Faculdade de Engenharia da Universidade do Porto

Assessing the Economic Viability of Price Arbitrage through Storage Devices: A Case Study Using MIBEL Market Prices in 2021

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Abstract

The Iberian Electricity Market, known as MIBEL, is a collaborative market established between Portugal and Spain with the primary objective of enhancing the interconnection between both countries' electrical systems. This market facilitates the submission and acceptance of energy purchase and sale proposals for each hour of the following day, leading to the determination of market prices. As the supply and demand dynamics fluctuate throughout the day, the market prices also vary, resulting in both higher and lower prices within the same day in response to changing supply and demand conditions.

This dissertation investigates the influence of energy storage devices on the price dynamics of the daily market when performing daily arbitrage. Specifically, 2021 will be analysed, and simulations will be conducted to assess the impact of introducing new purchase and selling proposals to the market based on the charging and discharging activities of the considered storage devices.

To facilitate this analysis, a custom Python program was developed, which enables the user to select the year in analysis and define the characteristics of the storage system. The Linear Approximation approach involves linearizing the collective buying and selling curves to quantify the effect of the storage devices' charging and discharging activities on the market price.

From the obtained prices, it was possible to observe the price oscillations, which were positive during the hours of charging and negative during the hours of discharging. Using the new prices, the possible profits by performing daily arbitrage for the year were calculated, and an investment analysis was conducted.

The findings highlight that the average daily price difference between energy purchase and selling significantly impacts potential profits. More recent years exhibited higher profitability due to increased renewable energy production and rising natural gas prices, influencing the price during discharging hours. However, the investment in Li-ion batteries to perform daily arbitrage is still economically unviable.

Resumo

O Mercado Ibérico de Eletricidade, conhecido por MIBEL, é um mercado colaborativo estabelecido entre Portugal e Espanha com o objetivo primordial de potenciar a interligação entre os sistemas elétricos de ambos os países. Este mercado facilita a submissão e aceitação de propostas de compra e venda de energia para cada hora do dia seguinte, conduzindo à determinação dos preços de mercado. Como a dinâmica de oferta e demanda flutua ao longo do dia, os preços de mercado também variam, resultando em preços mais altos e mais baixos no mesmo dia em resposta às mudanças nas condições de oferta e demanda.

Esta dissertação tem como foco investigar a influência dos dispositivos de armazenamento de energia na dinâmica de preços do mercado diário ao realizar arbitragem diária. Especificamente, será analisado o ano de 2021, e serão realizadas simulações para avaliar o impacto da introdução no mercado de novas propostas de compra e/ou venda com base nas atividades de carga e descarga dos dispositivos de armazenamento considerados.

Para facilitar essa análise, foi desenvolvido um programa em linguagem *Python* customizado, que permite ao utilizador selecionar o ano em análise e definir as características do sistema de armazenamento. A abordagem de Aproximação Linear aplicada envolve a linearização das curvas coletivas de compra e venda para quantificar o efeito das atividades de carga e descarga dos dispositivos de armazenamento no preço de mercado.

A partir dos preços obtidos foi possível observar as oscilações de preços, que foram positivas no caso das horas de carregamento e negativas durante as horas de descarga. A partir dos novos preços, foram calculados os ganhos possíveis pela realização da arbitragem diária do ano e realizada uma análise de investimento.

Os resultados destacam que a diferença de preço médio diário entre compra e venda de energia tem um impacto significativo nos lucros potenciais. Os anos mais recentes apresentam maior rentabilidade devido ao aumento da produção de energia renovável e ao aumento dos preços do gás natural que influenciam o preço durante as horas de descarga. No entanto, ainda é economicamente inviável o investimento em baterias de ião de lítio para realizar arbitragem diária.

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I would like to express my deepest gratitude and appreciation to all the individuals and institutions whose support and contributions have been instrumental in completing this dissertation.

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Francisco Sousa Lobo

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Abbreviations and Symbols

List of Abbreviations

CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CMVM	*Comissão Nacional Valores Mobiliários*
CNE	*Comisión Nacional de Energia*
CNMC	*Comisión Nacional de los Mercados y la Competencia*
CNMV	*Comisión Nacional del Mercado de Valores*
COP	Conferences of the Parties
CSP	Concentrating Solar Power Plant
DCF	Discounted Cash flow
DoD	Depth of Discharge
EBIT	Earnings Before Interest and Taxes
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization
EDP	*Energias de Portugal*
EnTEC	Energy Transition Expertise Centre
ERSE	*Entidade Reguladora dos Serviços energéticos*
ESD	Energy Storage Device
ESS	Energy Storage System
ETP	Energy Technology Perspectives
EU	European Union
FCF	Free Cash Flow
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRC	*Imposto sobre rendimento das Pessoas Coletivas*
KPI	Key Performance Index
LAES	Liquid Air Energy Storage
LIB	Lithium-Ion Battery
MIBEL	*Mercado Ibérico de Eletricidade*
NPV	Net Profit Value
NREL	National Renewable Energy Laboratory
OMI	*Operador do Mercado Ibérico*
OMIE	*Operador do Mercado Ibérico - Polo Espanha*
OMIP	*Operador Mercado Ibérico - Polo Portugal*
OPEX	Operational Expenditure
PHF	*Programa Horário Final*
PHS	Pumped Hydro Storage
PIBCI	*Programa Intradiário Básico de Emparelhamento Incremental*
PM	Price Maker
PNEC	*Plano Nacional Energia e Clima*
PNIEC	*Plan Nacional Integrado de Energía y Clima*

PT	Price Taker
RES	Renewable Energy Source
RI	Rentability Index
RNC	*Roteiro para Neutralidade Carbónica*
SMES	Superconducting Magnet-Based Energy Storage
TRL	Technology Readiness Level
TTF	Title Transfer Facility
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WACC	Weighted Average Cost of Capital

Chapter 1

Introduction

1.1 - Motivation and Objective

Since the 1st of July 2007, the daily electricity market of Portugal and Spain has been managed by the Mercado Ibérico de Eletricidade (MIBEL). Multiple suppliers and electrical energy producers submit bids for each hour of the following day. By analysing these bids, the market price for each hour is obtained. This price is directly related to the load and production for each hour. Given that these parameters vary during the day, there will be hours with higher prices when compared to others.

With the addition of storage devices to the grid, it may be possible to take advantage of these price differences between different hours of each day to buy energy when the prices are lower and sell the energy when it is more expensive.

This dissertation aims to identify the adequate sets of hours each day when to charge and discharge the stored energy, to estimate the impact on the market price of each hour, as well as the annual profits to evaluate the economic viability of introducing such devices on the Iberian market. The analysis was done considering the data of all the bids on the MIBEL market for 2021 and other years, considering the investment cost and the life span of the adopted storage technology. This work was done in collaboration with *Energias de Portugal* (EDP).

The globe is facing a challenge in the energy sector with the need for more reliable energy sources at moderate prices and low environmental impacts. This has led countries to adopt various renewable energy sources (RESs), mainly solar and wind energy, which are expected to supply 50% of the world's energy demand by 2050. The use of these resources presents several challenges given that they are non-dispatchable; the hours with more production do not coincide with the hours with high energy demand. This reality, combined with the emergence of commercially cheaper energy-storing technologies, has led to an exponential growth of grid support and storage installations worldwide. This dissertation also reviews the present state of the art regarding storage technologies and the impacts of their widespread adoption on the energy markets.

With the results obtained at the end of the dissertation, it will be possible to assess whether the investment in this technology commercial is initially available today will achieve its break-even point during their life expectancy.

1.2 - Structure

Chapter 2 presents the background and fundamental aspects for comprehending the dissertation. It introduces the Iberian Electricity Market, explaining its origins and primary goals. It also describes the daily market's functioning, how the negotiation is conducted and how the price is obtained for each hour. This chapter also addresses the *Plano Nacional Energia e Clima* (PNEC) 2021-2030 to contextualise the current dissertation.

In Chapter 3, a State-of-the-Art report is elaborated regarding the current context of energy storage technology. This is essential to understand the development level of each technology, its economic impacts, and recent developments. At the end of this chapter, a decision is made about which energy storage technology will be considered for the analysis.

Chapter 4 presents the applied methodology of analysis, providing a theoretical description of how all calculations are made and how each section of the Python program functions.

Chapter 5 contains the results obtained for all case studies considering different configurations of storage devices. A comparison of results obtained for different years is also presented. In the end, an investment analysis is also conducted for both case studies considering two different scenarios of the evolution of prices in the following years. A conclusion is derived on the viability of the investment.

To finalize, Chapter 6 includes all conclusions obtained by the analysis of the results, as well as an evaluation of the viability of installing Li-ion batteries for price arbitrage on MIBEL. A section regarding future projects on this topic is also included.

Chapter 2

Background and Fundamental Aspects

2.1 - Iberian Electricity Market

2.1.1 - General Aspects

The *Mercado Ibérico de Energia Elétrica* (MIBEL) was created to integrate the electrical systems in Portugal and Spain to benefit the consumers of both countries. It represents a physical, economic, legal, and regulatory convergence of both markets, allowing any consumer to buy energy from any producer in Portugal or Spain, with the option of establishing bilateral agreements under free market competition. MIBEL also allows all its agents to have the same conditions of treatment, transparency, and objectivity regarding market access [1].

The MIBEL was established by a cooperation agreement between the governments of Spain and Portugal and approved by the Portuguese *Assembleia da República* on the 23rd of March 2006 [2]. The principles for this market are stated in *Directive nº 2003/54/CE* of the European Parliament and the Council of the European Union [3].

The Board of Regulators supervises the market, comprised of representatives from Portugal, such as the Portuguese Energy Services Regulatory Authority (ERSE) and the Portuguese Securities Market Commission (CMVM), and representatives from Spain - the Spanish National Energy Commission (CNE, now CNMC) and the Spanish Securities Market Commission (CNMV) [4].

Following public consultation of the CMVM and CNMC, the following principles should be applied to the organisation of MIBEL:

- Organizing the market and ensuring equality between the participants;
- Ensuring the transparency and liquidity of the organised market;
- Providing equal opportunities for all consumers;
- Incentivizing investment by payments of "power guarantees" to the producers;
- Avoiding that recovering "stranded costs" constitute market distortion;
- Ensuring stability and predictability.

2.1.2 - Market Organization

The organisation of the MIBEL is based on the possibility of participating in the daily markets and of making contracts between the market participants, restricting only to the necessary rules to keep an adequate level of liquidity and competition.

Contracts of electricity in MIBEL can only be processed as:

- Free market for physical bilateral agreements;
- Markets managed by the Iberian Market Operator (OMI):
    - Markets of Future physical products
    - Daily market

There is also an auction intraday market, managed by the OMI, where agents can change their contractual positions on the daily market. Since June 2018, a continuous intraday market has been added to facilitate energy trading between European market areas [5].

