carbon pricing
- RES are intermitent
- Energy once transformed into electricity cannot be stored

Figure 2.1 - SWOT analysis for electric energy

The opportunities and the threats can be considered as starting points for new projects to meet the climatic goals. With that in mind, the next chapter presents possible future strategies to decrease the carbon emissions, as well as increase the country's energetic independence.

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3. Strategies description and examples

In this chapter different possible future strategies will be presented, to meet the targeted climate goals that will also enable to overcome some shortcomings related to electricity and even enhance its opportunities – for example reduce energy dependency, create new business opportunities through exportations, ease the over tension in the electric grid, etc.

To improve the electric system, four different strategies are analysed: storage thorough pumped hydroelectricity and lithium ion batteries, power-to-gas and demand side management. Each one of them will be further explained, analysed and some practical applications of such strategies will be presented.

Energy storage technologies can support energy security and climate change mitigation goals by providing valuable services in developed and developing energy systems, as well as help to better integrate electricity and heat systems while playing a crucial role in the energy system decarbonisation.

While some energy storage technologies are mature or near maturity, most are still in the early stages of development and currently struggle to compete with other non-storage technologies due to high costs. They will require additional attention before their potential can be fully realised. [18]

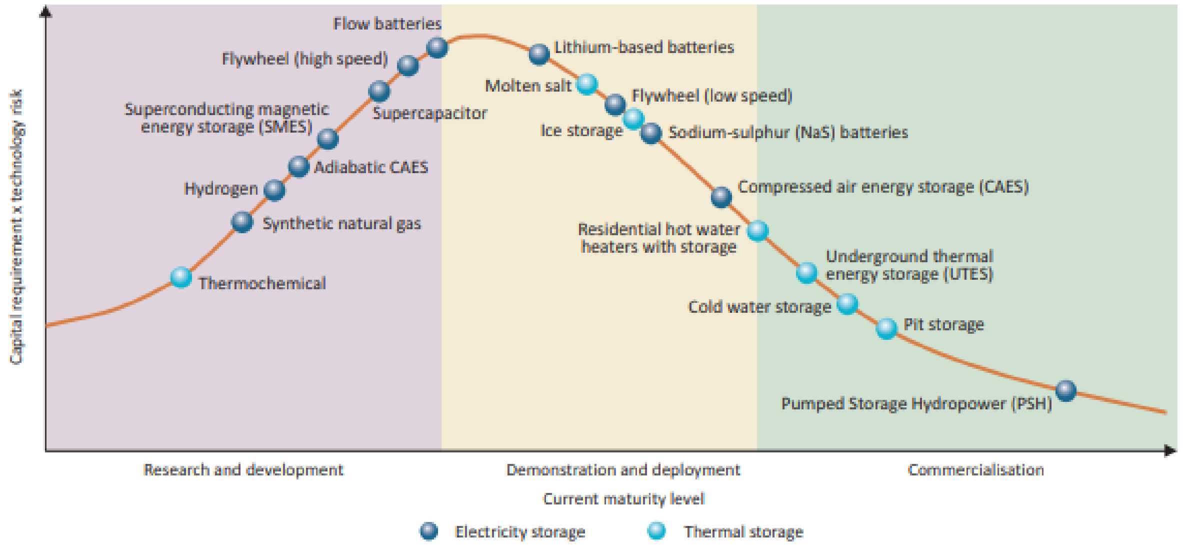


Figure 3.1 - Maturity level versus capital investment per energy storage technology [18]

Looking forward, the most important drivers to increase the use of energy storage will be: [18]

- Improving energy system resource use efficiency
- Increasing use of variable renewable resources
- Rising self-consumption and self-production of energy (electricity, heat/cold)
- Increasing energy access (e.g. via off-grid electrification using solar photovoltaic (PV) technologies)
- Growing emphasis on electricity grid stability, reliability and resilience
- Increasing end-use sector electrification (e.g. electrification of the transport sector).

The two energy storage technologies that will be analysed in this work are pumped hydroelectric storage (PHS) and lithium-ion batteries. Pumped hydroelectric storage in Portugal was already proven economically viable as well as non-pollutant and lithium-ion batteries are the most used in the market, nowadays, especially in the electric vehicles market.

According to the Technology Roadmap for Energy Storage [18], and as Figure 3.1 shows, energy storage technologies usage depends on its final purpose. For example: PHS is a large-scale electricity storage that might provide the most short-term benefits in areas with developed electricity grids that can more easily accommodate centralised energy supply resources, whereas batteries are a small-scale electricity storage that might provide the most short-term benefits in areas with remote and off-grid communities as well as those looking to diversify their transportation fuel resource demand.

3.1. Pumped hydroelectric storage

Pumped hydroelectric storage plants, also known as PHS, are a solution for storing energy, in artificial lakes created by dams. The water is pumped from a downstream reservoir to an upstream reservoir, usually when there is an excess of energy production at very low market prices, so, it can be later re-turbined, producing electricity in the hours it is most needed. [19] In Figure 3.2 is a schematic illustration of a functioning PHS.

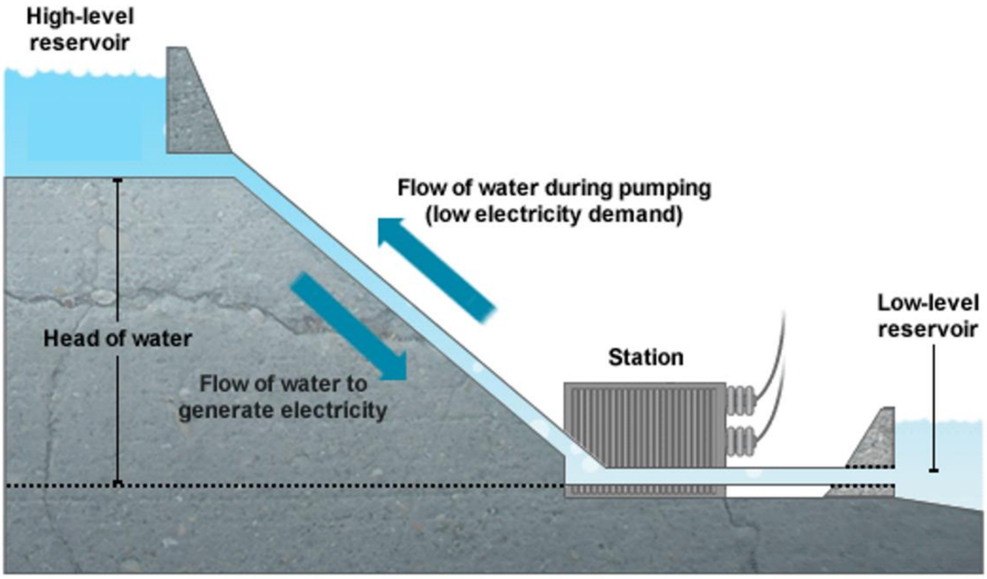


Figure 3.2 - Pumped Hydroelectric Storage scheme [67]

The efficiency of hydroelectric plants is 70-80% and varies with the technology used. However, when speaking of the whole pumped/turbined system, the efficiency of the pumped hydroelectric plant can drop down to 65-70%.

Like every project, pumped hydroelectric storage has advantages and disadvantages which are important to take into consideration when planning its implementation. In the following SWOT analysis for PHS (Figure 3.3) are described some of those advantages and disadvantages.

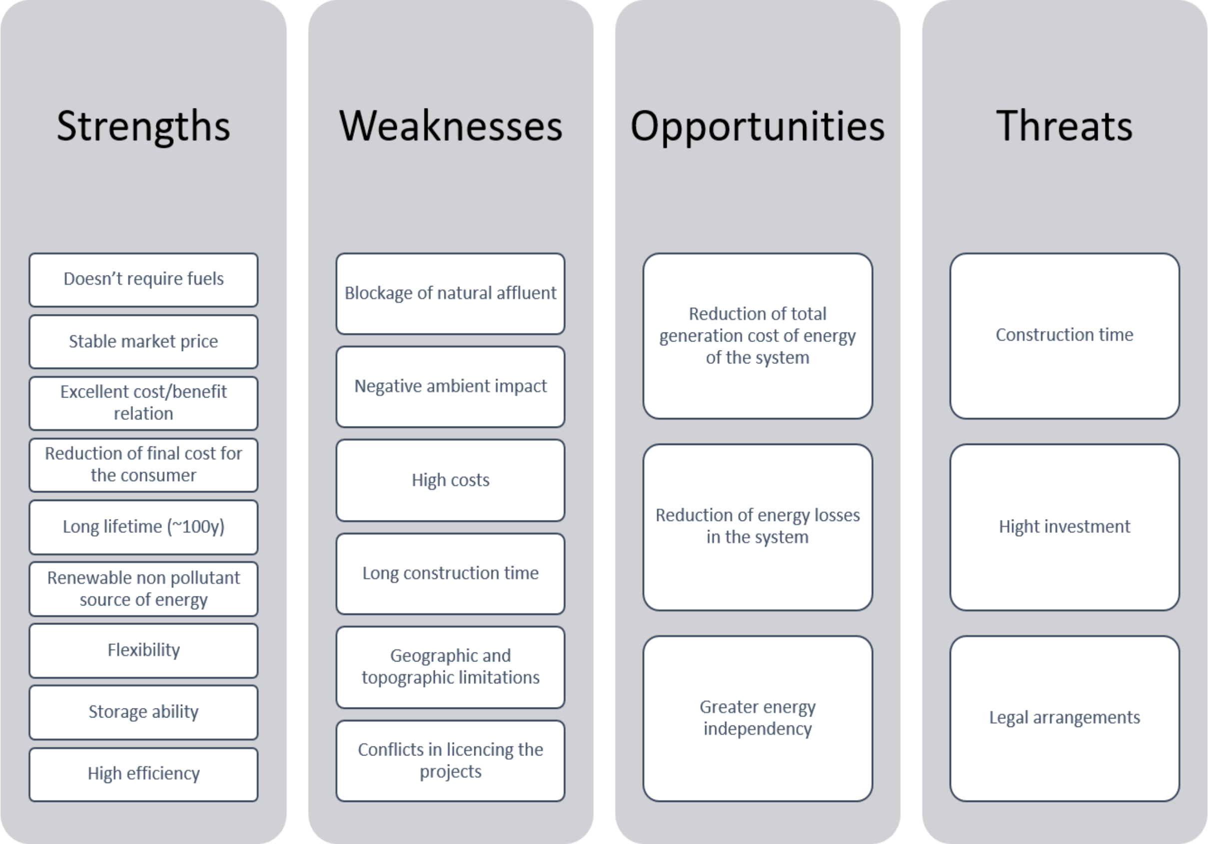


Figure 3.3 - SWOT analysis for Pumped Hydroelectric Storage plants, adapted from [20]

The first hydroelectric plant in continental Portugal, Poço Agueirinho, located in Corgo river, whose sole purpose of city illumination, was founded in 1894. [21] [22]

After this one, many others followed all over the mainland, as well as on the islands, but it was not until 70 years later (in 1964) that the first pumped hydroelectric plant was built (the Alto Rabagão dam). Only in 1981 the second pumped hydroelectric, named Aguieira, started working.

In Table 1 the current PHS installations in Portugal are presented, as well as predicted future works, their inauguration years and their installed capacity.

Nowadays, the investments in pumped hydroelectric plants can be either for totally new developments or reinforcements of previous ones, with addiction of pumps. This second approach implies a significant smaller investment cost, which is a clear advantage to the project. The investment cost topic will be further explained in Chapter 4 and it will be also used in calculations, whose results will be then presented in Chapter 5.

Even with all the already existing hydroelectric plants in Portugal, there is still room for PHS to grow, since overall installed capacity is 6 550,3 MW (including the islands), and around only 50% of that installed capacity is pumped. In annex 1 is a table, adapted from the Renewable Power Plants in

Portugal Map ([23]), with all the large hydroelectric (>10 MW) plants and its installed power. Between those are Alto Rabagão, Aguieira, Alqueva, Baixo Sabor, and others that are already installed as pumped hydroelectric storage.

Table 3.1 - Planed pumped hydroelectric installations in Portugal, adapted from [21], [24], [25], [29], [64]

Inauguration year	**Name**	**Power installed (nowadays)**
1964	Alto Rabagão	68 MW
1981	Aguieira	336 MW
1987	Vilarinho das Furnas	125 MW
1988	Torrão	140 MW
2005	Frades	191 MW
2012	Alqueva	512 MW
2015	Salamonde II	224 MW
2016	Baixo Sabor	189 MW
2017	Venda Nova III	781 MW
2017	Foz Tua	270 MW
2017	Frades II	n.d.
2022	Paradela II	318 MW
2022	Alvito	225 MW
2022	Covão-Ribeira	555 MW
2023	Alto Tâmega	1 158 MW

3.2. Batteries

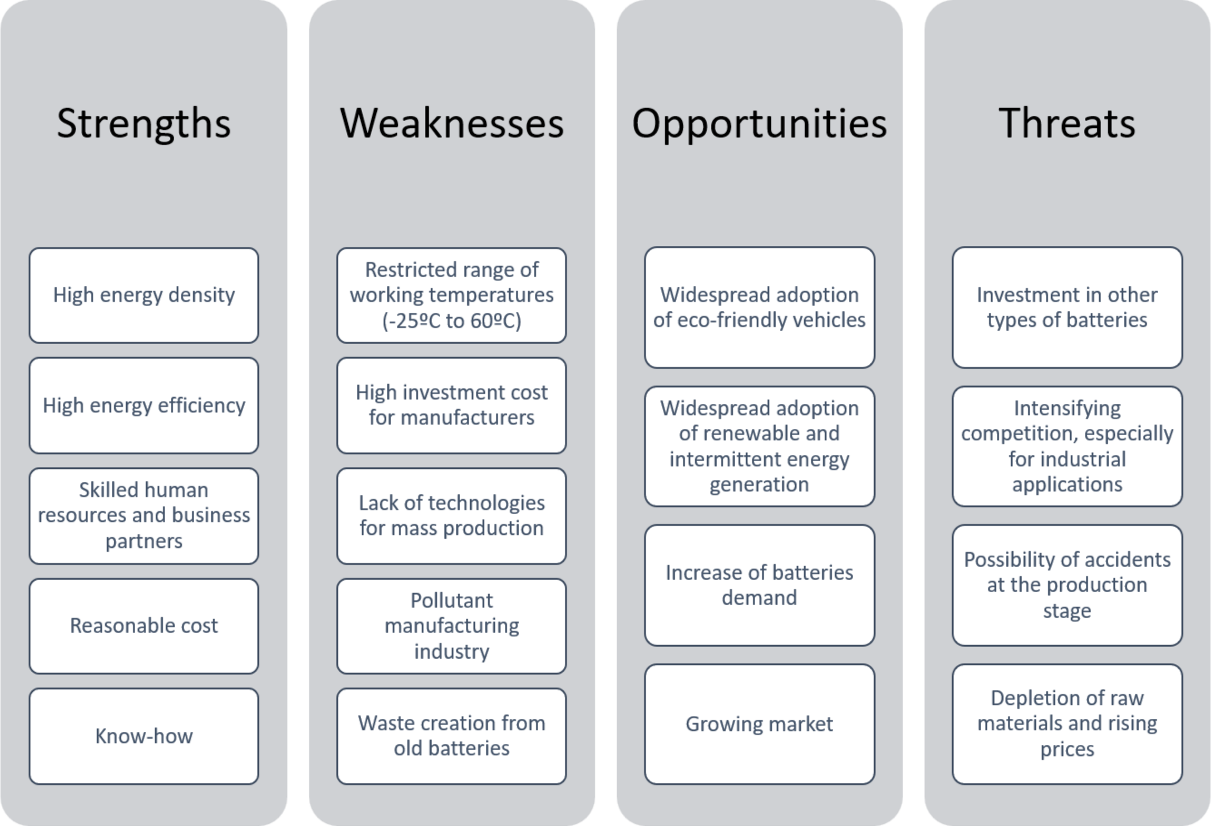
A battery is composed of electrochemical cells, where chemical energy is transformed into electrical energy. [26]

There are different ways to classify batteries. Distinguishing them into primary and secondary is one of them. According to professor Fátima Montemor classes [27], primary (single-discharge) batteries have a finite quantity of reactants and once they are consumed, this type of battery cannot be used again. Secondary (multiple-cycle) batteries, can be recharged on the completion of discharge by forcing an electric current through it in the opposite direction, which will regenerate the original reactants from the reaction products. Therefore, electric energy supplied by an external power source is stored in the battery in the form of chemical energy. Consequently, the reactions happening inside a secondary battery must be chemically reversible. Finally, good rechargeable batteries will sustain a large number of such charge-discharge cycles.

Within the secondary batteries classification, many different batteries are included in this category, such as lead acid batteries, sodium-sulphur (NaS) batteries, nickel cadmium (NiCd) batteries, nickel metal hydride (NiMh) batteries, lithium-ion (Li-ion) batteries and redox flow batteries. [26]

Most of the batteries used for electricity storage from renewable sources, electric vehicles energy storage and storage in gadgets are lithium ion batteries (Li-ion batteries). For that reason, this sort of battery will be the focus in this work.

As mentioned for PHS, storage has advantages and disadvantages that are important to take into consideration when planning its implementation. Therefore, in Figure 3.4 a brief SWOT analysis regarding lithium ion batteries is presented.



Strengths	Weaknesses	Opportunities	Threats
High energy density	Restricted range of working temperatures (-25ºC to 60ºC)	Widespread adoption of eco-friendly vehicles	Investment in other types of batteries
High energy efficiency	High investment cost for manufacturers	Widespread adoption of renewable and intermittent energy generation	Intensifying competition, especially for industrial applications
Skilled human resources and business partners	Lack of technologies for mass production	Increase of batteries demand	Possibility of accidents at the production stage
Reasonable cost	Pollutant manufacturing industry	Growing market	Depletion of raw materials and rising prices
Know-how	Waste creation from old batteries		

Figure 3.4 - SWOT analysis for Lithium-ion batteries, adapted from [30], [31], [32]

The charge-discharge cycle of a battery is a succession of chemical reactions. When discharging, the electrons flow from the carbon material (anode), with Li^+ insertion in the metal oxide (cathode), whereas when charging the reverse process takes place, with the electrons being supplied to the carbon material with Li^+ insertion, according to equation 1. This process is schematically explained in Figure 3.5.

$$Li_xC_6 + Li_{1-x}MO_2 \underset{Charge}{\overset{Discharge}{\rightleftarrows}} C_6 + LiMO_2 \qquad Equation\ 1$$

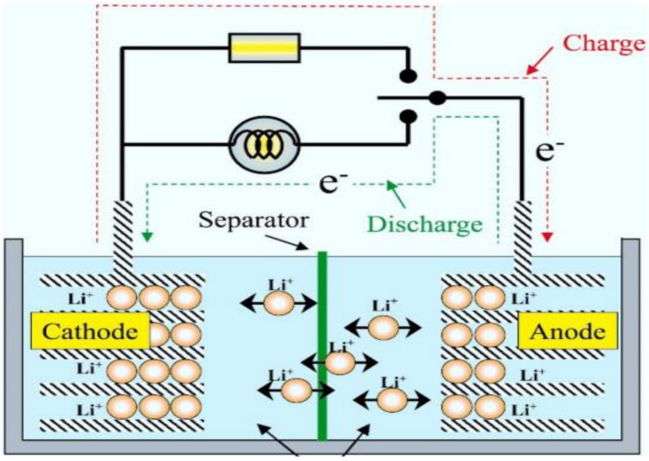


Figure 3.5 - Lithium-ion battery charge-discharge scheme [28]

In the example image, Figure 3.5, and in Equation 1, the cathode used ($LiMO_2$) is representative since M represents any metal. Originally, the primary active component of the cathode was cobalt. Cathode materials require extremely high purity levels and must be almost entirely free of unwanted metal impurity. [33]

EDPR, also known as EDP Renewables, opened a pioneering facility for the battery-based storage of wind energy amassed from the Cobadin wind farm in Romania. [34]

The Stocare Project, as this EDPR venture has been named, represents a key technological development in the storage of energy. When there is excess production, the system charges the batteries, and when production is lower than expected, the energy stored in the batteries is provided to consumers.

3.3. Power-to-gas

The share of electricity from renewable sources in the European electricity mix is increasing. As the power generation from wind and solar fluctuates, the match between renewable power supply and demand is becoming more challenging. At the same time, there are additional challenges to transmit the increasing volumes of renewable power from wind or solar farms to end users.

The gas infrastructure, however, can accommodate large volumes of electricity converted into gas, in case the supply of renewable power is larger than the grid capacity, or in case the electricity supply is greater than the electricity demand.

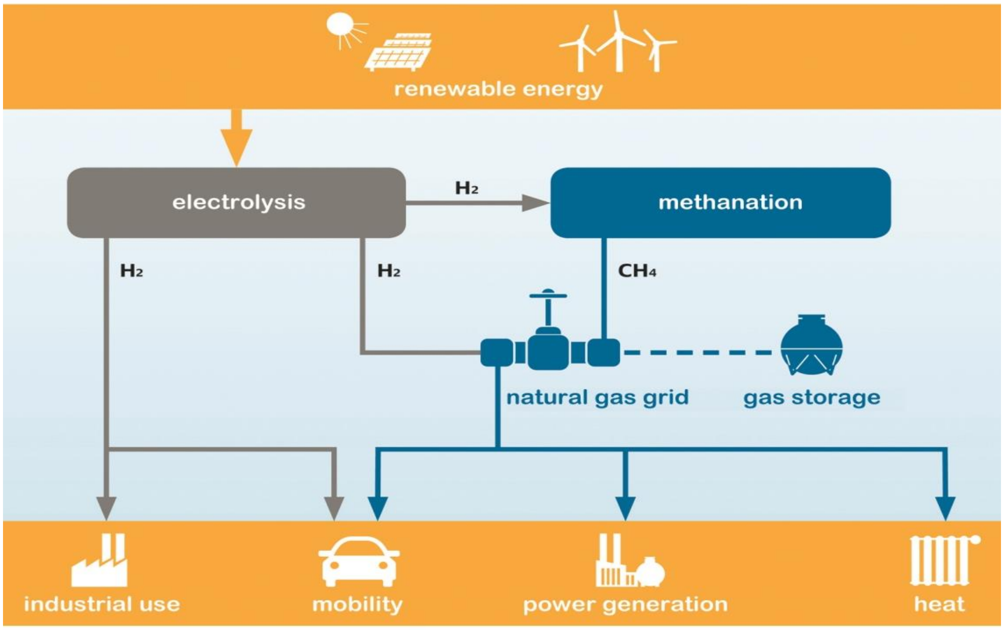
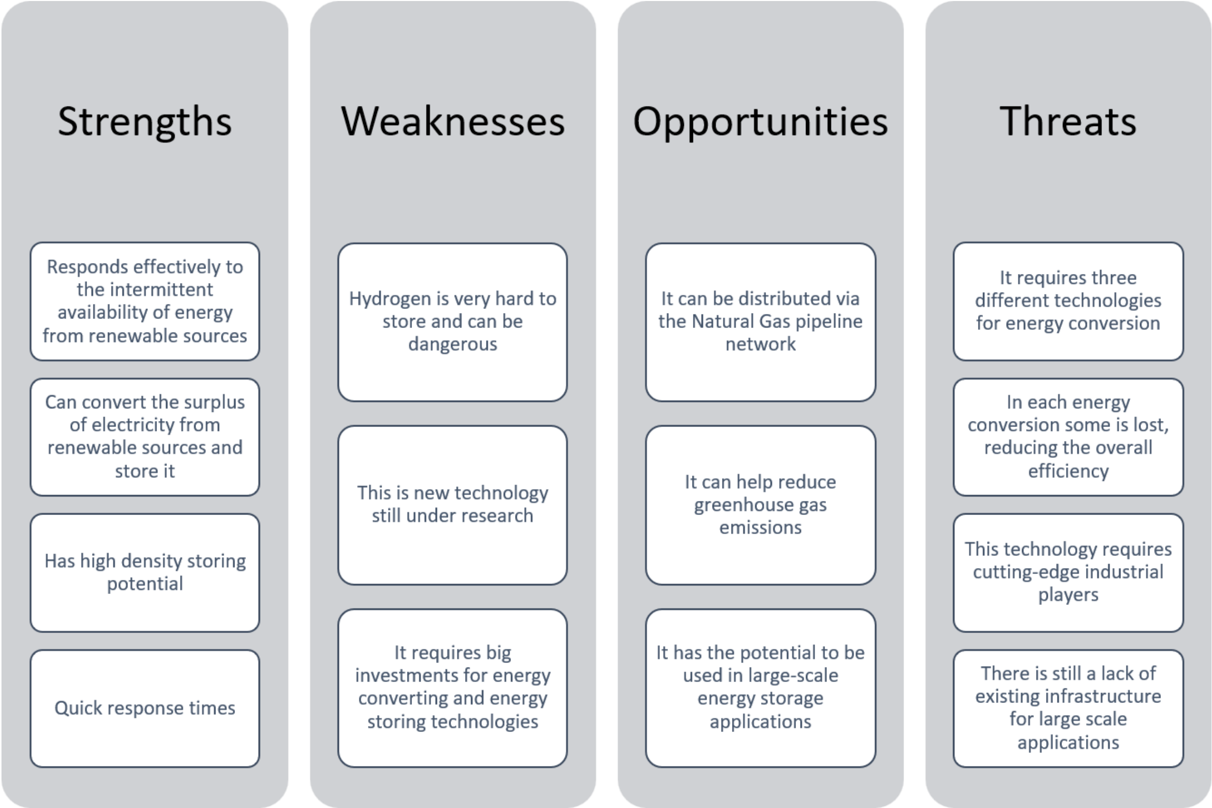


Figure 3.6 - Flowchart of a Power-to-Gas plant [68]

The Power-to-Gas principle is based on storing surplus energy from renewable sources by converting it into hydrogen (H_2) through electrolysis, or subsequently into methane (CH_4) syngas through methanation of H_2. As a result, power-to-gas enables the share of renewables in the energy mix to increase and provides an option for inter-seasonal long term storage of electricity, making this innovation a relevant strategy to achieve carbon neutrality by 2050.

The existing natural gas pipeline networks can also carry the resulting hydrogen and/or methane, facilitating the storage and transportation of these gases, which can then be blended with natural gas. [36]. These advantages and some others, along with some disadvantages and challenges, are briefly shown in the SWOT analysis in Figure 3.7.



Strengths	Weaknesses	Opportunities	Threats
Responds effectively to the intermittent availability of energy from renewable sources	Hydrogen is very hard to store and can be dangerous	It can be distributed via the Natural Gas pipeline network	It requires three different technologies for energy conversion
Can convert the surplus of electricity from renewable sources and store it	This is new technology still under research	It can help reduce greenhouse gas emissions	In each energy conversion some is lost, reducing the overall efficiency
Has high density storing potential	It requires big investments for energy converting and energy storing technologies	It has the potential to be used in large-scale energy storage applications	This technology requires cutting-edge industrial players
Quick response times			There is still a lack of existing infrastructure for large scale applications

Figure 3.7 - SWOT analysis for Power-to-Gas plants, adapted from [36], [37], [18]

This technology comes as a solution to two different problems: (1) related to renewable energy sources and (2) related to natural gas.

Being a fossil fuel energy source, natural gas use should decrease. However, what would happen to the existing pipeline network and plants?

Renewable energy, on the other hand, is not only intermittent, as there are also times when the generated electricity amount is greater than the electricity needed as well as there are times when the opposite happens and the generated electricity is not enough to satisfy the demand.

P2G presents a solution to these problems. As mentioned before, and as presented in the flowchart, (Figure 3.6) the surplus of renewable electricity can be transformed into hydrogen, H_2, by electrolysis, which can either be (1) used for mobility or industrial purposes, (2) transformed into CH_4, through methanation, and be injected to the natural gas grid, where it can be used, once again, for mobility, power generation and heat, or (3) it can even be stored.