MIBEL started its operation on the 1st of July 2007, managed by the OMI, which is divided into OMIE regarding the daily market and OMIP for bilateral contracts and futures trading.

2.1.3 - Daily Markets

Under MIBEL rules, electricity is primarily sold on the daily market. In this market, all participating agents submit their transaction proposals for selling and purchasing electricity for each hour of the following day. These proposals are aggregated by the Market Operator, who will announce the electricity prices and the cleared bids for the next day.

As is the case for all European markets, a marginal cost model is used, where electricity producers provide offers based on their marginal generation cost (which depends on the fuel cost, emission cost, operating cost, taxes, and production forecast).

As for the purchasing bids, these represent consumers' assessment of the benefit of consuming energy [6].

All the bids sent to the operator must disclaim the hour of the day to which they report, the amount of energy and the bidding price.

After submission to the market operator, the production bids are ordered in ascending order of price. Regarding the demand side, the bids for purchasing electricity are ranked in descending order of price. The point of interception of these two aggregated curves will determine the market-clearing price. All the bids to the left side of this intersection point are matched and accepted, and the energy will be traded at the market closing price, following a uniform price auction model.

The balanced pool approach in this market uses a mathematical model based on maximising the Social Welfare Function. Assuming simple bids, that is, admitting that there are no interactions between trading periods along the day, this model is presented in equations (2-1) until (2-4) for a specific hour of the next day.

$$\mathrm{Max}\, Z = \sum_{i=1}^{nD} (C_{DI}^{of} * P_{Di}) - \sum_{j=1}^{nG} (C_{Gj}^{of} * P_{Gj}) \tag{2-1}$$

Subject to:

$$0 \leq P_{Di} \leq P_{Di}^{MAX} \tag{2-2}$$

$$0 \leq P_{Gj} \leq P_{Gj}^{MAX} \tag{2-3}$$

$$\sum_{j=1}^{nG} P_{Gj} = \sum_{i=1}^{nD} P_{Di} \tag{2-4}$$

In this formulation:

- P_{Di} is the amount of purchasing bid i;
- P_{Gj} is the amount of selling bid j;
- P_{Di}^{MAX} is the maximum amount of purchasing bid i;
- P_{Gj}^{MAX} is the maximum amount of selling bid j;
- C_{Di}^{of} is the price of purchasing bid i;
- C_{Gj}^{of} is the price of selling bid j;
- nD is the total number of purchasing bids.
- nG is the total number of selling bids;

In the graphical representation, the Social Welfare Function (Z) corresponds to the area between the purchasing and selling curves, as represented in Figure 2.1. The Market Operator's objective is to maximize this function.

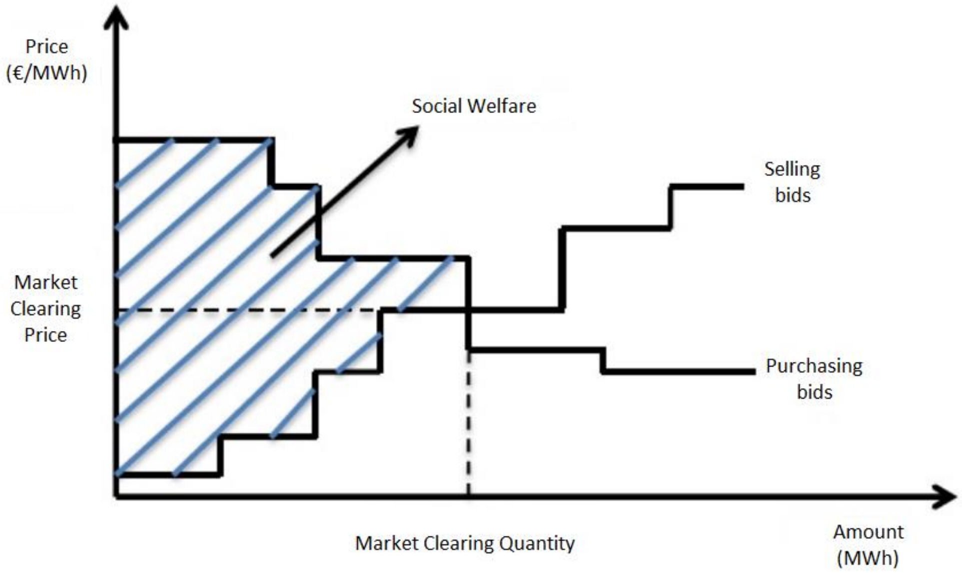


Figure 2.1 – Representation of the selling and purchasing bid curves in a spot market [1].

2.1.4 - Interconnections

The management of the interconnections between Portugal and Spain is based on a model of implicit available capacity for commercial activity in the daily and intraday markets.

Currently, the interconnection infrastructure comprises six lines of 400 kV and three lines of 220 kV. The minimum capacity of each line is presented in Table 2.1, while their geographical location is in Figure 2.2.

Table 2.1 - Characterization of the interconnections on 31st December 2020 [7].

Line	Minimum Thermal Capacity (MVA)
400 kV:	
Alto Lindoso -Cartelle 1	1477
Alto Lindoso -Cartelle 2	1477
Lagoaça -Aldeadávila	1469
Falagueira -Cedillo	1386
Alqueva -Brovales	1280
Tavira -Puebla de Guzman	1386
220 kV:	
Pocinho -Aldeadávila 1	374
Pocinho -Aldeadávila 2	374
Pocinho -Saucelle	360
Total	9583

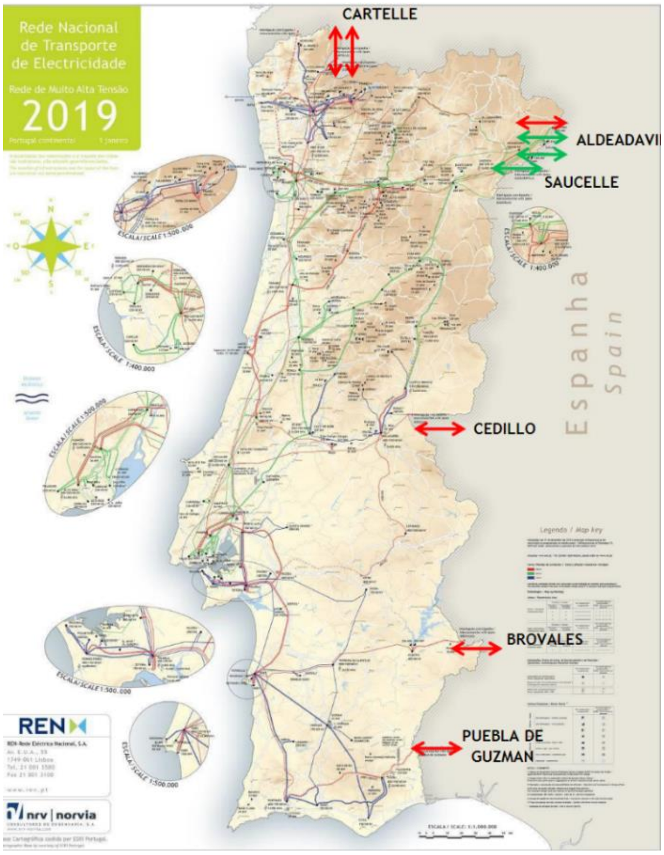


Figure 2.2 – Map with interconnections Portugal-Spain [7].

After the Market Operator has ordered the bids from the daily market and concluded the market clearing, the next step is to analyse if the interconnections can withstand the power flows determined by the dispatch. If no constraint is violated, the electricity price will be the same in Portugal and Spain. However, if the capacity of any line is exceeded, it is necessary to separate the two areas to obtain a different price for each country. This process is called market splitting, illustrated in Figure 2.3.

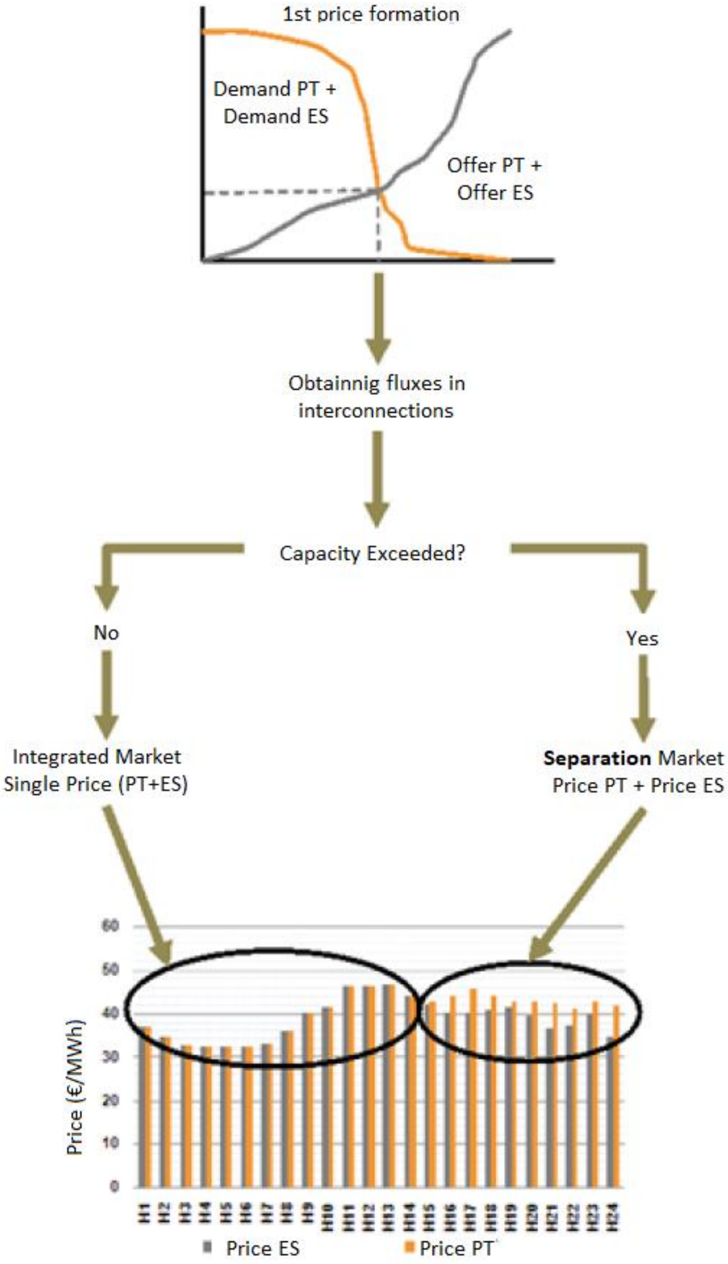


Figure 2.3 – Flowchart of Market Splitting [8].

Figure 2.4 shows market splitting in some hours of a given day (from hours two until six and from 14 to 18). During these hours, the obtained flow of electricity from Spain to Portugal was equal to the capacity of the interconnections. This can be seen when the green bars (export occupation) coincide with the yellow line (export capacity).