This technology is of particular interest for Europe as its onshore and offshore natural gas infrastructure is well developed. In addition, the combined generating capacity of offshore wind farms could reach around 100 GW by the year 2030, while the PV capacity installed is expected to increase from 35 GW in 2012 to almost 60 GW in 2020, which P2G could give substance to. [35]

ENGIE (known as GDF Suez prior to April 2015), a French energy company, is trialling the injection of hydrogen into the natural gas distribution network of a new neighbourhood, Le Petit village, and an NGV refuelling station for buses located in the Dunkirk Urban Community. Heating and domestic hot water needs will be satisfied by an innovative energy solution: Hythane, a new gas composed of hydrogen and natural gas. The aim of the project is to demonstrate the technical, economic, environmental and social advantages of this new energy solution for sustainable cities and green mobility in real operating situations. [37]

The French government is supporting the GRHYD hydrogen energy storage demonstrator project, being conducted by ENGIE and a consortium of industrial partners. France has set the target of meeting 23% of its gross end-user energy consumption from renewable sources by 2020. This ambitious project aims to convert surplus energy generated from renewable sources into hydrogen, which will then be blended with natural gas for a broad range of applications, including space heating, water heating and fuel. As a result, generators of energy from intermittent renewable sources, such as wind and solar power, will have a new solution for marketing the electricity they generate, at the same time as reducing greenhouse gas emissions.

3.4. Demand side management

As a consequence of the high penetration of renewable sources and the decentralisation of production sources, grid managers in many countries are now encountering increased instability on the grid and consequent disruptions to services. To limit these impacts and ensure a balance between energy consumption and the amount of power fed into the grid, grid managers can now utilize generation and consumption systems that offer so-called “grid services”, in return for payment, thus increasing the costs for the electrical system. [39]

The term Demand Side Management (DSM) is used to refer to a group of actions designed to efficiently manage a site’s energy consumption with the aim of cutting the costs incurred for the supply of electrical energy, grid charges and general system charges, including taxes, by deployment and use of improved technologies and changes in end-user behaviour or energy practices.

The aim of these optimisation actions is to modify features of electricity consumption with reference to the overall consumption picture, consumption time profile, contractual supply parameters (contractual power and grid connection parameters) in order to achieve savings in electricity charges. [39]

Dynamic demand response is the ability to control end-user devices (appliances) by rescheduling their operation. This enables the utilities to operate some of the appliances in periods when there is a large amount of renewable energy available, and not to operate them when demand levels increase drastically [41] Figure 3.8 schematically explains demand side management starting from the bottom, where electricity producers dictate the amount of available electricity, escalating all the way to the top, where consumers conciliate their activities to match the supply, while everything is controlled by an aggregated demand site control centre.

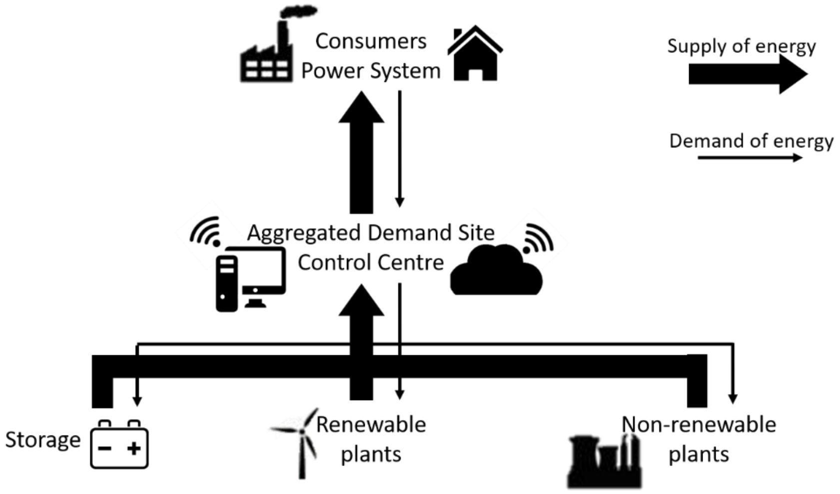


Figure 3.8 - Schematic explanation of demand side management

The consumers would be incentivised to shift their consumption away from peak periods (Figure 3.9) since those are the moments non-renewable plants are most definitely required to produce energy and when electricity's price is the highest.

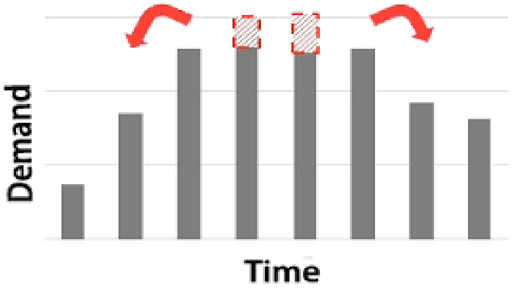


Figure 3.9 - Energy demand peak smoothing

This new energy paradigm has its advantages, such as reducing the electricity pricing and peak smoothing however, it also has its disadvantages such as, for its implementation, it would be required a great deal in investment in IoT devices and legislation would need to be changed. In Table 3.2 are presented some of the most important advantages and disadvantages that must be considered, if this new electricity paradigm is to be implemented.

Table 3.2 - Advantages and disadvantages for Demand Side Management

Advantages	Disadvantages
The electric grid is already installed	Requires a change of legislation and people’s behaviour
No new energy technology investment needed	Investment in IoT needed
Every MW reduction of peak demand translates to system-wide savings	Requires monitor and check all assets involved
Reduce electricity bills	Requires the creation of a new independent entity to manage the electric grid
Shifting of energy consumption from peak to non-peak hours	

At this point there has been many studies regarding the demand side management scenario in general, its implementation and its application in specific places. There are some on-going projects in DSM implementation however, they are still experimental and do not substitute the currently adopted electricity system.

4. Methodology and data

In this chapter it will be explained the logic and the calculations behind each scenario hypothesis. There are four scenario hypotheses: pumped hydroelectric storage, lithium ion batteries, power-to-gas and demand side management.

As a reference scenario, for Portugal, it was used the EU28: Reference Scenario (REF2016) [42].

According to the European Commission page, [42], the EU Reference Scenario is one of the European Commission's key analysis tools in the areas of energy, transport and climate action. It allows policy-makers to analyse the long-term economic, energy, climate and transport outlook based on the current policy framework. It is not designed as a forecast of what is likely to happen in the future, but it provides a benchmark against which new policy proposals can be assessed. National experts from all EU countries actively participate in its preparation.

Using the data from the European Commission will be made an energy model aiming to simulate possible futures for the Portuguese electric system through the installation of different storage technologies.

Energy-modelling is the virtual or computerized simulation that focuses on energy consumption, utility bills and life cycle costs of various energy related items. It is also used to evaluate the payback of green energy solutions like solar panels and photovoltaics, wind turbines and high efficiency appliances. This simulation helps take any hard decision more easily and efficiently while saving both time and resources. [44]

4.1. Reference Scenario

In an attempt to understand how the values presented in the EU Reference Scenario were obtained, it was calculated the impact of each source of energy given (hydro, wind, solar, coal, oil, gas and biomass) in the final overall energy generation cost.

From the new installed capacity, presented in tranches of 5 years from 2000 to 2050, it was calculated, for each source, the investment cost taking into account each technology has its investment cost per MW installed. The following table shows the values of each investment cost for power plants depending on the energy source.

Table 4.1 - Investment cost for power plant by energy source [45]

Power Plant by source of energy		Investment cost [k€/MW]
Hydroelectric	New PHS	3 550
	Power upgrade PHS	1 400
Wind		1 400
Solar		1 250
Coal		1 500
Natural Gas		600
Oil		500
Biomass		1 616

Given in the Reference Scenario [42] are the gross electricity generation, in GWh, and the net generation, in MW, for each energy source along the years. From those values the capacity factor is calculated for each energy source over the years, from 2000 to 2050 in tranches of 5 years, following equation 2.

$$capacity\ factor = \frac{gross\ electricity\ generation\ [GWh]}{net\ generation\ capacity\ [MW]} * \frac{1}{8760\ [h]} \qquad equation\ 2$$

The capacity factor of a power plant is the ratio of its actual output over a period, to its potential output if it were possible for it to operate at full nameplate capacity indefinitely. To calculate the capacity factor, the total amount of energy the plant produced during a period of time is taken and divided by the amount of energy the plant would have produced at full capacity. Capacity factors vary greatly depending on the type of fuel that is used and the design of the plant.

Next, based on the CF, it is calculated the energy production from the new installed capacity (equation 3) so that further, can be calculated the production cost from the new installed capacity. Multiplying this by the Levelized Cost of Electricity (LCOE), the costs from different energy sources can be compared (equation 4).

$$\begin{matrix} Energy\ production\ from \\ new\ installed\ capacity \\ [GWh] \end{matrix} = \begin{matrix} New\ installed\ capacity \\ [MW] \end{matrix} * \begin{matrix} 8760 \\ [h] \end{matrix} * capacity\ factor \qquad equation\ 3$$

The LCOE determines how much money must be made per unit of electricity (kWh, MWh etc.) to recoup the lifetime costs of the system. This includes the initial capital investment, maintenance costs, the cost of fuel for the system (if any), any operational costs and the discount rate. [48]

$$\begin{matrix} Production\ cost\ from \\ new\ installed\ capacity \\ [k€] \end{matrix} = \begin{matrix} Energy\ production\ from \\ new\ installed\ capacity \\ [GWh] \end{matrix} * \begin{matrix} LCOE \\ \left[€/_{MWh}\right] \end{matrix} \qquad equation\ 4$$

A LCOE analysis can help firms determine the benefits and drawbacks of various energy systems. When comparing conventional fossil fuel systems such as coal-fired power plants and natural gas power plants with renewable systems such as solar, wind or nuclear, a LCOE analysis can tell which is the most viable system to implement. [48] In Table 4.2 are shown the values of LCOE for each energy system used in calculations in this work.

Table 4.2 - Value of LCOE for each energy source, adapted from [49], [50]

Power Plant by source of energy		**LCOE [€/MWh]**
Hydroelectric	New PHS	66,94
	Power upgrade PHS	33,47
Wind		37,2
Solar		37,62
Coal		25
Natural Gas		50,31
Oil		192
Biomass		90

For the biomass case, it was made an average considering the installed capacity on biomass, biogas and municipal solid waste plants in Portugal [23] so that a more appropriate value for investment cost and LCOE were found.

Finally, it was calculated the new total electricity cost (equation 6), in €/MWh, by summing the impact on the total electricity cost due to the new installed capacity (equation 5) to the reference scenario's total electricity generation cost.

$$\begin{matrix} Differential\ on\ total\ electricity \\ cost\ from\ new\ installed\ capacity \\ \left[{}^{€}/_{MWh}\right] \end{matrix} = \frac{\begin{matrix} Production\ cost\ from \\ new\ installed\ capacity \\ [k€] \end{matrix}}{Gross\ electricity\ generation\ [GWh]} \qquad equation\ 5$$

$$\begin{matrix} Estimated\ cost\ of \\ electricity\ generation \\ \left[{}^{€}/_{MWh}\right] \end{matrix} = \begin{matrix} Total\ electricity\ cost\ calculated \\ by\ the\ EU\ Refence\ Scenario \\ \left[{}^{€}/_{MWh}\right] \end{matrix} + \begin{matrix} Differential\ on\ total\ electricity \\ cost\ from\ new\ installed\ capacity \\ \left[{}^{€}/_{MWh}\right] \end{matrix} \qquad equation\ 6$$

For non-renewable sources such as coal, oil and natural gas, was also added to the differential of the total electricity cost the decommissioning costs since in the reference scenario is predicted their turn off along the years, specially from 2020 forward, and a carbon tax to their CO_2 emissions. The decommissioning cost and the CO_2 emissions are presented in Tables 4.3 and 4.4, respectively.

Table 4.3 - Decommissioning cost for non-renewable power plants [51]

Power Plant by source of energy	**Decommissioning cost [k€/MW]**
Coal	83,85
Natural Gas	10,48
Oil	20,97

The calculation of the estimated cost of electricity is then readjusted, adding the decommissioning cost of all predicted power from the selected power plants.

The CO_2 emissions from electricity generation are also different depending on the fuel used, and they were added to the generation cost, accordingly.

$$\begin{matrix} CO_2\ emissions \\ [Mton] \end{matrix} = \begin{matrix} Gross\ electricity\ generation \\ from\ non-renewable\ sources \\ [GWh] \end{matrix} * \begin{matrix} CO_2\ emissions\ per\ GWh \\ of\ energy\ generated \\ \left[{}^{ton\ CO_2}/_{GWh}\right] \end{matrix} \qquad equation\ 7$$

Table 4.4 – CO_2 emissions per GWh generated depending on the fuel used [47]

Fuel used for electricity generation	**CO_2 emissions [tonCO_2/GWh generated]**
Coal	900
Natural Gas	370
Oil	500

The carbon tax of 30 € per tonne of CO_2 emitted [46] was only applied from 2020 forward. The final estimated cost of electricity is, once again, readjusted to add this parcel, where is used the result from equation 8 into equation 5 and finally equation 6.

$$\begin{matrix} Carbon\ cost \\ [k€] \end{matrix} = \begin{matrix} CO_2\ emissions \\ [Mton] \end{matrix} * \begin{matrix} Carbon\ tax \\ \left[{}^{k€}/_{ktonCO_2}\right] \end{matrix} \qquad equation\ 8$$

In the search for the most accurate result, in Table 4.1, are two different values for investment cost for hydroelectric power: one referring to a new pumped hydroelectric storage plant, and the second referring to a power upgrade and pumping system installation in an already existing hydroelectric plant. Being the investment cost in a new PHS much higher than a simple power upgrade and being difficult to know how much of the hydroelectric investment will be for which purpose, it was created a range of investment. The lower value assumes the entire investment is towards power upgrade alone, and the higher value assumes the entire investment is towards new PHS.

From this point forward there will be presented the methodology used to calculate the estimated electricity cost for each scenario hypothesis which, in Chapter 3, were explained what they are and their working principle.

4.2. Strategies

As a first step for the energetic strategies' calculations it was assumed that there is a relation between Portugal's electricity exports and its electric generation from solar and wind.

According to the data found in *Pordata* [52] Portugal not only exports electric energy, but also its exports have been increasing in the last years, specially from 2008, and so have the generation of electricity from RES, particularly from wind.