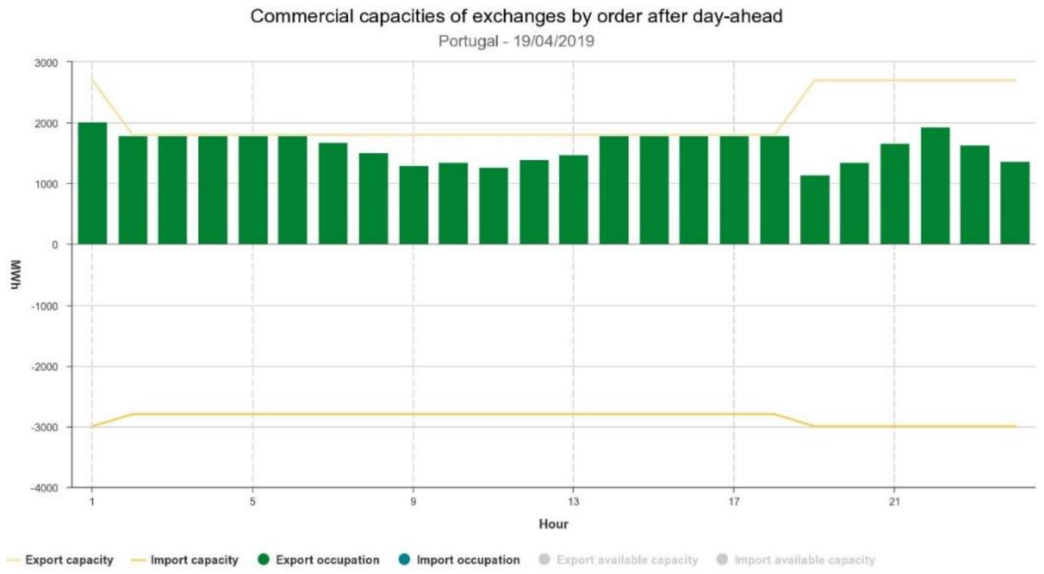
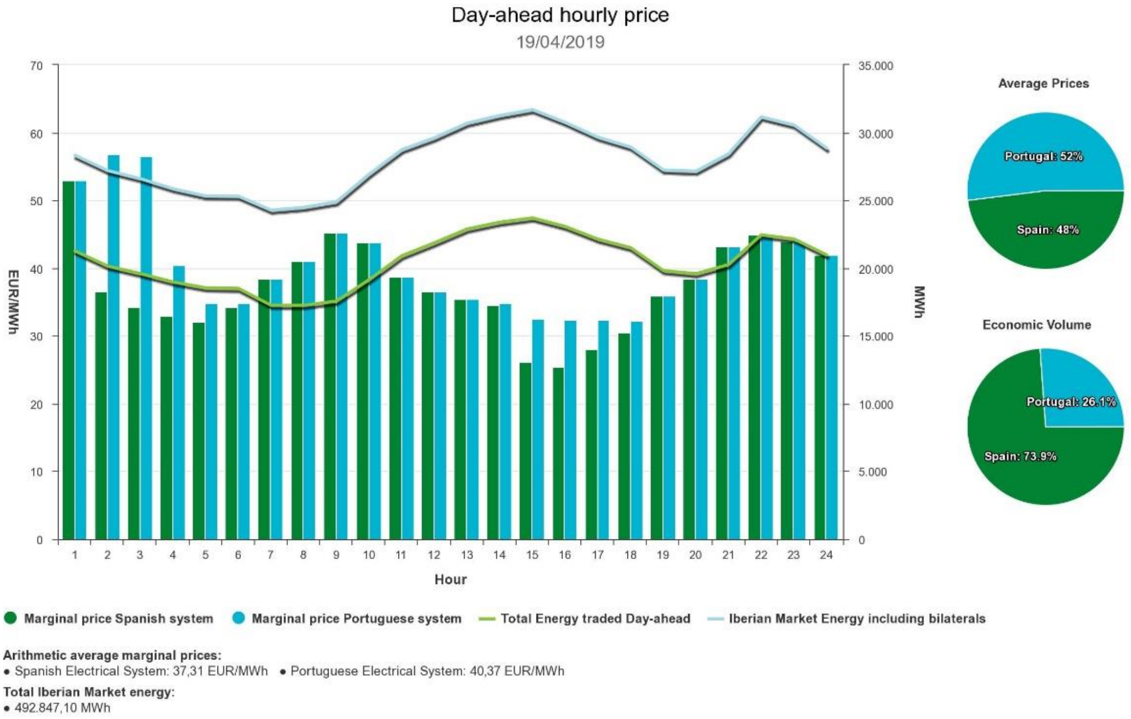


Figure 2.4 – Interconnection occupation for Portugal 19th April 2019 [9].

The prices for each hour of that day are presented in Figure 2.5, and they show that during the hours with market splitting, the prices were higher in Portugal than in Spain. The Spanish average price was 37.31 €/MWh and 40.37 €/MWh in Portugal.



Arithmetic average marginal prices:
- Spanish Electrical System: 37,31 EUR/MWh
- Portuguese Electrical System: 40,37 EUR/MWh

Total Iberian Market energy:
- 492.847,10 MWh

Figure 2.5 – Spot Market Prices in Portugal and Spain 19th April 2019 [9].

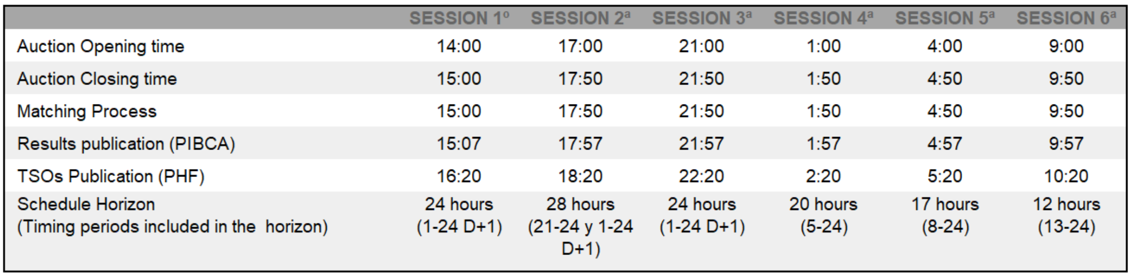
2.1.5 - Intraday Market

The Intraday Market is a mechanism that allows adjustments to match the demand and the production in a better way and closer to real-time than the permitted by the daily market, solving possible discrepancies. In this market, producers can also buy energy, and consumers can also sell energy.

The intraday markets are structured into an auction market in MIBEL and a continuous European Market.

Six different sessions manage Portugal and Spain's price zones and interconnections in the intraday auction market. The schedule for these sessions is presented in Table 2.2.

Table 2.2 – Schedule of MIBEL Intraday market [9].



	SESSION 1º	SESSION 2ª	SESSION 3ª	SESSION 4ª	SESSION 5ª	SESSION 6ª
Auction Opening time	14:00	17:00	21:00	1:00	4:00	9:00
Auction Closing time	15:00	17:50	21:50	1:50	4:50	9:50
Matching Process	15:00	17:50	21:50	1:50	4:50	9:50
Results publication (PIBCA)	15:07	17:57	21:57	1:57	4:57	9:57
TSOs Publication (PHF)	16:20	18:20	22:20	2:20	5:20	10:20
Schedule Horizon (Timing periods included in the horizon)	24 hours (1-24 D+1)	28 hours (21-24 y 1-24 D+1)	24 hours (1-24 D+1)	20 hours (5-24)	17 hours (8-24)	12 hours (13-24)

After the pairing of the bids, the results of the session are published on the *Programa Intradiário Básico de Emparelhamento Incremental* (PIBCI), from where the System Operators post the *Programa de Horário Final* (PHF), which is the final program that will be used in the next day, already considering the technical limits of the grid.

Parallel to the Iberian Intraday Market, a common European market managed by various market operators started in June 2018. Two main differences exist between this market and MIBEL's intraday auction market. First, in the continuous market, agents can benefit from the availability of bids in markets in other areas of Europe, benefitting from the interconnections between zones. Secondly, the adjustments can be made up to one hour before delivery. This allows for increasing the global efficiency in the transactions between the intraday markets in Europe, making the management of energy transaction mismatches between market agents easier [9].

2.2 - *Plano Nacional Energia e Clima (PNEC)*

As part of the Paris Agreement concluded in 2015, long-term goals for containing the rise in global temperature to a maximum of 2ºC above the pre-industrial levels were established by the international community, which promised to go through all efforts for this rise not go above 1.5ºC [10].

Following this agreement, in 2016, at the United Nations Framework Convention on Climate Change (UNFCCC), Portugal assumed the goal of reaching carbonic neutrality until 2050, having developed the *Roteiro para a Neutralidade Carbónica 2050* (RNC2050) that established the vision, guidelines for policies and measures to achieve in this timeframe. The RNC2050 was published as the Council of Ministers Resolution nr 107/2019, 1st of July and submitted to the UNFCCC in the same year.

In line with the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5ºC, it is concluded that most of the efforts to reduce emissions of greenhouse effect gases should be developed in the decade 2021-2030 [11]. In this context, the Plano Nacional Energia e Clima (PNEC) was created, establishing ambitious goals to be achieved by 2030 and the energy and climatic policy guidelines to be followed during the same decade.

The PNEC includes a characterization of Portugal's energy and climate situation regarding the five dimensions of the Regulation: decarbonization, energy efficiency, supply security, the internal market of energy and research, innovation and competitivity. It then defines the national contributions, planned policies and measures for compliance with the global commitments made by the European Union, including greenhouse effect gas emission reduction, renewable energies, energy efficiency and interconnections. There are also eight main goals which contemplate 58 lines of action and 206 measures.

As part of the energy security dimension of the PNEC, a set of national objectives to increase storage capacity has also been established. These consist of reversible hydroelectric plants and the use of batteries and Hydrogen later in the decade. A significant part of this capacity should be associated with renewable energy production. The storage of electrical energy is regarded as a tool for the flexibilization and stability of the national electrical system [10].

2.2.1 - Estimated trajectories regarding renewable energy sources

To fulfil the general and sectorial goals set in PNEC, it is estimated that until 2030 the installed capacity will increase in Portugal from 20.8 GW in 2020 to 30.5-32.0 GW in 2030, from which solar and wind energy will represent most of the growth. Figure 2.6 shows the Installed capacity and the electricity production by technology in Portugal until 2030.

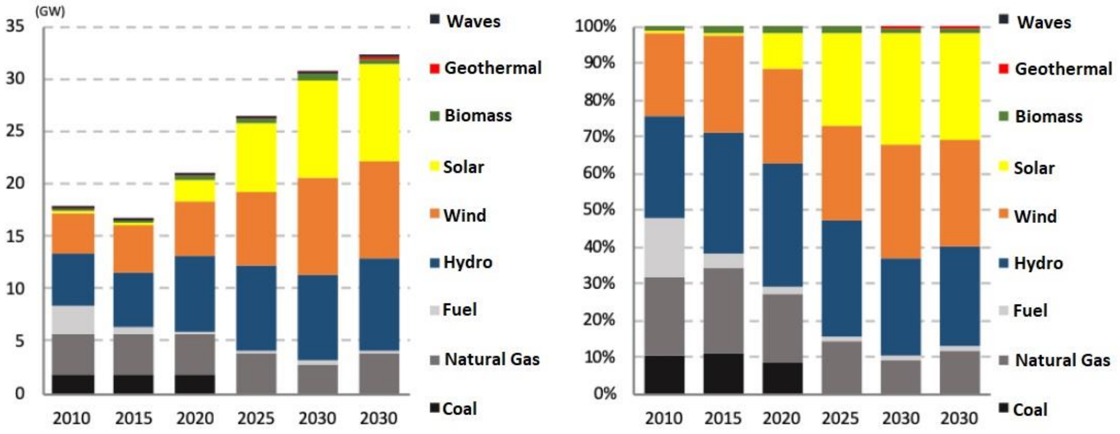


Figure 2.6 – Installed capacity in GW (Left) and the electricity production by technology (Right) in Portugal until 2030 [10].

Given the predictions for the installed capacity, it is estimated that in 2030 RES will represent 80% of the electricity produced in Portugal, with hydro representing 22%, wind 31% and solar 27%.

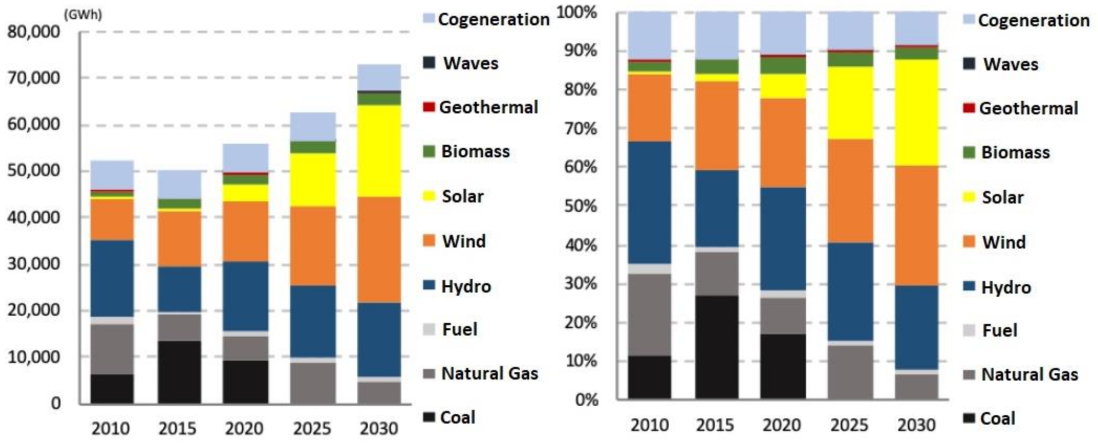


Figure 2.7 – Estimation of the evolution of electricity generation by technology in Portugal in GWh (Right) and in percentage (Left) [10].

2.2.2 - Planed measures and policies regarding energy storage

Table 2.3 details the main measures proposed in the PNEC 2030 regarding energy storage grouped according to the dimension they are integrated and action line.

Table 2.3 - Main measures proposed in the PNEC 2030 regarding energy storage grouped by dimension and action line [10].

Dimension: Decarbonization
1.1. Action line: Promoting the decarbonization of the electricity generator sector
Measure: 1.1.2. Evaluate the installation of solar-thermal generation with storage to produce renewable vapour that could replace coal generation in the current turbines and the use of green Hydrogen as fuel to replace coal
3.1. Action line: Accelerate electricity production from renewable energy sources
Measure: 3.1.7. Promote projects in still demonstration phase technologies such as solar-thermal generation with storage
3.5. Action line: Promote the proper planning of transportation and distribution networks to strengthen the integration of new renewable electricity
Measure: 3.5.1. Plan transport and distribution networks considering the integration of renewable energy sources and storage systems
3.6. Action line: Promote the production and consumption of renewable gases
Measures: 3.6.1. Regulate renewable gas injection into the natural gas transport and distribution network; 3.6.2. Study and define goals of renewable gas integration; 3.6.3. Define a quality certification for renewable gases; 3.6.4. Implement a guarantee of origin system for renewable gases; 3.6.5. Promote the production and consumption of green Hydrogen by developing a production cluster from solar energy
Dimension: Energy Security
4.1. Action line: Promoting storage systems
Measures: 4.1.1. Create the legal framework for implementing storage systems; 4.1.2. Promote the creation of a Roadmap for energy storage in Portugal; 4.1.3. Promote the implementation of storage projects associated with renewable power plants; 4.1.4. Promote storage on the islands
Dimension: Research, Innovation and Competitivity
2.6. Action line: Encourage research, innovation and competitivity in the field of energy efficiency
Measures: 2.6.1. Encourage Research and Innovation in the field of Energy Efficiency, namely solutions and strategies for integration systems of renewable energy and storage
3.8. Action line: Encourage R&D&I in renewable energy, storage, Hydrogen, advanced biofuels and other 100% renewable fuels
Measures: 3.8.1. Promoting articulation with the Thematic Research and Innovation Agendas of the Foundation for Science and Technology; 3.8.2. Promoting national R&I programs to support technological development; 3.8.3. Fostering a collaborative laboratory for renewable gases; Promoting the training of specialized technicians

Chapter 3

Energy Storage

3.1 - Policy Framework

Starting in 2007 with the "Climate and Energy Package", the European Union (EU) has provided many increasingly ambitious strategies and targets to achieve a low-carbon energy system. It was later followed by the agreement of the targets for 2030 between all EU Member States in 2014 of reaching a 40 % cut in greenhouse gas emissions compared to 1990 levels, at least a 27% share of renewable energy consumption, and at least 27% energy savings compared with the business-as-usual scenario. The Paris Agreement, approved at the Conference of the Parties (COP21) in December 2015 and became legally binding in November 2016 following its ratification, requires the EU to further strengthen its 2030 energy and climate framework through legislative action. It also steers the entire global community to decarbonisation, increasing the global need for low-carbon energy generation and, therefore, for low-carbon balancing and flexibility [12].

In 2015 the European Commission issued the Energy Union strategy, linking climate and energy policies to ensure a secure, sustainable, competitive, and affordable European energy supply. This was followed in November 2016 by the "Clean Energy for all Europeans" package, including the Accelerating Clean Energy Innovation communication. This communication states that "developing affordable and integrated energy storage solutions" is one of four priority R&I areas [12].

This chapter will focus on the currently available Energy Storage Systems (ESS), reviewing their operation principles, technological development, investment costs and efficiency. There is also an overview of the roles and application of these technologies to the Energy Grids.

3.2 - Role of Energy Storage

For a long time, energy storage was not considered a priority for the energy system, partially because the technologies were not economically viable. Also, storage benefits were less relevant in a centralised fossil fuel-based energy system. However, given the cost-performance improvements in energy storage technology and the greater integration of renewable energy sources (RES) into the electricity production mix, using energy storage systems could lead to several advantages to the overall energy system performance [12].

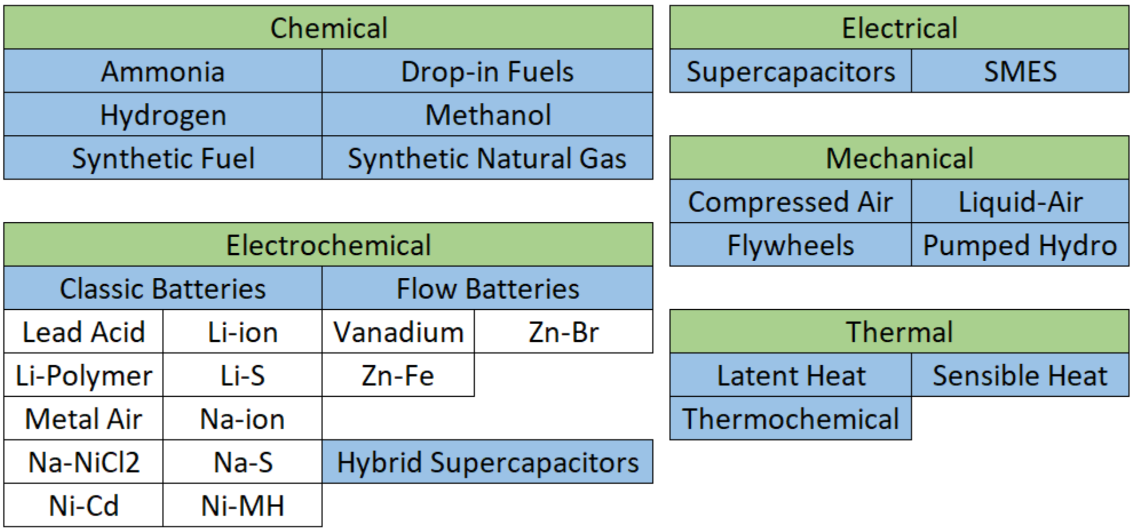
Currently, energy grids are being modified to accommodate the rapid growth of renewable energy sources, mainly solar and wind energy, which is expected to reach a share of 48% of the energy mix by 2050. This increases the demand for grid support and storage installations around the globe, which is expected to grow from 9 GW/17 GWh in 2018 to 1095 GW/2850 GWh by 2040 worldwide. Given this predicted growth, there is great motivation to improve the current and develop new technologies for energy storage [13].

Given the sharp rise in renewable energy generation, the electrification of the heating and cooling sector and the integration of electric vehicles are increasing the demand for reliable, efficient, and economical energy storage solutions.

Granted the greater integration of renewable energy production, there is a need to use technologies to absorb the surplus electricity and decarbonise industries highly reliant on fossil fuels.

3.3 - Description of Energy Storage Technologies

The leading storage technologies currently available or being developed are presented in Figure 3.1.



Chemical	
Ammonia	Drop-in Fuels
Hydrogen	Methanol
Synthetic Fuel	Synthetic Natural Gas

Electrochemical			
Classic Batteries		Flow Batteries	
Lead Acid	Li-ion	Vanadium	Zn-Br
Li-Polymer	Li-S	Zn-Fe	
Metal Air	Na-ion		
Na-NiCl2	Na-S	Hybrid Supercapacitors	
Ni-Cd	Ni-MH		

Electrical	
Supercapacitors	SMES

Mechanical	
Compressed Air	Liquid-Air
Flywheels	Pumped Hydro

Thermal	
Latent Heat	Sensible Heat
Thermochemical	

Figure 3.1 - Classification of Energy Storage Technologies [12].