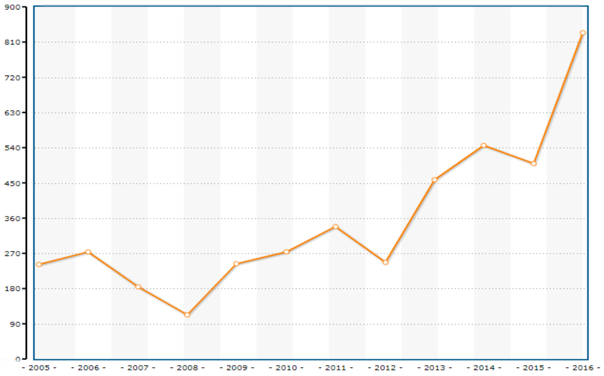


Figure 4.1 - Exports of electric energy in Portugal over the years in ktoe [52]

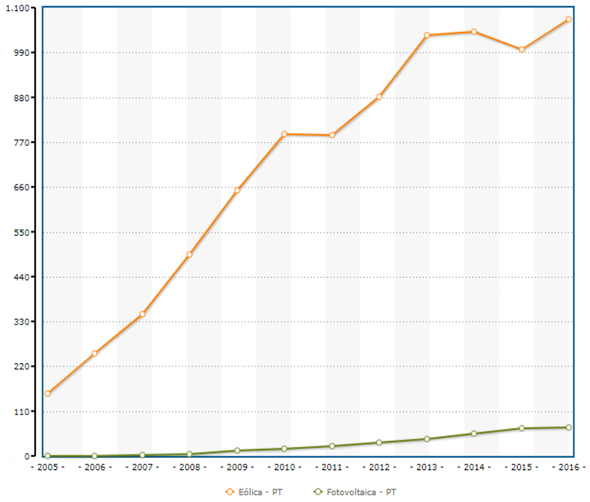


Figure 4.2 - Electric Generation from solar PV and wind in Portugal over the years in ktoe [53]

From these values, given by *Pordata* in ktoe, it is possible to create a function, equation 13, correlating both variables. That equation was later used to estimate the electricity exports for the following years. Subtracting from this value the electric energy imports it is obtained the amount of electric energy surplus which may contribute to the country's energetic dependency.

4.2.1. PHS

Knowing the electric energy surplus, values presented in Table 5.4, and multiplying them by the efficiency of the system (the whole pumped/turbined system the efficiency of the plant can drop to 65-70%) the energy stored is obtained, in GWh.

Once the amount of electricity that can be stored is known, the storage cost is calculated through equation 9.

$$\underset{[€]}{Storage\ cost} = \underset{[MWh]}{Energy\ stored} * \overset{LCOE}{\left[{€}/_{MWh}\right]} \qquad equation\ 9$$

Studying the impact of pumped hydroelectric storage for the electric surplus on the final electricity generation cost, is made a sensitivity analysis where is considered (i) the whole PHS investment as new ones and (ii) the whole PHS investment as power upgrade. Once again, as mentioned before, this investment differentiation creates a final cost range and the LCOEs used are presented in Table 4.2 – 66,94 €/MWh for new PHS and 33,47 €/MWh for power upgrade PHS.

Finally, as in equations 5 and 6, the storage cost divided by the gross electricity generation and then added to the total electricity cost calculated by the EU Reference Scenario, the final estimation for electricity generation cost is obtained. The values obtained are shown in Table 5.5.

4.2.2. Batteries

Similarly, as for the PHS strategy, the energy surplus (equation 13 and Table 5.4) multiplied by Li-ion batteries' efficiency of 90% [59] gives the amount of energy stored, which though equation 10 is obtained the storage cost.

$$\underset{[€]}{Storage\ cost} = \underset{[MWh]}{Energy\ stored} * \overset{LCOS}{\left[{}^{€}/_{MWh}\right]} \qquad equation\ 10$$

According to Lazard's LCOS report, [54], the observed costs and revenue streams associated with commercially available energy storage technologies are analysed and therefore is provided an overview of illustrative project returns. The Levelized Cost of Storage, usually referred as LCOS, aims to provide a robust, empirically based indication of actual cash costs and revenues associated with leading energy storage technologies, which leads to a preliminary view of project feasibility.

Following Lazard's report ([54]), the batteries being taken into account in this work are in-front-of-the-meter utility scale batteries, which are energy storage systems designed to be paired with large solar PV (or wind farms) facilities to improve the market price of solar generation, reduce solar curtailment and provide grid support when not supporting solar objectives. Their estimated LCOS is 108,5 €/MWh.

Finally, just as before, is calculated the differential on the total electricity cost due to Li-ion batteries implementation so that the final total electricity cost can be estimated (equations 5 and 6).

To completement the study on the impact of Li-ion batteries implementation in the total electricity cost a sensibility analysis was made on the LCOS for these batteries. The results for this sensibility analysis on the electricity generation cost are presented in both Table 5.6 and Figure 5.4.

4.2.3. Power-to-gas

Following the same logic as for the battery's scenario, the first step is to calculate an estimation for electricity surplus using equation 13.

This estimation will then, with an electrolysis processes' efficiency of 70% [56], be used to calculate the amount of hydrogen that could be produced in Portugal in these conditions – equation 11 – which results are later shown in Table 5.7.

$$\underset{[GWh]}{H_2\ produced} = \underset{[GWh]}{Electricity\ Surplus} * 0{,}7 \qquad equation\ 11$$

According to the European Power-to-Gas ([57]) the current natural gas grid can accept up to 20% of hydrogen in the mix without requiring any additional cost to upgrade nor change the existing natural gas pipelines. This means, if the production of H_2 is smaller than 20% of the NG mix, then the whole H_2 production is what can be avoided in NG imports however, if the production of H_2 is greater than the 20% the NG grid can support, then the natural gas avoided imports are only 20% of original imports and the surplus of hydrogen produced can be exported – equation 12.

The surplus H_2 produced could be exported, at a market price of 48,5 €/MWh ([60]), which divided by the gross electricity generation (equations 5and 6) contributes, negatively, to the final electricity generation cost.

$$\begin{array}{c}Avoided\\ Natural\ Gas\ imports\\ [ktoe]\end{array} = \begin{cases} \begin{array}{c}Natural\ gas\ imported\\ (Reference\ Scenario)\\ [ktoe]\end{array} - \begin{array}{c}H_2\ produced\\ [ktoe]\end{array} & if\ H_2 \leq 20\% \\ \begin{array}{c}Natural\ gas\ imported\\ (Reference\ Scenario)\\ [ktoe]\end{array} - 20\% \begin{pmatrix}Natural\ gas\ imported\\ (Reference\ Scenario)\\ [ktoe]\end{pmatrix} & if\ H_2 > 20\% \end{cases}$$

$$equation\ 12$$

The net cost for power-to-gas is the difference between the production cost for H_2, with an LCOE of 150 €/MWh ([56]) and the natural gas import's savings whose market price is 23 €/MWh ([61]).

Through equations 5 and 6 it is obtained the impact of power to gas in the final electricity generation cost.

To complement the study on the impact of a power-to-gas strategy implementation in Portugal it was made a sensibility analysis based on the non-decommission of the natural gas plants, as well as a sensibility analysis on the LCOE for H_2, the results are presented in Figures 5.6 and 5.7 respectively.

In a non-decommission case, the generation of electricity had to be readjusted since it was assumed the country does not need more electric energy than the one that was originally predicted by the Reference Scenario [42]. This means that some investments originally predicted can be avoided. However, in some cases there is still an excess generation compared to the predicted generation, which was then assumed as electricity exports at a 50 €/MWh ([62]) market price.

All calculations are presented and explained in the next chapter – Chapter 5.

4.2.4. Demand side management

The demand side management, as explained in Chapter 3, is more of a legislative measure than a technological one, so it would not be as simple as the previous strategies to calculate the impact on the electricity generation costs through the implementation of such strategy. Nevertheless, based on a smart meter project implementation in France [63], it was estimated an investment cost for Portugal.

This investment will be then compared – Chapter 6 – to the investments in the other strategies. If the investment in smart meters is greater than the investment for any of the other strategies, then it is a solution not worth investing. If, however, the investment in smart meters is smaller than the investment for any of the strategies, then it would be recommended further studies to assess their viability.

5. Results and discussion

In this chapter will be shown and discussed the results and graphs for all the strategies suggested. The logic behind the calculations and the equations were previously explained in Chapter 4.

5.1. Reference Scenario

The capacity factor, as mentioned before, is the ratio between a power plant's actual output over a period and its potential output if it was possible for it to operate at full nameplate capacity all year long.

Table 5.1 - Calculated Capacity Factors for different fuel plants

FUEL	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	94%	101%	47%	98%	70%						
Oil	34%	34%	12%	8%	29%	23%	21%	19%	19%	47%	44%
Natural Gas	54%	63%	35%	22%	20%	28%	13%	16%	40%	53%	25%
Biomass	80%	93%	98%	64%	55%	65%	50%	52%	55%	70%	80%
Hydro	29%	11%	36%	15%	23%	22%	22%	22%	22%	22%	22%
Wind	23%	19%	28%	26%	26%	26%	28%	29%	29%	29%	30%
Solar	13%	20%	18%	17%	17%	20%	22%	22%	23%	23%	24%
AVERAGE	45,1%	39,2%	32,4%	27,2%	25,3%	25,6%	22,8%	23,7%	26,2%	27,1%	26,9%

Table 5.1 shows the CF calculated with the given data from the Reference Scenario. With fluctuations, all the calculated capacity factors for each source of energy is within the expected range. The important observation to take from all these values is the average capacity factor.

The capacity factor from renewable energy sources plants is smaller than the capacity factor from fossil fuel plants, this means once the electricity mix is mainly fed by RES, the overall average capacity factor will be smaller too. Consequently, to generate the same amount of electric energy, it will be required more installed capacity.

Although the overall average CF will decrease due to a greener electric energy mix, the calculations show that from 2030 it is expected to increase, possible as a result of the technology efficiency's improvement.

In this report, regarding hydroelectric power, it was considered two different values for investment cost (Table 4.1): one referring to a new pumped hydroelectric storage plant, and the second referring to a power upgrade and pumping system installation in an already existing hydroelectric plant.

The different investment costs for hydroelectric plant, either new ones or updated power, aims to create an estimated electricity cost range that will depend on the construction decision. It is known that Portugal intends to build new hydroelectric plants as well as upgrade already existing ones however, it is not known however, how many of each. Therefore, by assuming all new installed capacity would be through a power upgrade in already existing dams or through the construction of new ones, it is created a “worst case” (which corresponds to the new hydroelectric plants) and a “best case” (which corresponds to the power upgrade hydroelectric plants) scenarios for the estimated electricity generation cost.

Once summed up all differentials on the total electricity generation cost from all different electric plants and the decommissioning of some fossil plants into the given electricity cost, as explained before in Chapter 4, the calculated cost is compared with the electricity costs given by the Refence Scenario, Figure 5.1.

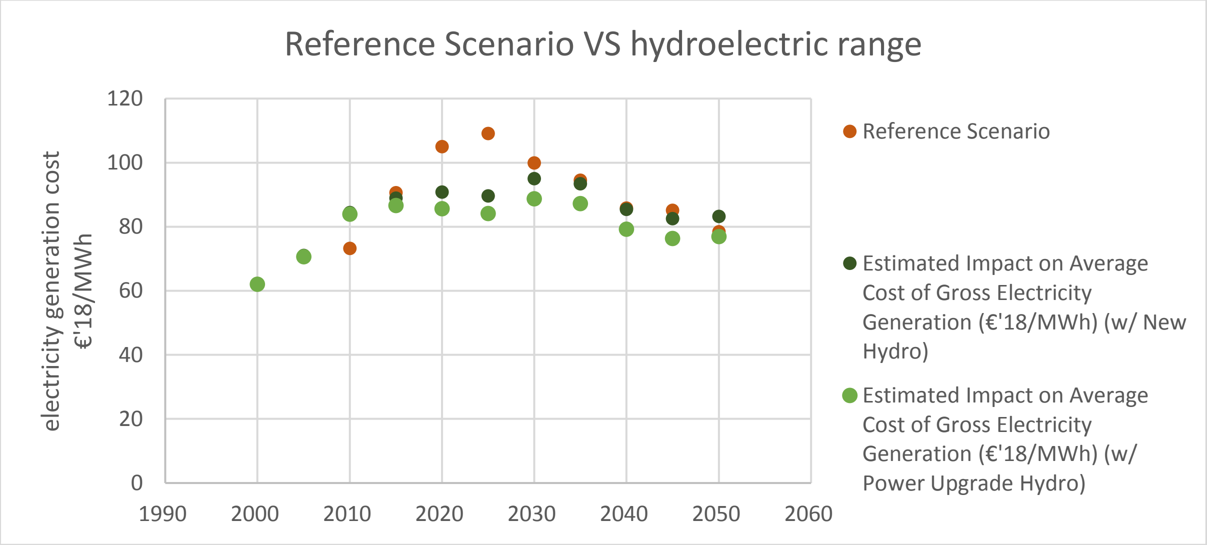


Figure 5.1 - Electricity generation cost for Reference Scenario, hydroelectric power upgrade and hydroelectric new installed capacity

From the graph in Figure 5.1 it is possible to see that the calculated electricity cost, although presenting similar values to the ones in the reference scenario electricity costs, it still has some differences.

On the search for a more accurate representation of the electricity generation cost was, therefore, added a carbon tax, from 2020 forward, of 30 € per tonne of CO_2 emitted taking into consideration that each fossil fuel has a different CO_2 emission when generating electricity (Table 4.3). This tax increases around 1 to 4 €/MWh the estimated electricity cost.

From this point forward the results presented will include the carbon tax.

Comparing Figures 5.1 and 5.2 it is visible that once the carbon tax is added to the calculation, the values of the calculated total electricity cost gets closer to the ones given by the reference scenario. However, there is a difference in the cost trend from 2020 and 2030, where the calculations lead us to believe it will decrease, whereas the reference scenario predicts an increase of the electricity costs.

Such difference can be explained by the payment of the electric debts that were accumulated over the years [55]. The Portuguese Government predicts all debts will be paid around 2030, which could explain the difference in the electricity cost to which there was not enough information to get to those values.