The storage technologies can be divided into five main categories:

- **Chemical Energy Storage** – storing energy in chemicals that can be gaseous, liquid or solid, which can later be released in chemical reactions. They are characterized by high energy density and have vast options for storage and transport.
- **Electrochemical Energy Storage** – commonly denominated batteries in which chemical energy is stored and converted to electrical power.
- **Electrical Energy Storage** – energy is stored as electrons, which can stay in an electrostatic field between two electrodes (capacitor) or a coil's magnetic field (Superconducting Magnetic Energy Storage - SMES). The capacity is usually low, but the activation time is reduced, and the efficiency is very high.
- **Mechanical Energy Storage** – energy is stored as potential energy in hydro storage, volume and pressure work in air compression systems or the rotational energy of a mass in flywheels.
- **Thermal Energy Storage** – it includes the storage of energy by heating or cooling a material. It can be very cost-effective.

It is expected that energy storage in the future will not only rely on one kind of technology but rather on a combination of different technologies, depending on the kind of use they are projected for [13].

In 2015, installed large-scale energy storage capacity worldwide was estimated at 150 GW, with approximately 96% of this capacity consisting of pumped hydro storage (PHS). More than 70% of new installations completed in 2014 were still PHS. The main components of the non-PHS energy storage capacity are thermal energy storage, large-scale batteries, flywheels, and compressed air energy storage (CAES).

3.3.1 - Mechanical Energy Storage

3.3.1.1 - Pumped Hydro Storage (PHS)

Pumped Hydro Storage (PHS) allows energy to be stored in water in a more elevated reservoir, which allows water to be pumped from a lower reservoir. In periods of high electricity demand, power is generated by releasing water, like a conventional hydropower station. During periods when the prices of electricity are lower, the upper reservoir is refilled with water by pumping it upstream [14]. Figure 3.2 presents the operation principle of PHS.

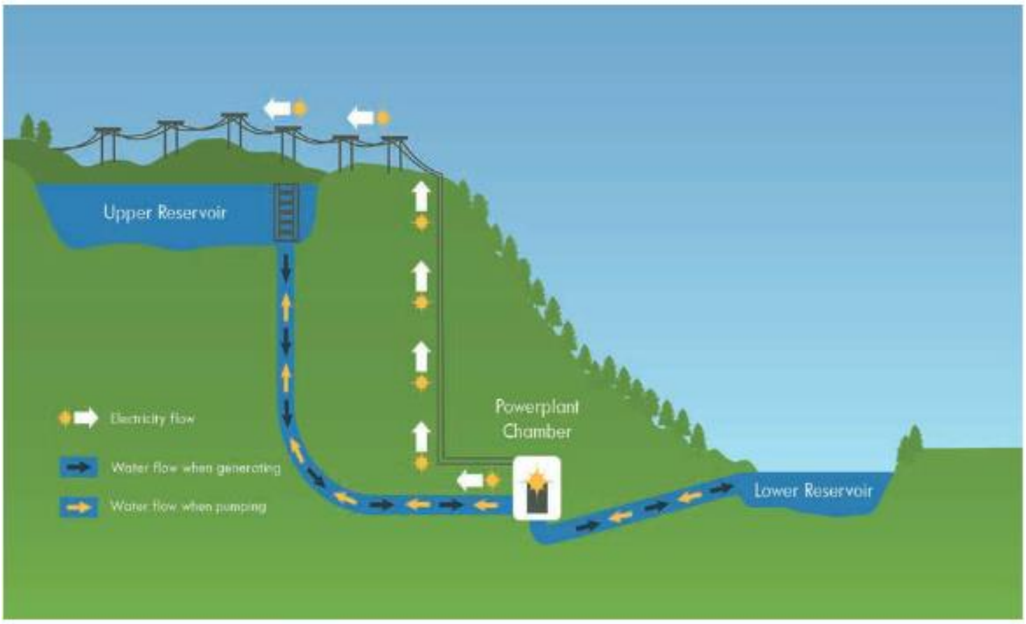


Figure 3.2 - Working principle of PHS [12].

In some hydroelectric plants, pump-turbine/motor-generator assemblies can work as pumps and turbines. Plants with this kind of technology are usually net consumers of energy. Still, they are highly efficient (around 80%). They can prove beneficial due to their ability to balance power system loads and their potential to provide ancillary grid services.

This storage technology requires specific site conditions, including ground conformation, the difference in elevation between reservoirs and water availability.

PHS is considered the most mature large-scale energy storage technology, being the most prevalent in Europe. It is used for peak shifting and to manage fluctuations in RES production.

3.3.1.2 - Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) is a process in which energy is stored in high-pressure compressed air. During low-demand periods, the air is compressed and stored in caves or metal containers, such as depleted natural gas reservoirs, salt formations or in porous rock formations, which must be isolated to avoid leaks and pressure drops [15]. In high-demand periods the compressed air is used to power a generator and produce electricity for the grid. This process is represented in Figure 3.3.

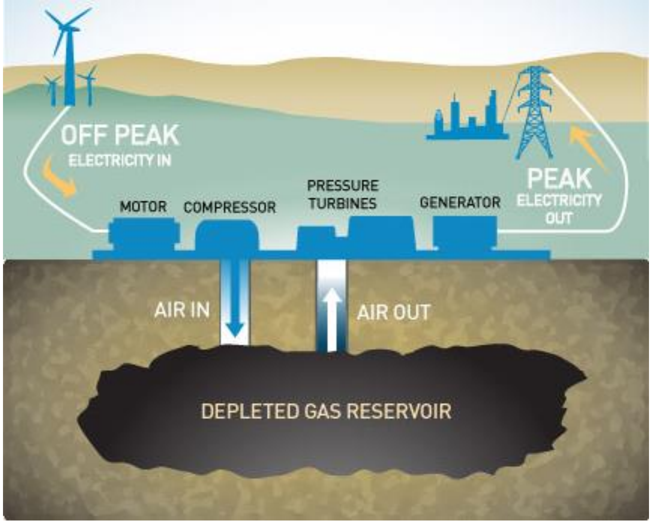


Figure 3.3 - Working principle of CAES [15].

There are currently two utility-scale CAES installations, one in Huntorf, Germany and the other in McIntosh, Alabama, USA. A common feature between the two installations is that electricity generation involves burning fossil fuels (natural gas) [12].

The specific geological conditions needed for this kind of technology, reliance on fossil fuel burning, and low efficiency make this technology difficult/disadvantageous to implement.

3.3.1.3 - Flywheels

Flywheels are devices capable of storing kinetic energy. They are coupled with an electrical machine. When the electrical machine operates as a motor, it exerts positive torque T to the flywheel with a moment of inertia J, it increases the rotation speed at the rate of T/J until it reaches maximum speed, storing energy from the grid. To release the power, the electrical machine will work as a generator applying negative torque -T to the flywheel, breaking at a rate -T/J, and providing energy back to the grid [12]. A basic scheme of a flywheel is presented in Figure 3.4.

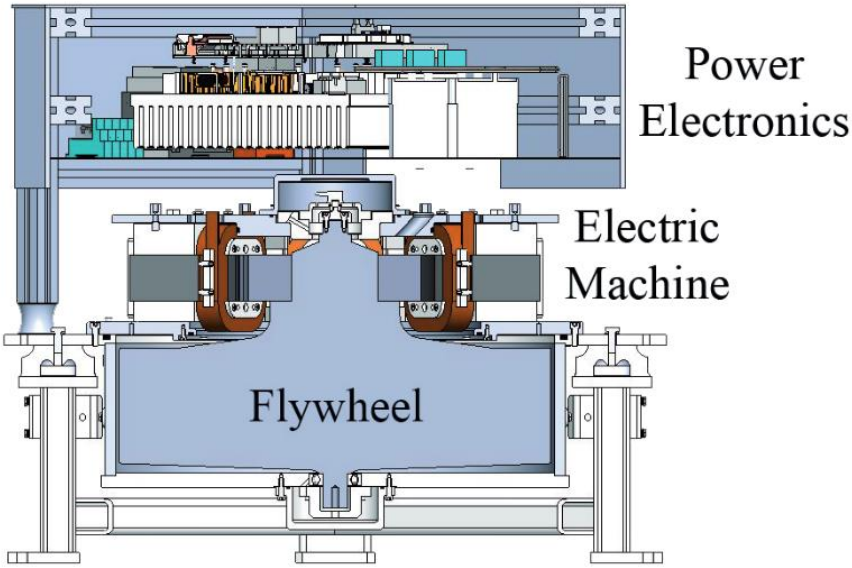


Figure 3.4 - Flywheel scheme [12].

This device is based on a mechanical approach, so it is inserted in a vacuum container to reduce friction losses. Expression 3.1 presents the relation between the kinetic energy stored in a flywheel (E_c), its angular speed (ω) and moment of inertia (J) [8].

$$E_c = \frac{1}{2} \cdot J \cdot \omega^2 \tag{3.1}$$

The advantages of this technology are its high-power density and a high number of charge/discharge cycles. However, it has low energy density and high self-discharge due to friction losses.

3.3.1.4 - Liquid Air Energy Storage (LAES)

Liquid Air Energy Storage (LAES) stores liquid air as an energy vector. It consists of a charging system and a discharging system. The charging system can be an industrial air liquefaction plant that uses electricity to reject heat from ambient air, generating liquid air that can be stored in an insulated tank at low pressure. When there is a power demand, the discharging system starts by removing liquid air from the tank, pumping it up to high pressure and evaporating it. The expanded gas can drive a piston engine or a turbine, producing electricity. Cold storage can be used to reduce the liquefaction process's power consumption, and heat storage can be used to increase the work output. A diagram showing the mode of operation of this technology can be found in Figure 3.5 [12].

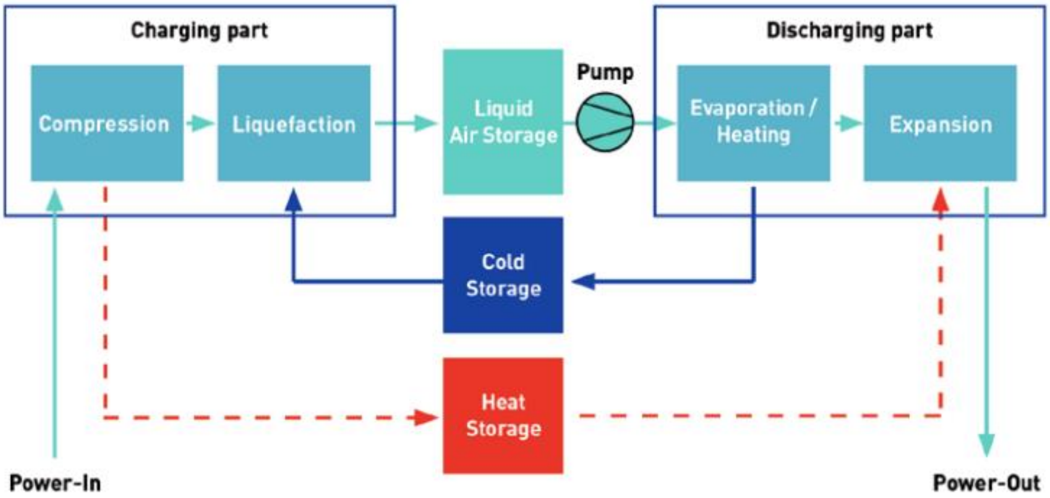


Figure 3.5 - Diagram of LAES [12].