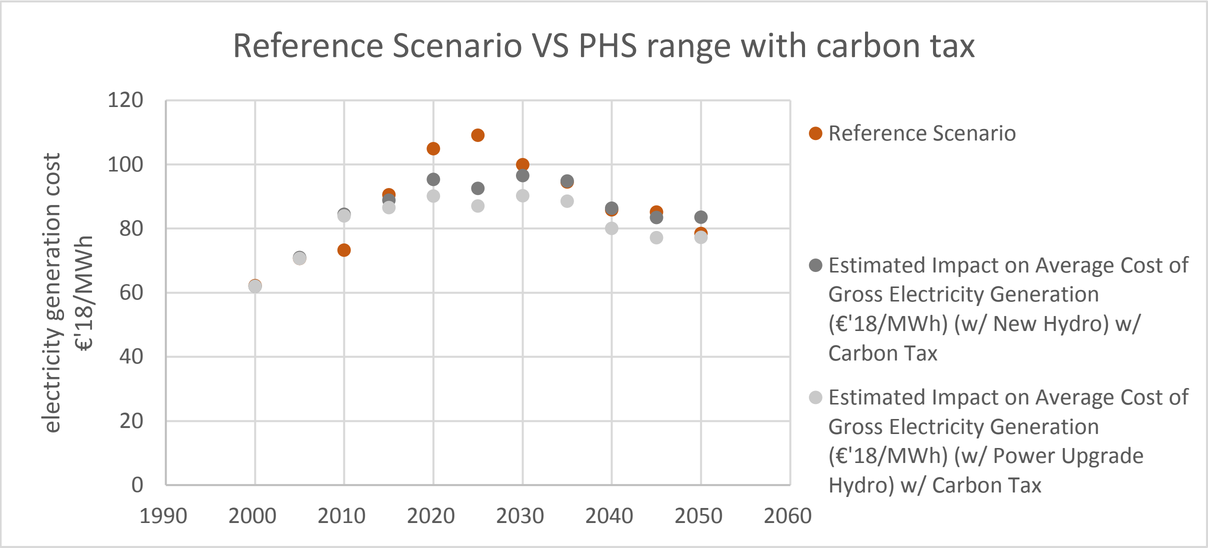


Figure 5.2 - Electricity generation cost for Reference Scenario, hydroelectric power upgrade and hydroelectric new installed capacity with carbon tax

The generation cost difference between both new and power upgrade PHS hypothesis corresponds to a maximum 7% of the total value, which is up to 6€ per MWh of electricity generated.

Table 5.2 - Estimated electricity generation cost for Reference Scenario, Calculated Reference Scenario (New PHS) and Calculated Reference Scenario (Power Upgrade PHS) (w/ carbon tax)

€/MWh	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Reference Scenario	62	71	73	91	105	109	100	94	86	85	78
Calculated Ref Scen (New PHS)			84	89	95	93	96	95	86	83	84
Calculated Ref Scen (Power Upgrade PHS)				87	90	87	90	89	80	77	77

When comparing the calculated impact on the electricity generation cost with the given electricity generation cost on the Reference Scenario (Table 5.3), the most accurate hypothesis is the one that assumes all hydroelectric investments as being new plants. For that reason, from this point forward, this will be the cost used as the calculated reference scenario for future comparisons.

Table 5.3 - Share of increase on the electricity generation cost compared with the values from the Reference Scenario

%	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Calculated Ref Scen (New PHS)	0%	0%	15%	-2%	-9%	-15%	-3%	-0%	1%	-2%	7%
Calculated Ref Scen (Power Upgrade)	0%	0%	15%	-4%	-14%	-20%	-10%	-6%	-7%	-9%	-1%

5.2. Strategies

Based on the evolution of Portuguese electricity generation from both solar PV and wind sources (Figure 4.1), the evolution of electricity exports (Figure 4.2) and their assessment for electric energy for the same sources [42], was estimated how much electricity the country could export, and follows equation 13.

$$\begin{matrix} Estimated\ exports \\ [GWh] \end{matrix} = 0{,}5909 * \begin{matrix} solar\ PV + wind \\ generation \\ [GWh] \end{matrix} - 207{,}26 \qquad equation\ 13$$

The difference between the estimated exports and the electricity imports originally given in the Reference Scenario [42] gives an amount of electricity that could assure the country's auto sufficiency and this value is used, in this work, as the of electric energy surplus.

Table 5.4 - Electric Energy Surplus and its share in the Gross Electricity Generation

	2020	2025	2030	2035	2040	2045	2050
Electricity Surplus [GWh]	1973	1976	6365	5905	7587	9399	11749
% electricity surplus	4%	4%	13%	12%	15%	18%	23%

5.2.1. PHS

Following the methodology explained in topic 4.2.1, here are presented the results calculated for the impact of pumped hydroelectric storage to store electric surplus in the final electricity generation cost.

Table 5.5 shows the increasing cost of electricity generation once the hydroelectric plants are used as storage technologies. As a result of this technological decision, the electricity cost would increase between 19% to 42% from the 2015 values, since the implementation of the strategy is due 2020.

Table 5.5 - Estimated electricity generation cost for PHS strategy

€/MWh	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
New PHS	62	71	84	89	97	96	106	111	109	115	126
Power Upgrade PHS					96	94	101	103	98	99	105

In a more graphic representation comes Figure 5.3 comparing the PHS strategy with the calculated reference scenario.

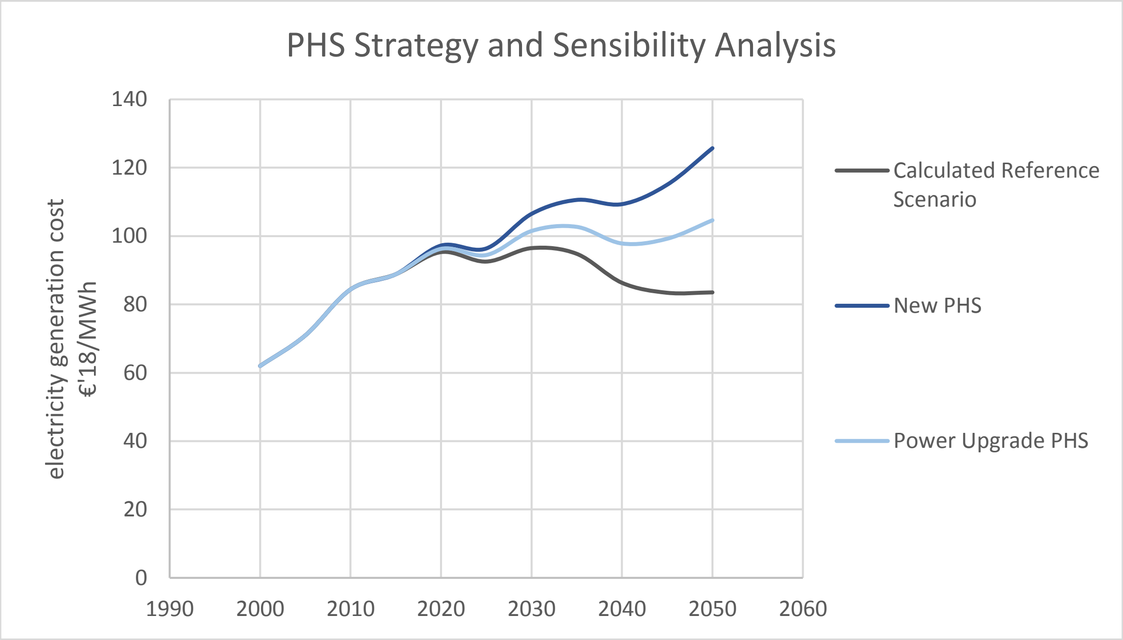


Figure 5.3 - Electricity generation cost for PHS strategy

5.2.2. Batteries

If the electricity surplus were stored in Li-ion batteries from 2020 forward, there would be an increasing impact on the final electricity generation cost presented in both Table 5.6 and in Figure 5.4.

The current LCOS for Li-ion batteries (108,5€/MWh [54]) is very high which makes this an economically non-viable solution. For that reason, it was calculated how the electricity generation cost would vary if the LCOS were 80 €/MWh or even 50 €/MWh.

Even though the likelihood of the LCOS dropping to such values is very low, these values were chosen for a sensibility analysis purpose only. Their relation, presented in Figure 5.4, compares the impact of different lithium ion battery's LCOS in the electricity generation cost.

Table 5.6 - Estimated electricity generation cost for lithium-ion batteries strategy

€/MWh	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
LCOS 108,5	62	71	84	89	99	100	117	127	133	148	170
LCOS 80					98	98	111	118	121	131	147
LCOS 50					97	96	105	109	107	117	123

The electricity generation cost decreases when the batteries' LCOS decreases however, the LCOS is not yet small enough to make this solution alone a viable one. In the batteries' scenario, the electricity generation cost is constantly increasing over the years, reaching costs as high as 170 €/MWh, whereas in the calculated reference scenario is predicted a maximum electricity generation cost of 96 €/MWh in 2030.

If batteries, as they are, with a LCOS of 108,5 €/MWh were implemented the final electricity generation cost in 2050 would increase by 91% comparing with 2015 electricity generation cost, before batteries were implemented. However, if the LCOS were to decrease to 80 €/MWh or 50 €/MWh, the increase in the electricity generation cost would be only around 65% and 38%, respectively, compared to 2015 cost.

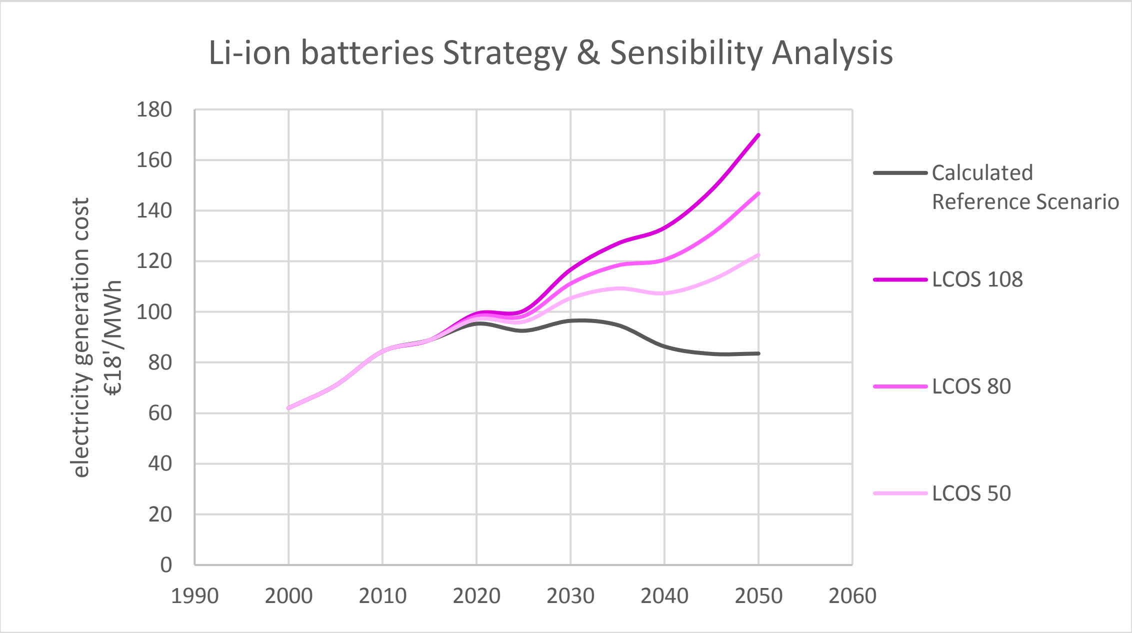


Figure 5.4 - Electricity generation cost for Li-ion batteries strategy

5.2.3. Power-to-gas

As in the previous scenarios, it was used the electricity surplus (equation 13) however this time it was used to estimate Portugal's capacity to produce H_2, equation 11, which is presented in Table 5.7. Since electricity surplus is the same no matter the scenario, then the H_2 produced is always the same no matter what sensibility analysis will be done later.

Table 5.7 - H_2 production, in GWh, from the electricity surplus

GWh	2020	2025	2030	2035	2040	2045	2050
H_2 production	1381	1383	4455	4133	5311	6579	8225

In a situation where the natural gas plants are going to be decommissioned, as the Reference Scenario predicts, Portugal could be capable of exporting H_2 from 2045. This would mean the electricity generation cost could decrease by this transaction and consequently, Portugal would even save money from the decrease import dependence on natural gas.

Then, calculating the net cost for power-to-gas, which includes the cost of H_2 production and the avoided natural gas imports, and dividing by the gross electricity generation, the final electricity generation cost is obtained.

In this first power-to-gas scenario, where some natural gas plants are decommissioned, the electricity generation cost would increase 62% in 30 years.

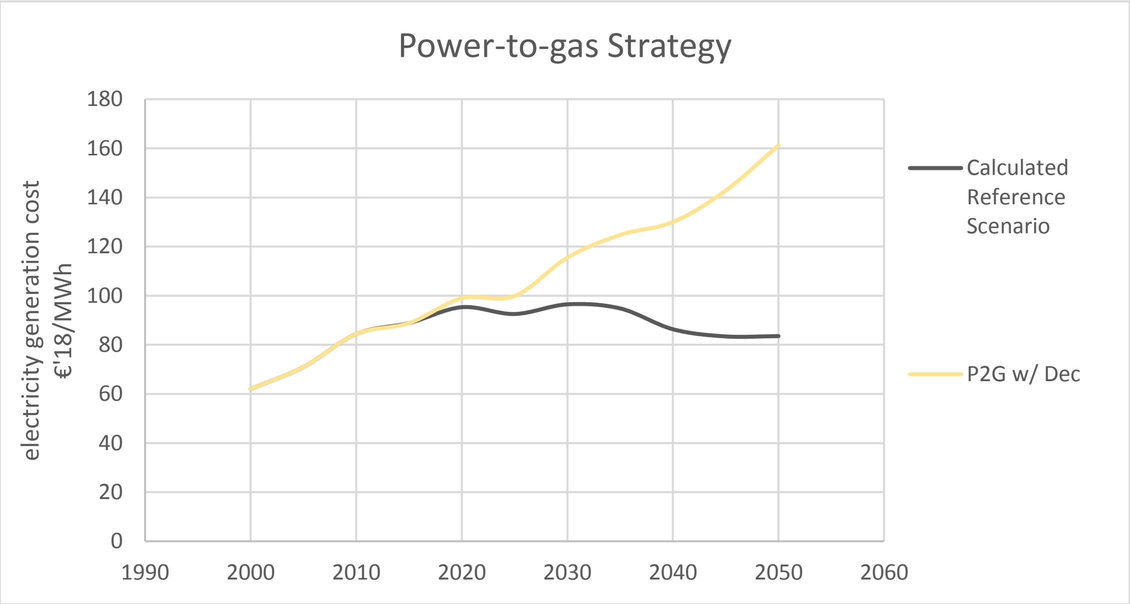


Figure 5.5 - Electricity generation cost for Power-to-gas strategy with decommission of natural gas plants

If Portugal would produce their own H_2 to use it in their natural gas grid, then it could be an advantage not to decommission the plants, as it is planned, or at least to delay that same decommission. For this case was calculated the impact on the electricity generation cost if (i) there were no natural gas plants decommission at all and (ii) if the decommission would be delayed, as in to decommission starting in 2040.