This technology uses commercially available components, making it in near market conditions. It also does not require the use of caves and specific geological conditions. However, it has high investment costs and lower efficiency when compared with other Mechanical storage technologies.

3.3.2 - Chemical Energy Storage

Chemical Energy Storage is based on transforming electrical energy into the energy of chemical bonds, allowing the exchange of energy between different vectors of the energy system. This kind of storage can be done as Power-to-Gas (Hydrogen) and Power-to-Liquid (produce fuels or combine with nitrogen to produce chemicals such as ammonia) [12].

3.3.2.1 - Hydrogen

In recent years, researchers have regarded hydrogen as the most promising energy storage vector [16]. It can be produced using electrolyser technology which splits water into hydrogen and oxygen, but other techniques are being developed to improve the efficiency of this process.

One of the drawbacks of this technology is that the current production of hydrogen is made from the steam methane reforming process (76%), and the remaining is produced from coal, which is not a clean source. It also has low volumetric energy density, which requires compression or liquefaction. However, it is versatile and can be reconverted to energy for stationary applications (power and heat generation, internal combustion engines and turbines, direct steam generation, catalytic combustion, and fuel cells) or mobile applications (transport), giving only water vapour as the product. It is also possible to transport it in dedicated pipelines to production sites and can be mixed with natural gas [12].

Many aspects need to be developed on the path to a more generalised use of hydrogen. The first aspect is the production method that needs to rely more on RES – "green hydrogen". Using renewable energy sources facilitates the use of storage devices such as fuel cells, which are presented in Figure 3.6. These devices offer high power density, fast response to load variations and low functioning temperature [8].

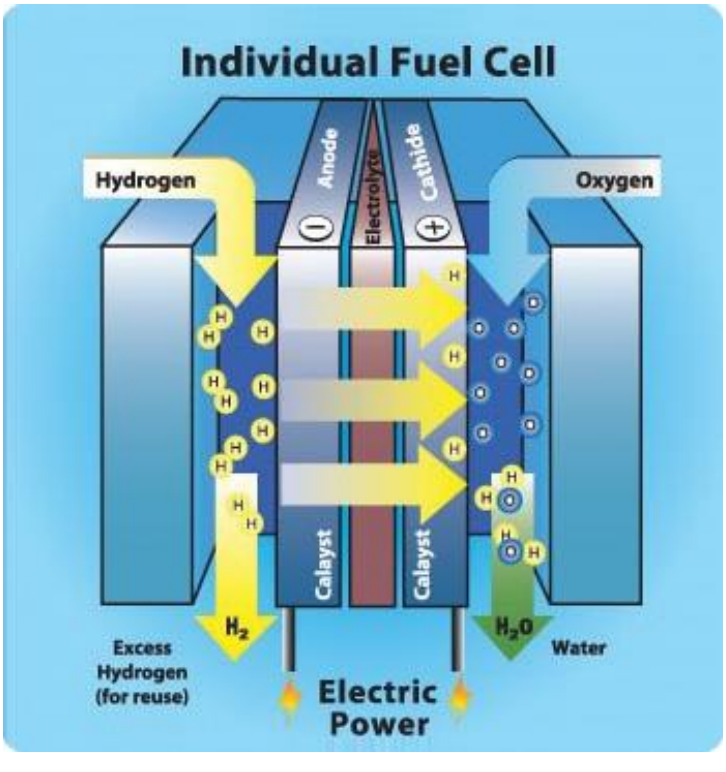


Figure 3.6 - Fuel Cell scheme [17].

3.3.2.2 - Power to Gas

Specialists regard Power to Gas as one of the most promising long-term storage methods, although it currently has high investment costs and limited performance [8].

In this kind of storage, the excess energy obtained from RES is used to produce hydrogen, which, combined with CO_2 in a methanization process, makes synthetic natural gas. This gas can be stored and transported in the same way natural gas is and can be utilized in a time of need as an energy source.

Given the high costs and low efficiency (between 30% to 40%), it is still in development and has a long way to go until it becomes commercially viable [8].

3.3.2.3 - Other chemical energy carriers

Besides hydrogen, other chemical energy carriers can be utilised. These can increase the volumetric energy density and use the existing infrastructure. These are mainly methane, methanol, and ammonia, which can be further synthesised to produce dimethyl ether and kerosene which facilitates the long-term storing of energy [12].

3.3.3 - Electrochemical Energy Storage

3.3.3.1 - Conventional batteries

Conventional batteries are based on oxidation and reduction reactions where an ion flux is formed between a positive and a negative electrode, producing an electrical current. There are three main types of conventional batteries: Lead-Acid Batteries, Nickel-based batteries, and Lithium-ion Batteries.

- **Lead-Acid batteries**

These were the first commercially available batteries, having high efficiency and low investment cost. Other advantages are the good retention of charge, excellent energy density, fast response rate and large life span of around 15 years. However, they present a reduced number of cycles, reduce specific energy, require water maintenance, and can have premature failure due to sulphation [18].

Its charging process is based on a reaction between carbon dioxide and porous lead with sulphuric acid to create lead sulphate, water, and lead. The discharging corresponds to the reverse process [8].

- **Nickel-Cadmium batteries**

Nickel-Cadmium batteries have positive electrodes of nickel hydroxide and negative electrodes of cadmium. They are low-cost, have a high number of cycles and reduced maintenance. However, many European countries have banned their use due to their composition containing toxic materials.

The self-discharge rate is also high, making it inefficient for long-term use [8].

- **Lithium-ion batteries (LIBs)**

Lithium-ion batteries (LIBs) have five key components as follows: the anode (usually copper or carbon), cathode (usually aluminium or metal oxides), electrolyte (non-aqueous solution such as $LiPF_6$, $LiCoO_2$ and $LiClO_4$ which contain lithium salts) and current collectors. Other materials can also be used and are currently being studied [19]. Figure 3.7 represents the typical structure of a LIB [19].

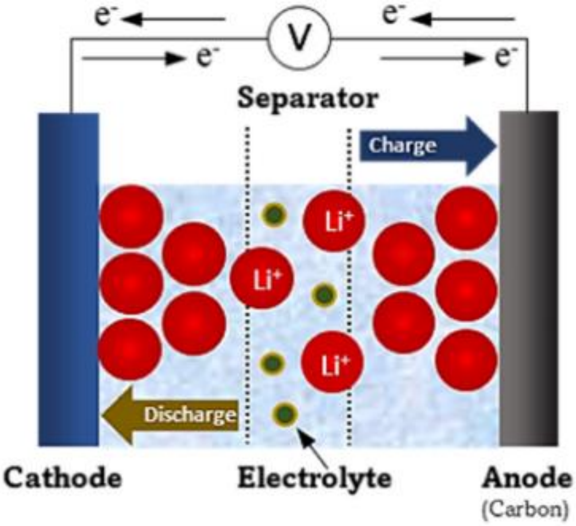


Figure 3.7 – Typical configuration of LIBs [19].

LIBs have gained importance and are regarded as the fastest-growing technology in storage capacity. They offer high efficiency (around 90 %), significant energy density, a fast response time (in milliseconds) and a low self-discharge rate. Lithium-ion moves to the anode through the cathode during the charging process, while during discharge, the ions travel in the opposite direction [8], [18].

3.3.3.2 - High-Temperature batteries

High-Temperature batteries such as NaS batteries consist of molten electrodes made of sodium and sulphur (anode and cathode, respectively). In the discharging process, sodium gets oxidized, releasing sodium ions. These ions then combine with sulphur and form polysulphide (Na2Sx), causing the electrons to flow in the external circuit. The opposite happens during the charging process [18].

These batteries present high efficiency, high energy density, and many charge/discharge cycles. However, they have the major drawback of only operating at high temperatures (350ºC) to maintain high reactivity and ensure the conversion of sodium and sulphur to liquid. This characteristic, together with its high self-discharge rate, causes this kind of battery to be unsuitable for long-term storing of energy [8], [18].

3.3.3.3 - Flow batteries

A flow battery is a rechargeable battery in which an electrolyte flows through an electrochemical cell from one or more tanks, where electrical and chemical energy conversion occurs. This cell contains a porous membrane where ionic conduction occurs. The most commonly used redox pairs for the electrodes are vanadium/vanadium, iron/chromium, and zinc/bromide. Figure 3.8 presents an example of a flow battery [8], [20].

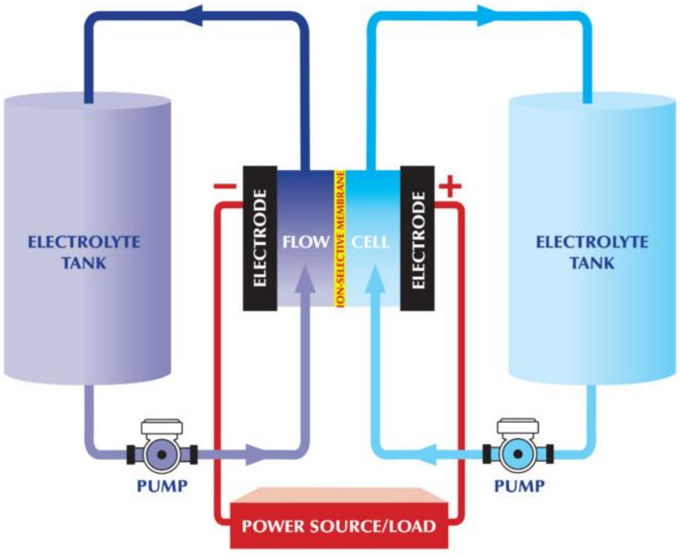


Figure 3.8 - Flow battery example [20].

The scalability of flow batteries is easily achieved by increasing the volume of electrolytes in the tanks and connecting electrochemical cells in parallel and series [20].

Flow batteries display high efficiency (between 70% and 80%) and a low self-discharge rate (around 10%) [8].

3.3.4 - Electrical Energy Storage

3.3.4.1 - Supercapacitors

Supercapacitors are energy storage devices based on using two conducting electrodes which, when charging, move the anions to the negative electrode and cations to the positive electrode. This creates a dielectric that prevents charge movements between electrodes. Given the high reversibility, they can support many charging and discharging cycles at high power rates without affecting the capacitance. The electrode surface area and characteristics of the separator layer determine the capacitance and, thus, the amount of energy that can be stored [8], [12]. Figure 3.9 presents the structure of an electrostatic capacitor (a) and a supercapacitor (b).