In either case, without decommission or with a later decommission, the gross electricity production increases comparing to the predicted gross electricity generation by the Reference Scenario.

Assuming the predicted generation is enough to fulfil the country's demand, then there would be no necessity in overdoing this production. In this case, when there would be an excess in electricity generation, it means there could be savings in the investments originally predicted for energy generation.

In the next table, Table 5.8, is shown the calculated electricity generation, in GWh, when the natural gas plants are not decommissioned and their decommission is delayed, comparing them to a scenario where the NG are decommissioned, as planned by the Reference Scenario.

Here can be read "w/ Dec" as the first P2G scenario, where there is decommission of the natural gas plants as predicted by the Reference Scenario, "w/o Dec" where will be considered a scenario with no decommission of any natural gas plant, maintaining a constant production of 10 868 GWh from 2025 until 2050, and finally, "w/ Dec 2040" where is considered the natural gas plants decommission starting only in 2040.

Table 5.8 - Gross electricity generation, in GWh, for each P2G scenario

GWh	2020	2025	2030	2035	2040	2045	2050
w/ Dec	48507	47988	48243	48076	49144	51140	52085
w/o Dec	48630	49499	49059	50435	63270	71226	61776
w/ Dec 2040					63023	68348	60259

Comparing with the expected electricity generation by the Reference Scenario and the P2G w/ Dec strategy, the generation can increase up to 39% or 33,6% for the P2G scenario without decommission and with decommission from 2040, respectively. In both cases, the generation reaches a maximum in 2045, since this is the year the CF for NG plants is the highest.

To avoid excess generation, the approach adopted was not to invest in the originally predicted new renewable capacity. However, in most of the 5-year tranches, the predicted investment in new renewable capacity (hydroelectric, solar, wind and biomass) is smaller than the excess generation caused by non-decommission of NG plants. In those cases, the whole new generation predicted is not installed, and the still remaining electricity excess is assumed as exported electricity, contributing to decrease the generation electricity cost.

Table 5.9 - Gross electricity generation adjusted, in GWh, for each P2G decommission strategy

GWh	2020	2025	2030	2035	2040	2045	2050
w/ Dec	48507	47988	48243	48076	49144	51140	52085
w/o Dec		48155		50419	61205	69873	59999
w/ Dec 2040					60958	66995	58482

Once again, Table 5.9, the bigger differential between the predicted electricity generation and the electricity generation from the power-to-gas scenarios happen in 2045 however, this time the differential is slightly lower: 36,6% for the no decommission scenario and 31% for the decommission starting in 2040 scenario.

Also, contributing to the decrease of the electricity generation cost in these strategies are the H_2 production surplus (Table 5.10), that can later be exported, and the avoided cost in natural gas imports (Table 5.11). The H_2 was considered to be exported at a market price of 48,5 €/MWh ([60]) and the natural gas importing price was considered to be 23 €/MWh ([61]).

Table 5.10 - H_2 exports, in GWh, for each Power-to-Gas decommission strategy

GWh	2040	2045	2050
w/ Dec	0	1235	3636
w/o Dec	0	0	1095
w/ Dec 2040	329	1979	3961

The natural gas avoided imports start when the H_2 production starts, which is in 2020, and is equal to all decommission strategies until 2045. The H_2 exports however is different for every strategy and the sooner it can happen is in 2040 for the strategy where the decommissioning starts that same year.

Table 5.11 - Natural gas avoided imports, in GWh, for each Power-to-Gas decommission strategy

GWh	2020	2025	2030	2035	2040	2045	2050
w/ Dec	1381	1383	4455	4133	5311	5344	4588
w/o Dec						6579	8225
w/ Dec 2040						5750	5329

Considering all three power-to-gas hypotheses and calculating the whole electricity generation and generation adjustment, the sale of excess electricity generation and H_2 excess production is calculated, based on the equations presented in the previous chapter the final electricity generation cost is calculated and presented in Figure 5.6.

The power-to-gas strategy allows to export both electricity and H_2 that neither the PHS nor the Li-ion batteries strategies allow. These exports translate in earnings – Table 5.12 - that help ease the final electricity generation cost.

Table 5.12 - Earnings, in M€, through exportation of electricity and H_2

M€	2020	2025	2030	2035	2040	2045	2050
w/ Dec	0	0	0	0	0	60	176
w/o Dec	0	8	0	117	603	937	449
w/ Dec 2040	0	8	0	117	607	889	512

There is a considerable difference in the electricity generation cost, Table 5.13, when pondering not to decommission or to delay the decommission. This difference reaches a maximum of around 30 €/MWh in 2050. The two strategies that involve to not decommission or to delay the decommission, have a very similar electricity generation cost however, the strategy to delay the decommission until 2040 has a slight lower generation cost (minus 2 €/MWh than the strategy where there is no decommission at all).

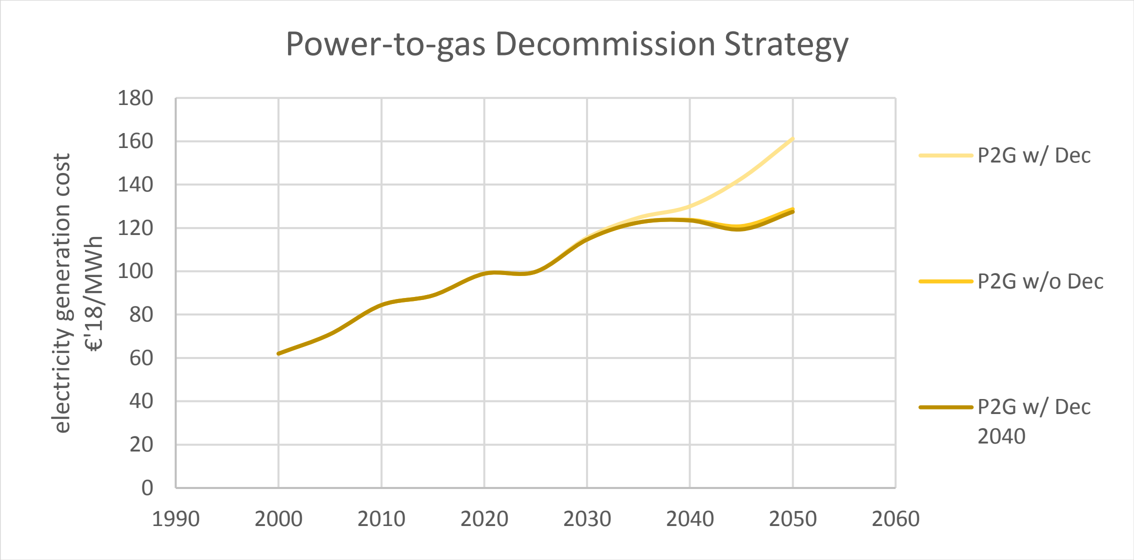


Figure 5.6 - Electricity generation cost for different Power-to-Gas decommission strategies

Table 5.13 - Electricity generation cost for different Power-to-Gas decommission strategies

€/MWh	2020	2025	2030	2035	2040	2045	2050
w/ Dec	99	100	115	125	130	143	161
w/o Dec	99	100	115	123	124	121	129
w/ Dec 2040	99	100	115	123	123	119	127

For the strategy that presents the lowest generation cost, strategy where the decommission of natural gas plants starts in 2040, was made a sensibility analysis for the LCOE of power-to-gas. Today the LCOE of P2G is 150 €/MWh ([56]) however, since the technology involved here is electrolysis and this is a very well-known process, it should be easy to lower the LCOE. Increasing the number of electrolysis technologies installed, both know-how and increasing the process optimization, will contribute to decrease the power-to-gas levelized cost of electricity. The LCOE could even decrease to a value as low as the natural gas' LCOE, which is 50 €/MWh (Table 4.2).

Table 5.14 - Electricity generation cost for different Power-to-Gas' LCOE for the P2G w/ Dec 2040 scenario

€/MWh	2020	2025	2030	2035	2040	2045	2050
LCOE 150 €/MWh	99	100	115	123	123	119	127
LCOE 100 €/MWh	97	97	107	111	108	98	100
LCOE 50 €/MWh	96	94	100	99	92	78	72

When decreasing the LCOE for P2G, the electricity generation cost decreases significantly, making the costs very competitive. The calculated costs can even be lower than the predicted ones by the Reference Scenario.

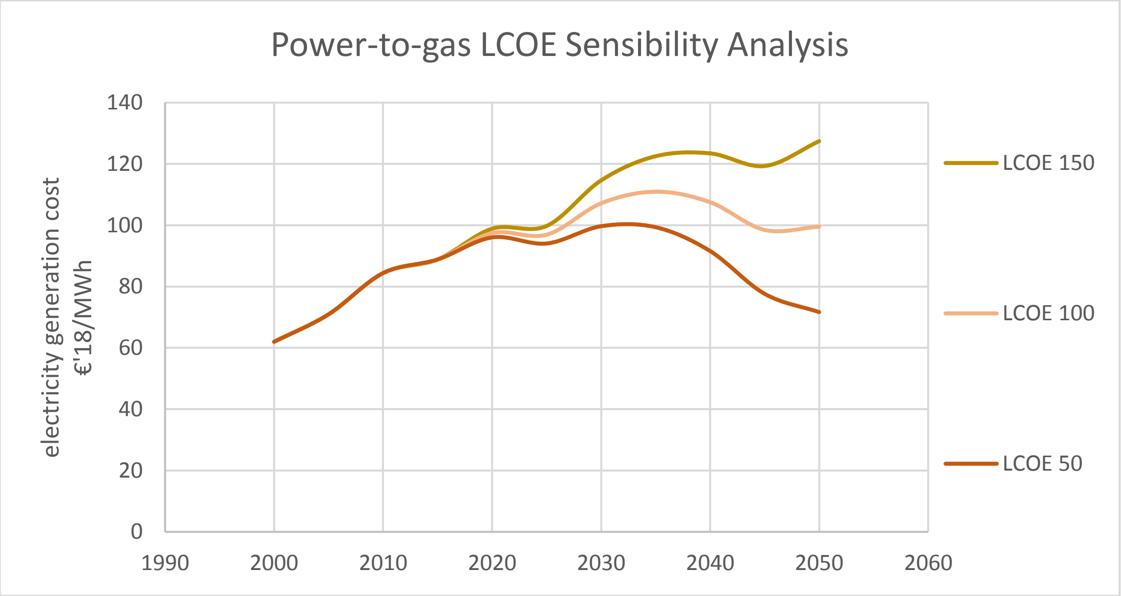


Figure 5.7 - Electricity generation cost for different Power-to-Gas LCOEs

In Figure 5.7 is graphically represented the values from Table 5.14, where it is easier to see how much the electricity generation cost can decrease from 2030/2035 to values equal or even lower than 2020, before any power-to-gas strategy were implemented.

5.2.4. Demand side management

In France was implemented a smart meter project ([63]), where they installed 35 million smart meters with an investment of 6 000 million euros. This means each smart meter has an approximate cost of 171,4 €.

Assuming the 35 million smart meters were for the whole population of France, 67 million inhabitants ([65]), when adapting for all 10 million inhabitants in Portugal ([66]), it is obtained a total need for 5,2 million smart meters, which would require an investment of 891 million euros.

The calculations present a very rough estimation, since each machine requiring energy should have a smart meter and each inhabitant has more than one machine, for example at home, not to mention all the machinery for the industry. Nevertheless, the investment cost in smart meters gives an idea of a value from which it could be worth implementing a demand side management strategy.

Without further information, it was estimated 891 M€ for the investment in smart meters and this will be used as a reference to compare with the investment cost from the other strategies.

Multiplying the electricity generation cost of each scenario with the gross electricity generation for each scenario – equation 14 - is obtained the national expenditure for each scenario, Table 6.2. The national expenditure was then used to foresee if an investment in smart meters would be a viable alternative or not.

$$\begin{matrix} National\ Expenditure \\ [M€] \end{matrix} = \begin{matrix} Electricity \\ generation\ cost \\ \left[€/_{MWh}\right] \end{matrix} * \begin{matrix} Gross\ electricity \\ generation \\ [GWh] \end{matrix} \qquad equation\ 14$$

If the national expenditure in a 10 or 20 years range would be lower than the predicted investment in smart meters (891 M€) than it would not be worth investing in them, If however, the difference would be equal or bigger than the smart meters predicted investment, then it would be recommended further studies with more accurate values to determine the viability of its implementation.

Since this is a comparative study between all the presented scenarios, the values are presented in the next chapter, Chapter 6.

6. Comparison between scenario

This chapter will be used to compare all the strategies together, discuss which ones are viable options and between them determine which Portugal should invest in.

As a first step is consolidated the generation electricity costs previously presented at different scenarios in one single table, Table 6.1, displayed from the most expensive to the least expensive. The presented values start in 2020 since that is the year the scenarios are being implemented, and before that the electricity generation cost is the same regardless the scenario.

For simplification purposes the name of each strategy was shorten, however clear enough to mention properly each case.

Table 6.1 - Electricity generation cost, in €/MWh, for all considered scenarios

€/MWh	2020	2025	2030	2035	2040	2045	2050
Battery 108	99	100	117	127	133	148	170
P2G w/ Dec	99	100	115	125	130	143	161
Battery 80	98	98	111	118	121	131	147
P2G w/o Dec	99	100	115	123	124	121	129
P2G w/ Dec 2040 LCOE150	99	100	115	123	123	119	127
PHS New	97	96	106	111	109	115	126
Battery 50	97	96	105	109	107	113	123
PHS Power Upgrade	96	94	101	103	98	99	105
P2G w/ Dec 2040 LCOE100	97	97	107	111	108	98	100
Ref Scen Calculated	95	93	96	95	86	83	84
P2G w/ Dec 2040 LCOE50	96	94	100	99	92	78	72

Table 6.1 shows all the studied scenarios however, some scenarios are more realistic than others. For example, it is more likely for the LCOE of power-to-gas to decrease from the current 150 €/MWh to 50 €/MWh (for the reasons given in Chapter 5.2.3) than the Li-ion batteries LCOE to decrease more than the current 108,5 €/MWh.

Looking at all strategies and their final electricity generation cost, it is safe to say that the investment in lithium ion batteries to store the electricity surplus is not a viable solution to adopt country wide since there are solutions more cost-effective, being pumped hydroelectric storage one of them.

Regarding pumped hydroelectric storage, there is a range of electricity cost, on the top of which is considered all electricity surplus is stored in new PHS whereas in the bottom is considered all electricity surplus is stored in power upgraded PHS. The difference in cost between both PHS strategies increases with the electricity surplus, which raises along the years and reaches its maximum in 2050 with a 21 €/MWh difference.

Within this range there is the Li-ion battery with a LCOE of 50 €/MWh. Since it is very unlikely for Li-ion batteries to reach such LCOE, and since all other hypothesis for batteries present a higher generation cost for electricity, it can be said that under these conditions, from these two strategies, the best strategy would be to implement pumped hydroelectric storage. This leaves PHS and P2G strategies left to compare.

When power-to-gas as a new strategy is presented with no further alterations to the electric system – P2G scenario with normal natural gas plants decommission (P2G w/ Dec) – the electricity generation cost increases almost as much as for the Li-ion battery scenario with a LCOS of 108,5 €/MWh.

However, if the goal is to implement such solution in the best way possible, then it may be worth considering not to decommission the natural gas plants or to delay the decommission. With such assumptions, the electricity generation cost decreases to equivalent values as the top range of the PHS strategy.

In the next figure, Figure 6.1, it can be compared the impact that PHS and P2G calculated strategies have on the final electricity generation cost.

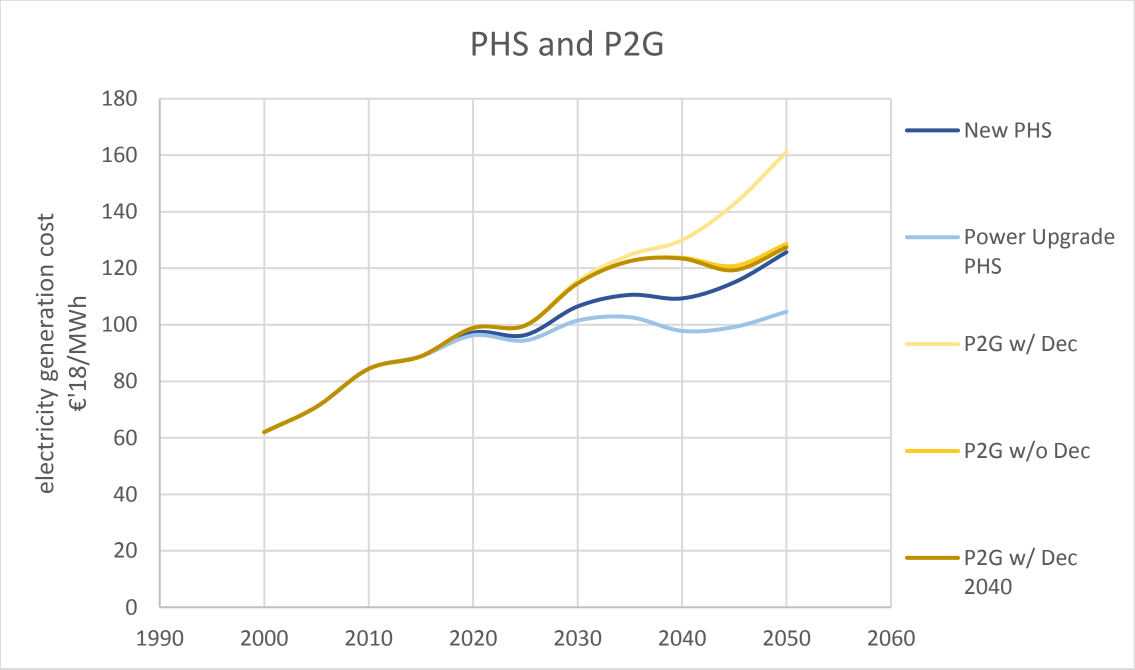


Figure 6.1 - Comparative impact of PHS and P2G strategies in the electricity generation cost

In both Figure 6.1 and Table 6.1 can be seen that for either power-to-gas later decommission strategy or no decommission strategy, the impact on electricity generation cost is very similar, presenting a maximum difference of 3 €/MWh. Although the new calculated electricity generation costs for these scenarios is much smaller than the ones calculated for lithium ion batteries, the electricity surplus storage in pumped hydroelectric plants is still the most viable option.

Once it is now being considered the production of H_2 it was considered relevant to study the impact of the non-decommission of the NG plants. The European Union however, is working towards carbon neutrality and by not decommissioning natural gas plants such goal cannot be accomplished. For that reason, the sensibility analysis on the power-to-gas LCOE was made for the strategy where the NG plants decommission starts in 2040, later than originally planned but still decommissioning them.

As mentioned before, the electrolysis technology is already known and so, to decrease the current LCOE of 150 €MWh it is necessary to improve the process optimization as well as increase the number of electrolysis technology installations.

Considering these new LCOE's for power-to-gas in the P2G w/ Dec 2040 strategy, the electricity generation costs are compared with other strategies – Figure 6.2 – and now, the best strategy to implement is no longer pumped hydroelectric storage.

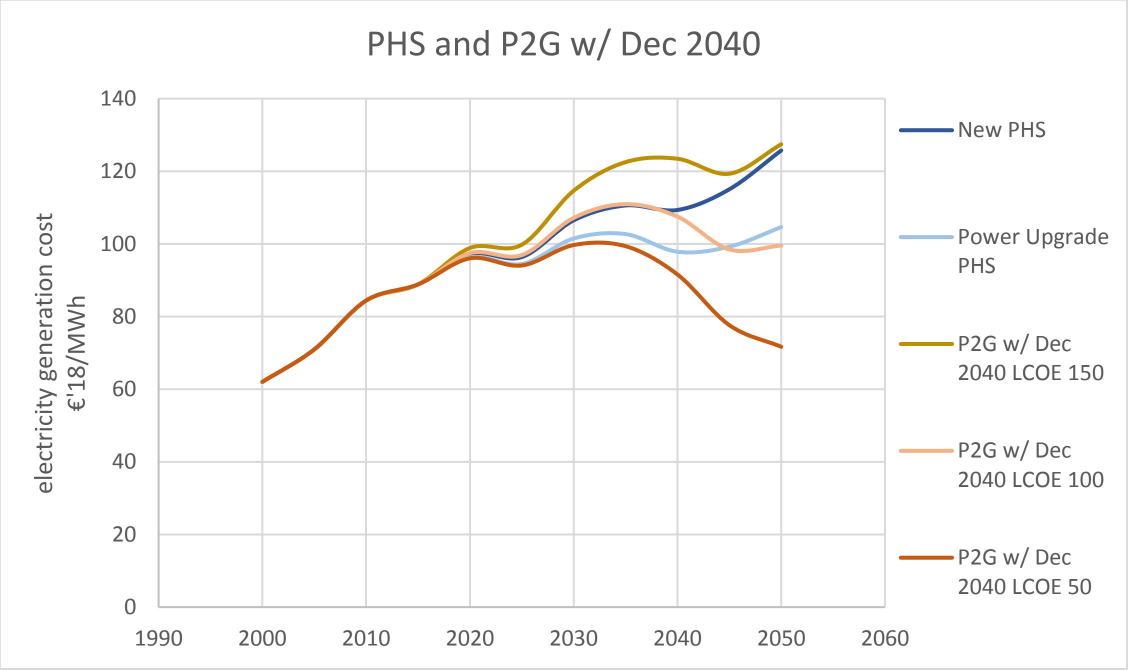


Figure 6.2 - Comparative impact of PHS and P2G w/ Dec 2040 strategies on the electricity generation cost

When comparing PHS and P2G energetic strategies, considering no decommissioning, the difference in the electricity generation costs is so small (1 - 3 €/MWh when comparing to new PHS) that the chosen strategy can depend on the decision maker's goals.

In a more optimistic vision, and still a realistic one, where the LCOE of power-to-gas decreases, the preferential strategy changes from PHS to P2G. The evolution of the cost of both storage strategies is slightly different due to its differences in nature however, in time power-to-gas strategy becomes more and more competitive. And for a power-to-gas LCOE of 50 €/MWh this strategy becomes, by far, the most economically viable solution of all.

Comparing the most economically viable strategies – Power Upgrade PHS, P2G w/ Dec 2040 for LCOEs of 100 €/MWh and 50 €/MWh – with the calculated reference scenario – Figure 6.3 – the P2G w/ Dec

2040 with a LCOE of 50 €/MWh is the ultimate strategy as it predicts a generation electricity cost even smaller than the one originally predicted by the reference scenario.

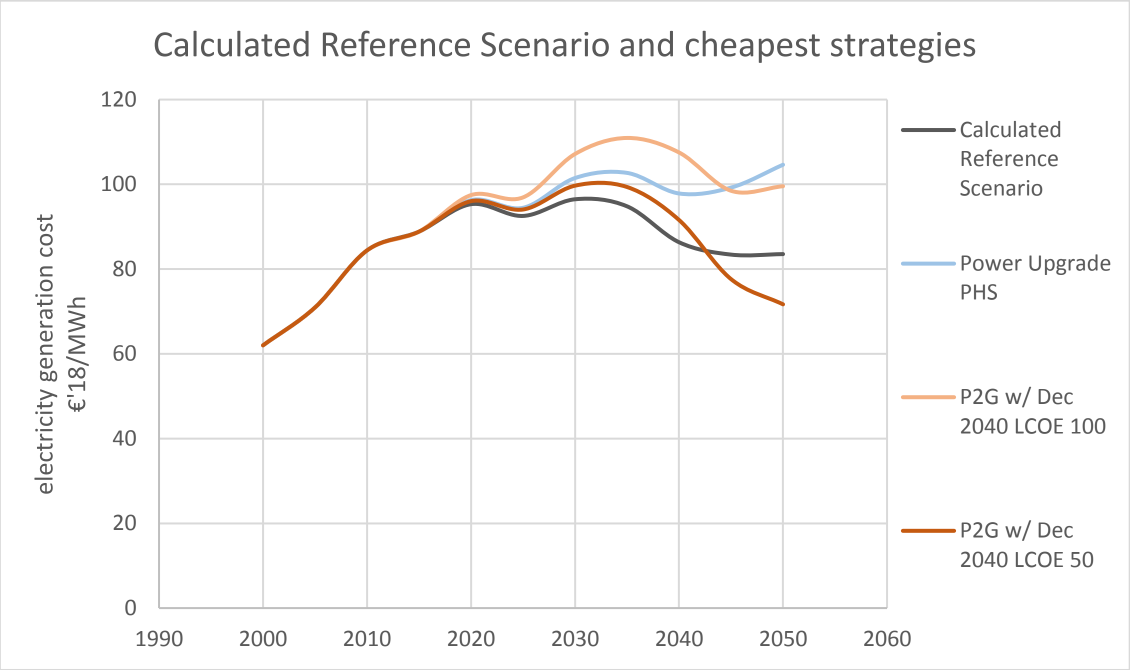


Figure 6.3 - Comparative impact of the less costly strategies and the calculated reference scenario on the electricity generation cost

It is important to mention that all calculations were made under several assumptions and consequently, there is an error margin. Nevertheless, the evolutionary behaviour of electricity generation cost is correct. For this reason, it is recommended that any decision maker would correct the assumptions made in this report into accurate values before taking any decision.

There are multiple criteria to evaluate which strategy is better to implement. The one most calculated up to this point was the generation electricity cost. Now will be put to evidence other important criteria such as (1) the share of electricity in the primary energy demand, (2) the import dependency and (3) the carbon dioxide emissions.

Europe, amongst other goals, wants to increase the share of electricity in the global energy consumption and so, as a measure of such goal, it is used the share of electricity in the overall primary energy demand, Table 6.2. Since all scenarios are to be implemented from 2020, it means before that the share of electricity in the overall primary energy demand is the same independently of the strategy.

Then, for the storage strategies - PHS and batteries – once the electricity generated as well as the net imports are the same - however, the imports have decreased compared to the reference scenario - then the share of electricity in the overall electricity consumption will also be the same. Only when considering a power-to-gas strategy, the share of electricity is different.

In the P2G strategy, the net imports decrease and the electricity generation increases or this last one is the same as before. Therefore, the share of electricity in the primary energy demand increases.

Table 6.2 - Share of electricity in the overall primary energy demand

%	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Calculated Ref Scen	14,7	14,5	19,1	18,8	19,5	19,5	20,7	21,0	21,9	22,9	23,6
PHS					19,9	20,0	21,2	21,5	22,4	23,4	24
Battery											
P2G w/ Dec					19,8	19,9	20,8	21,2	21,9	22,7	23,2
P2G w/o Dec								22,2	27,3	31	26,7
P2G w/ Dec 2040									27,2	29,8	26

The share of electricity in the storage strategies is a constant 0,5% higher than the share in the calculated reference scenario. The bigger differences occur for the P2G scenario, and even within the scenario it is different depending on the strategy chosen.

For a normal decommission strategy, the primary energy consumption increases because there is production of H_2. Consequently, the share of electricity decreases. For the other two, despite the increase of the overall primary consumption, the gross electricity generation also increases, resulting in an increase of the share of electricity in the overall primary energy consumption.