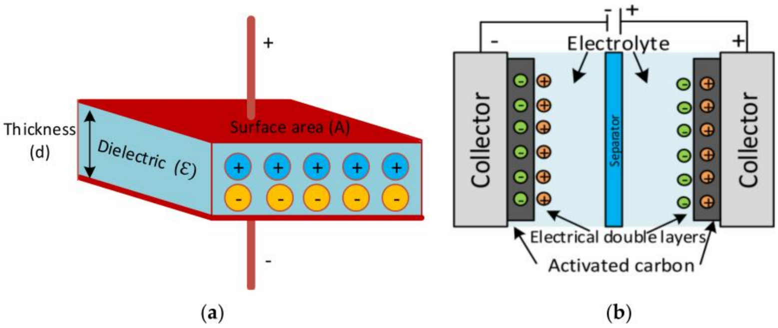


Figure 3.9 - (a) Structure of electrostatic capacitor, (b) structure of supercapacitor [21].

The most significant advantages of this storage technology are its high efficiency, high power density and quick response time. However, it has a high self-discharge rate and low energy density, making it inappropriate for long-term storage [12].

3.3.4.2 - Superconducting magnet-based energy storage system (SMES)

In Superconducting magnet-based energy storage systems (SMES), energy is stored in magnetic fields by circulating current in a superconducting coil using an AC/DC converter while charging. The magnetic field will remain until the power is needed and discharged. For discharging, the stored energy is returned to the grid using a DC/AC converter. Due to ohmic losses caused by the circulating current in the coil, it is necessary to have a refrigerator system to avoid significant losses [18]. Figure 3.10 shows a diagram with the working principle of SMES.

SMES are very efficient, have quick response times, a high number of cycles and allow the control of active and reactive power. However, the investment costs are very high, and they still need improvements on their refrigerator systems and coil material to become commercially viable [8].

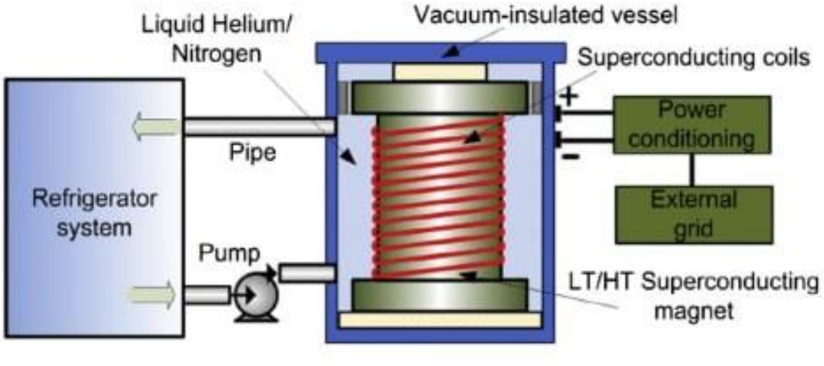


Figure 3.10 - Diagram with working principle of SMES [22].

3.3.5 - Thermal Energy Storage

3.3.5.1 - Sensible heat storage

Sensible heat storage techniques raise or lower the temperature of a liquid or solid material to store and release energy when convenient. They are commonly used on residential and industrial scales [12].

Water is the most common vector for lower temperatures due to its low cost and non-toxicity. It can be used in solar thermal heating applications, using well-insulated storage to keep the warm water until utilization. If more capacity is needed, underground thermal energy storage can be used.

In case of higher temperature storage in liquids, molten salt is usually used, which can be pumped between cold and hot storage. The heat exchanger and storage tank determine the power and the capacity.

As for higher temperatures in solids, it can be done by transferring heat from a gaseous form medium directly to solids like ceramic bricks, natural stones, or beds of smaller particles.

This technology is already in operation in Concentrating Solar Power Plants (CSP), which concentrate solar heat to warm up a fluid (water or molten salt) that can later be used to produce vapour and generate electricity [12]. Figure 3.11 is an aerial view of a CSP unit that uses molten salt.

District heating can also be considered part of this technology. It consists of a heating system of buildings through the circulation of warm water or low-pressure vapour through an underground network from industrial centres [8].

Figure 3.11 - Aerial view of CSP with molten salt storage [12].

3.3.5.2 - Latent heat storage

Latent heat storage uses the energy absorbed or released at a constant temperature during a phase change of the material. It is mainly used for solid/liquid phase change, where melting is used to store heat and solidification to release heat.

This technology allows for storing large amounts of heat at a constant temperature, making it ideal for applications that cannot tolerate significant temperature differences. Water (ice storage) and salt solutions can be deployed for temperatures below 0ºC; for temperatures below 100ºC, salt hydrates and paraffin waxes can be used.

Currently, it still has a small energy capacity [12].

3.3.5.3 - Thermochemical heat storage

Thermochemical heat storage can be operated in two different ways:

- Chemical reactions in which energy is stored as the heat of the response of a reversible reaction.
- Sorption processes store the energy by adsorption (physical binding) or absorption (uptake/dissolution of a material).

Thermochemical reactions based on gas-gas of gas-solid reactions allow for a theoretically lossless thermal energy storage, enabling a temporally and spatially independent thermal cycle.

This technology remains largely in the research and development phase, mainly based on chemical reactions. One of its drawbacks is the high cost of the equipment necessary for the chemical reactions, primarily the necessary heat pumps. On the other hand, the storage of the vectors can be done with materials available for low cost [12].

3.4 - Applications of Energy Storage

Classifying different storage applications according to their response and discharge time is possible. This classification is shown in Figure 3.12.

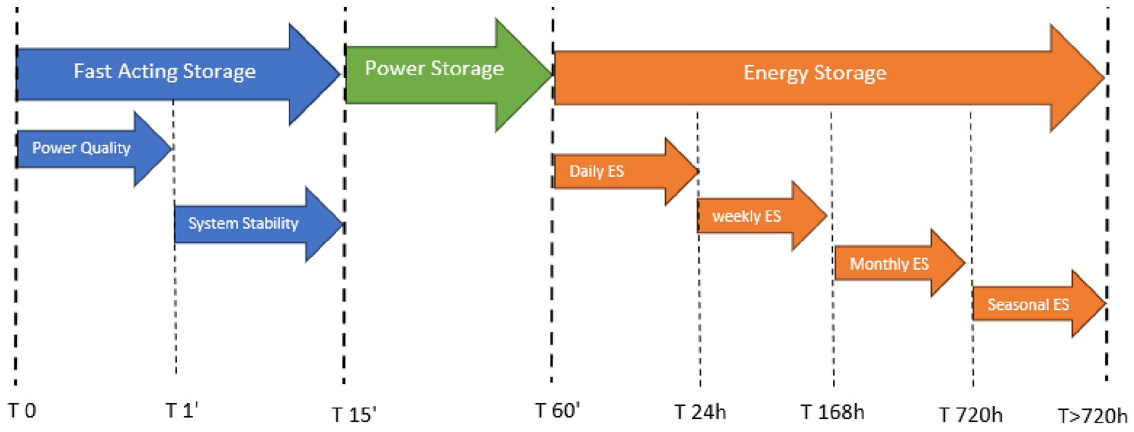
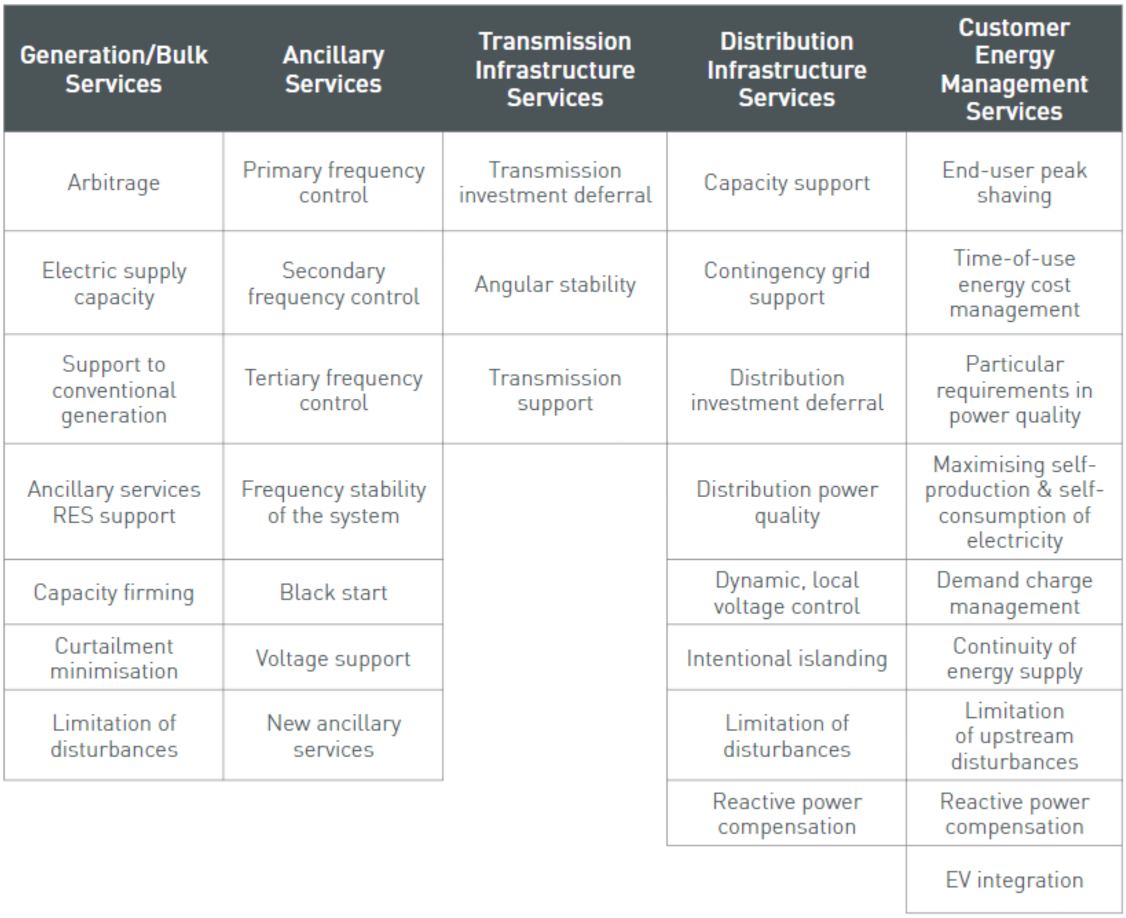


Figure 3.12 – ESS Classification according to their actuation timeframe [12].

The main applications of ESS in the electricity sector are presented in Figure 3.13, and the more relevant ones will be addressed throughout this section.