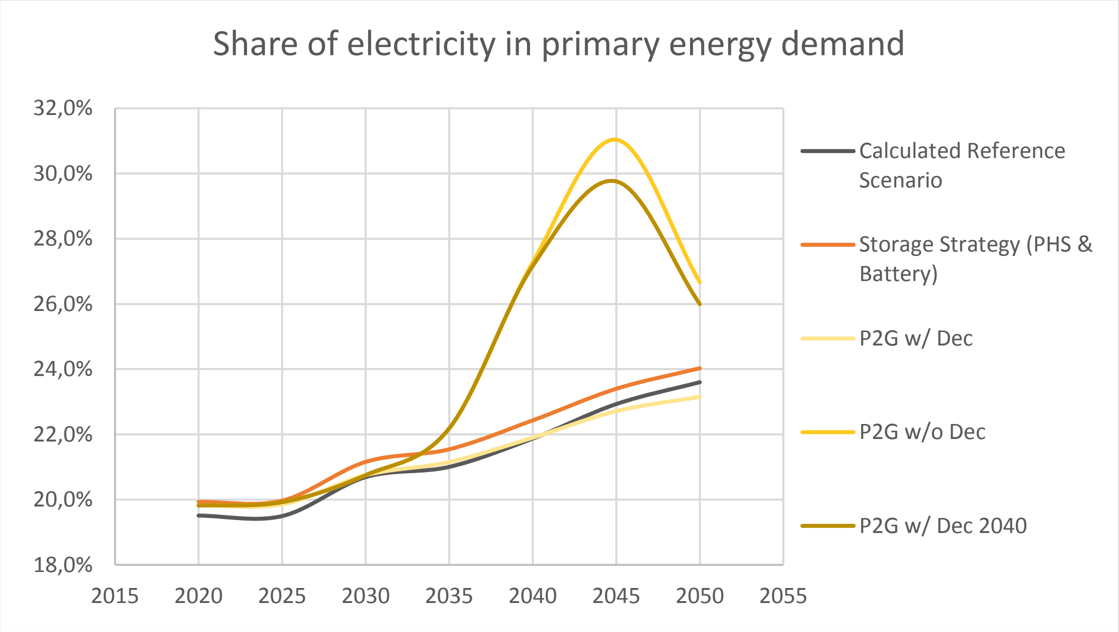


Figure 6.4 – Share of electricity in the primary energy demand from 2020

Directly related with the electricity share in the primary energy demand is the share of renewable energy sources in the overall electricity demand, Table 6.3. To all scenarios that present the same gross electricity generation – the reference scenario, the PHS and Li-ion batteries scenarios as well as the P2G with normal decommission strategies – the calculated RES share is the same and is constantly increasing. When considering the other power-to-gas strategies, where some natural gas plants are not decommissioned and some renewable plants are not invested in, the renewable share in the gross electricity generation decreases.

Table 6.3 - Renewable energy share in the gross electricity generation

%	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Scenarios with the same gross electricity generation	30	19	53	50	71	74	87	88	92	92	96
P2G w/o Dec								84	74	67	84
P2G w/ Dec 2040										70	86

Another important criterion is the county's energetic dependency, Table 6.4. Portugal depends on imports specially for fossil fuels, but also for electricity when the county's demand is higher than the supply. With these calculated scenarios, it is intended as well to decrease this external dependency either by increasing storage – PHS and batteries strategies – or by producing the country's own H_2 as a partial substitute on the natural gas grid – P2G strategy.

The scenario that provides the best independency is the scenario where Portugal consumes as much self-generated electricity as well as decreases as much as possible the net imports, and this one is a power-to-gas scenario with the originally predicted natural gas plants decommission – P2G w/ Dec.

Comparing all scenarios with the calculated reference scenario in term of imports dependency, any calculated scenario presents a decrease of this outside dependence, except for a P2G scenario with no natural gas plants decommission that would make the country 2% more dependent.

Due to lack of information, the calculated reference scenario has an error of 1% in the dependency imports share once compared with the given reference scenario share.

Table 6.4 - Share of imports dependency

%	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Calculated Ref Scen	87,3	90,4	77,7	79,3	73,3	71,8	68,6	68,6	67,1	66,0	64,1
Storage Scenario (PHS & Batteries)					72,7	71,2	67,9	67,8	66,3	65,3	63,4
P2G w/ Dec					71,7	70,2	64,7	64,8	62,3	61,0	59,1
P2G w/o Dec							70,6	71,4	70,0	68,1	66,8
P2G w/ Dec 2040									63,9	61,7	60,4

Another very important criterion that the EU has been working on is the carbon dioxide emissions mitigation. The goal is to reach carbon neutrality.

When reading Table 6.5, it is possible to conclude that, if not changing the electricity generation, all scenarios contribute without a difference to reduce the carbon emissions, reaching a value as low as 700 kilo tonnes by 2050. However, when the electricity generation changes – for power-to-gas strategies without decommission and delayed decommission – the carbon emissions changes as well. The more electricity is generated the more CO_2 is emitted.

Table 6.5 - Carbon emissions, in Mton, depending on the gross electricity generation

Mton	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Scenarios with the same gross electricity generation	20,0	23,1	13,4	17,3	7,4	4,7	2,5	2,3	1,6	1,6	0,7
P2G w/o Dec						5,3	2,8	3,2	6,8	9,0	4,3
P2G w/ Dec 2040									6,7	8,0	3,8

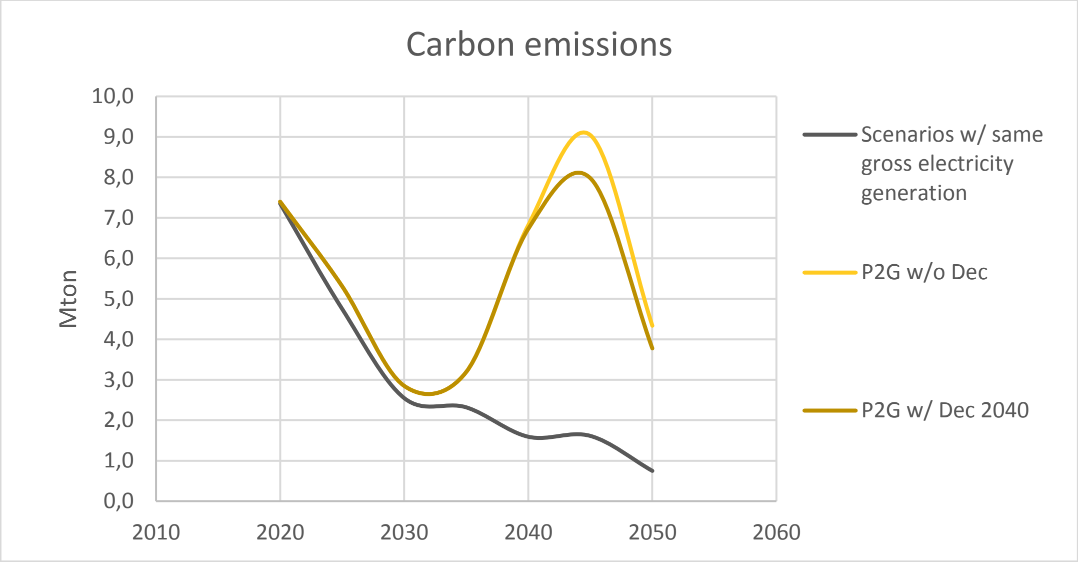


Figure 6.5 - Estimated carbon emissions, in Mton, from 2020

Finally, was compared the investment in all the presented strategies with the eventual investment in smart meters, which as explained in Chapters 4.2.4 and 5.2.4, the calculated investment for this technology in Portugal would be roughly around 891 000 000 €.

It is assumed that smart meters have a lifetime around 10 years. So, it was created 10-year ranges between 2020 and 2050 to compare the smart meters investment with the investment for the strategies calculated.

In Table 6.6 is presented the national expenditure, in millions of euros, in 10-years ranges for each scenario. When the value is negative it means the national expenditure decreased in that 10-year range, if however, the value is positive, it means the national expenditure in the same 10-year range increased.

With this table – Table 6.6 – the goal is to determine either if it would be viable or not to invest in smart meters rather than the proposed strategy. To help understand better this conclusion, the results written in green are the ones that would be worth considering investing in smart meters instead of the proposed strategy.

Table 6.6 - National expenditure, in M€, in 10-year ranges for the proposed calculated strategies

M€	2020 - 2030	2025 - 2035	2030 - 2040	2035 - 2045	2040 - 2050
Calculated Ref Scen	31	117	-411	-292	108
New PHS	421	692	236	566	1175
Power Upgrade PHS	226	404	-88	137	641
Battery 108	811	1285	920	1471	2303
Battery 80	597	971	565	1001	1719
Battery 50	372	640	192	506	1104
P2G w/ Dec	772	1207	817	1305	2007
P2G w/o Dec	816	1240	2204	2427	121
P2G w/ Dec 2040 LCOE150	816	1240	2156	1976	-101
P2G w/ Dec 2040 LCOE100	518	798	1519	1135	-777
P2G w/ Dec 2040 LCOE50	220	356	881	295	-1453

When the national expenditure is greater than 891 M€ the result in Table 6.6. is written in green, and it means, theoretically, it would be worth investing in smart maters. However, the calculations for smart meters are more of an estimation and, for that reason, it is widely recommended that before making any investment decision, the information regarding smart meters expenditure would be updated to more accurate values.

7. Conclusions

Most energetic goals, established by the European Union and Portugal concern the overall energy mix and therefore it includes not only electricity but also transports, heat and cooling and other minor parcels. In this report however, the obtained data was regarding electricity alone, and so, all the calculated scenarios concern electricity mix.

From the emissions mitigation and renewable electricity targets for 2020, Portugal set as a goal to have 60% of its electricity generation to come from renewable sources (the goal also says 31% of the gross energy consumption) and, by the calculations in all the scenarios presented in this report by 2020 the renewable electricity mix would be around 71%, which means the goal is achieved. By 2030 however, the goal specification concerns the overall energy consumptions as it says 40% of Portugal's gross energy consumption comes from RES but since through the scenario's calculations the RES share in the electricity generation is 87%, it can be concluded that Portugal is on the right track to achieve the desired goals.

The greenhouse gas emissions' reduction of 20% by 2020, and of 30% by 2030 compared to the 2005 values, are the goals Portugal set. Greenhouse gas emissions include carbon dioxide amongst other emission and in this report was only possible to calculate the CO_2 emissions. Once again, compared to the 2005 values, by 2020 the CO_2 emissions are predicted to suffer a reduction of 68% and of 89% by 2030. These reductions contribute to a significant reduction of the GHG emissions, as desired. Nevertheless, for more accurate values, it is advisable to search for information regarding GHG composition and shares of each component.

The main goal of this report is to help a decision maker decide which energetic scenario is best to implement, depending on the desired outcome.

The desired outcome, evaluated as different criteria - electricity generation cost, share of electricity in the primary energy demand, share of RES in the overall electricity generation, imports dependency, CO_2 emissions and even incomes from both electricity and H_2 exports – ranks differently for each of the selected scenarios and strategies.

From all the scenarios and strategies calculated and from all the criteria evaluated, it is not possible to conclude that one of the scenarios is definitely better than the others.

Pumped hydroelectric storage was initially chosen as a possible storage technology not only because it its already existent in Portugal but also because several studies already proved its economic viability, which was, once again, proven in this report.

Storing electric energy surplus in lithium-ion batteries however, was proven by the calculations, to be much more expensive than the other alternatives presented and did not present any stronger rank in any of the other criteria. That is why Li-ion batteries storage is not recommended as a nation's main storage solution.

Power-to-gas is a storage solution which rank varies the most depending on both the criteria evaluated and the strategy used. Once considering the predicted decommission of natural gas plants, P2G w/ Dec, the strategy is one of the most expensive whereas once considering decommission of the NG plants only starting in 2040, then the strategy becomes the cheapest one amongst all scenarios.

A similar behaviour occurs in the remaining criterion: while one of the power-to-gas strategies rank first, the others may rank last in the same criterion. Nevertheless, when comparing all strategies within the power-to-gas scenario it is possible to conclude that between the P2G w/ Dec and the P2G w/o Dec strategies they are equivalent, when comparing all the criteria. However, the decision to implement one or the other might depend on the importance weight the decision maker attributes to each criterion. Despite any importance weight the decision maker may attribute to each criterion, the decommission from 2040 strategy – P2G w/ Dec 2040 - is, within all three, the best one to adopt.

If the main decisive criterion is the electricity generation cost, then the best energetic option to adopt in Portugal would be a power-to-gas strategy considering the decommission of natural gas plants only from 2040 (P2G w/ Dec 2040) and secondly would be the implementation of pumped hydroelectric plants considering only a strategy of power upgrade (PHS Power Upgrade).

Finally, an implementation strategy of demand side management would only be worth considering if the investment in any other alternative would be higher than the implementation for DSM.

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A. Annexes

1. Big Hydroelectric Plants (>10 MW) in Portugal, July 2017

Table A.1 - Big Hydroelectric Plants (>10MW) in Portugal, July 2017

LOCATION	NAME	INSTALLED POWER [MW]
M	Aguieira	336
M	Alqueva	256
M	Alqueva II	256
M	Alto Lindoso	630
M	Alto Rabagão	68
M	Baixo Sabor	151
M	Belver	80,7
M	Bemposta	240
M	Bemposta II	191
M	Bouçã	44
M	Cabril	108
M	Caldeirão	40
M	Caniçada	62
M	Carrapatelo	201
M	Castelo de Bode	159
M	Crestume/Lever	117
M	Desterro	13,2
M	Feiticeiro (Baixo Sabor-jusante)	36
M	Frades	191
M	Fratel	132
M	Lindoso	44,1
M	Miranda	369
M	Paradela	54
M	Picote	195
M	Picote II	246
M	Pocinho	186
M	Ponte de Jugais	20,3
M	Pracana	41
M	Raiva	24
M	Régua	180
M	Ribeiradio	73,6
M	Sabugueiro I	12,8
M	Salamonde	42
M	Salamonde II	223
M	Santa Luzia	24,2
M	Torrão	140
M	Touvedo	22
M	Valeira	240
M	Varosa	25
M	Venda Nova	90
M	Venda Nova III	756
M	Vila Cova	23,4
M	Vilarinho das Furnas	125
M	Vilar-Tabuaço	58
I - M	Socorridos	24

M: Mainland; **I – M**: Madeira Island

- Total installed power in the country: 6550,3 MW
- Total installed power in the mainland: 6526,3 MW
- Total installed power in Madeira: 24 MW