Generation/Bulk Services	Ancillary Services	Transmission Infrastructure Services	Distribution Infrastructure Services	Customer Energy Management Services
Arbitrage	Primary frequency control	Transmission investment deferral	Capacity support	End-user peak shaving
Electric supply capacity	Secondary frequency control	Angular stability	Contingency grid support	Time-of-use energy cost management
Support to conventional generation	Tertiary frequency control	Transmission support	Distribution investment deferral	Particular requirements in power quality
Ancillary services RES support	Frequency stability of the system		Distribution power quality	Maximising self-production & self-consumption of electricity
Capacity firming	Black start		Dynamic, local voltage control	Demand charge management
Curtailment minimisation	Voltage support		Intentional islanding	Continuity of energy supply
Limitation of disturbances	New ancillary services		Limitation of disturbances	Limitation of upstream disturbances
			Reactive power compensation	Reactive power compensation
				EV integration

Figure 3.13 – Main applications of ESS in the electricity sector [12].

Given the scope of this dissertation, a more significant focus will be given to the applications to the Generation/Bulk Services:

- **Arbitrage** – Taking advantage of the difference in the wholesale electricity market prices by purchasing energy when the price is low and selling at a higher price.
- **Electrical supply capacity** – Adding storage devices can replace fossil fuel generation as energy supply for peak generation capacity.
- **Support to conventional generation -** Optimization of operation:
    - **Generator bridging** – Using ESS to pick up the load when one generator stops, and another activates. They can also avoid start-up costs by charging in moments of low load, preventing the shutdown of the generator.
    - **Generator ramping** – Using the ability of some ESS to pick up strong and fast load variations, providing time for the generator to ramp up/down.
- **Ancillary services RES support** – Using ESS to allow renewable generation contribution to ancillary services by keeping reserve power.
- **Capacity firming** – Using ESS to allow a more constant renewable generation output over a period. This way, during peak production of Photovoltaic or Wind energy, the system can be charged; during low production times, the stored energy can be discharged. This can also include RES smoothing by balancing short-term disturbances caused by wind speed variations or shading caused by objects in FV production.
- **Curtailment minimisation** – Absorbing RES energy that cannot be injected into the electric grid.
- **Limitation of disturbances:**
    - **Short duration -** Reduce the volatility caused by short-term variation of RES lasting seconds to minutes and improve power quality (reactive power, harmonics, voltage flicker, transmission line protection, transient stability, dynamic stability, and system voltage stability).
    - **Long duration -** Reduce the volatility caused by long-term variation of RES lasting several minutes to a few hours. They can also relieve congestion on transmission lines, serve as backup for unexpected wind/PV shortfalls and reduce minimum load violations.
- **Other important uses -** The installation of ESS, such as batteries in distribution grids, can avoid or delay investments in grid equipment by providing necessary power in peak periods.

3.5 - Techno-Economic comparison of Energy Storage Technologies

One of the most critical aspects of choosing a technology for a given use is to analyse its technical and economic characteristics and whether it fits the intended purpose.

The Energy Transition Expertise Centre (EnTEC) is an expertise centre for energy transition which aims to monitor and analyse trends in technologies and innovations relevant to the energy transition in the energy sector. In March 2023, EnTEC published the report “Study on Energy Storage”, which provides context on the current development state of energy storage technologies, their business cases, and best practices for enabling their development.

Table 3.2 summarises the most relevant technologies’ essential attributes according to the study [23].

Regarding the technical characteristics, the chosen key performance indicators (KPI) were Storage capacity, Round-trip efficiency (efficiency of electricity output to electricity input), Storage duration, the Response time (time that the technology needs to provide its full power after standstill), the Self-discharge rate, and the Lifetime (the time that the storage technology can operate without exchange of the major components) [23].

As for the economic characteristics, the KPIs were Power Capital Expenditure (CAPEX) and Energy CAPEX (for electrochemical technologies, the CAPEX is the total CAPEX of the system, once described per power and once per capacity. For all other technologies, the CAPEX is additional), the Energy CAPEX expected for 2030, the Operational Expenditure (OPEX) (describes the per power or electricity stored or annual cost of the technology. This typically includes operation and maintenance such as labour cost, exchange of components and fuels) [23].

Another relevant aspect of each analysed technology was its Technology Readiness Level (TRL). TRL is a concept used to assess the maturity of a technology or innovation. NASA originally developed it in the 1970s to evaluate the maturity of technologies used for space exploration missions[24].

The original TRL system is based on a scale of 1 to 9, with each level representing a specific stage of development and a corresponding set of criteria that must be met. The requirements include the technology's validated basic principles, a prototype built and tested, and the technology demonstrated in a relevant environment [24].

Many public and private organisations use the TRL scale to evaluate a technology's readiness for commercialization or implementation. The higher the TRL level, the closer the technology is to be ready for widespread use [24].

The *International Energy Agency* (IEA) has released and constantly updates the *Energy Technology Perspectives (ETP) Clean Energy Technology Guide*, which contains development and deployment plans, key initiatives, assessments on the importance of net-zero emissions, and Technology Readiness Level (TRL) ratings (on a scale of 1-11) for over 500 individual technology designs and components, including storage technologies [25]. The meaning of each level of the scale is presented in Table 3.1.

Table 3.1 – Technology Readiness Levels [25]

TRL	Description of rating
1	Initial idea: basic principles have been defined
2	Application formulation: concept and application of the solution have been formulated
3	The concept needs validation: solution needs to be prototyped and applied
4	Early prototype: prototype proven in test conditions
5	Large prototype: components are proven in conditions to be deployed
6	Complete prototype at scale: prototype proved at scale in conditions to be developed
7	Pre-commercial demonstration: prototype working in expected conditions
8	First-of-a-kind commercial: commercial demonstration, full-scale deployment in final conditions
9	Commercial operation in the relevant environment: the solution is commercially available but needs evolutionary improvements to stay competitive
10	Integration needed at scale: the solution is commercial and competitive but requires further integration efforts
11	Proof of stability reached: predictable growth.

Table 3.2 – Energy Storage Technologies and KPIs [23].

Technology		Technical KPIs					Economical KPIs				TRL
		Storage capacity	Round-trip Efficiency (%)	Storage duration	Response time	Lifespan (years)	Power CAPEX (€/kW)	Energy CAPEX (€/kWh)	Energy CAPEX estimated 2030 (€/kWh)	OPEX (year)	
Mechanical	Pumped Hydro Storage	0.5-100 GWh	70-85	min-some 10h	sec.-min.	50-100	1880	470	470	28 €/kW-year	11
	Compressed Air Energy Storage	100 MWh-10GWh	42-54	min-some 10h	minutes	25-40	940	112	112	0.47 €/kWh	8
	Flywheel	5kWh-5MWh	85-95	sec.-min.	minutes	20+	310	2800	200-500	1.1-2.9€/MWh	9
	Liquid Air Energy storage	10 MWh-7.8 GWh	45-70	2-24 h	minutes	40	2000	450	450	1-2% CAPEX	9
Chemical	Hydrogen	10 kWh-several GWh	20-40	hours-weeks	sec.-min.	5-30	2979	2265 €/kW	2000 €/kW	30 €/MWh	6-9
Electrochemical	Lead-Acid Batteries	<10 MWh	75-85	1-6h	milliseconds	8-20	1000	400	250	1-2% CAPEX	11
	Nickel-Cadmium batteries	some MWh	60-70	min-hours	milliseconds	10-25	1200	800	no data	1.5-3% CAPEX	11
	Lithium-Ion batteries	<1000 MWh	85-89	30 min to 6 hours	milliseconds	10-20	1200	400	150-250	1% CAPEX	11
	Sodium-ion batteries	<100 kWh	92	<4 to 5 hours	milliseconds	<10	no data	223	25-77	no data	7
	Flow batteries (Vanadium)	10 kWh-800 MWh	68-80	10-12 hours	ms-sec	10-25	1850	464	370	1-2% CAPEX	8
Electrical	Supercapacitors	<1 kWh	90-95	secs-mins	milliseconds	20+	no data	765	no data	no data	11
	SMES	<20 MWh	90-95	millisecond-mins	5 ms	no data	no data	no data	no data	no data	5-8
Thermal	Sensible heat storage	350-4000 MWh	98-99	no data	<1 min	no data	no data	23-27.6	<13.8	no data	8-9
	Latent heat storage	100 kWh	90	no data	no data	no data	no data	no data	no data	no data	5-7/9
	Thermochemical heat storage	0.015-4 MWh	40-60	no data	5 min	no data	no data	no data	no data	no data	5-7/3-4

3.5.1 - Mechanical Energy Storage

3.5.1.1 - Pumped Hydro Storage

- IEA Guide TRL: 11
- IEA Importance of PHS for net-zero emissions: High

With a storage capacity of up to 100 GWh, and high efficiency, it is a mature technology widely used on a large scale at the commercial level. However, the main issue for PHS is the geographical constraint. Due to sizeable environmental impact and geographical requirements, the potential for installation is limited [23].

The latest developments in this technology aim to improve some essential characteristics, including re-purposing and retrofitting for increased flexibility to accommodate variable renewables, expanding the reach of pumped hydro plants to seawater plants, or underground and smaller-scale modular projects [24].

Currently, 96% of global storage capacity is pumped hydro.

3.5.1.2 - Compressed Air Energy Storage

- IEA Guide TRL: 8
- IEA Importance of CAES for net-zero emissions: Moderate

Compressed Air Energy Storage presents high storage potential; however, it still has low round-trip efficiency and needs gas for discharge. Therefore, it has an environmental impact if not driven with carbon-free gas. CAES plants need to be installed where underground requirements can be fulfilled. This limits the places where CAES can be installed [23].

Current research in this technology aims to improve its efficiency by storing the heat generated during the gas compression phase to heat the compressed air before it enters the turbine, reducing the requirement for fuel [24].

There are currently 2 CAES plants, one in Germany and one in the USA.

3.5.1.3 - Flywheels

- IEA Guide TRL: 9
- IEA Importance of Flywheels for net-zero emissions: Moderate

Flywheels have very high idle losses and can only be used for short-term storage. OPEX is comparatively high due to the need for bearing maintenance [23].

3.5.1.4 - Liquid Air Energy Storage

- IEA Guide TRL: 9
- IEA Importance of LAES for net-zero emissions: Moderate

LAES has a low TRL and will still need several years to enter the market [23].

LAES has been demonstrated in two pilot-scale plants by Mitsubishi Heavy Industries Ltd and Highview Power Storage. A 5MW/15MWh plant, also by Highview Power, was connected to the grid in the UK in 2018 [24].

3.5.2 - Chemical Energy Storage

3.5.2.1 - Hydrogen

Electrolysers have a comparatively low efficiency and are still quite expensive. Hydrogen has a low energy density and, therefore, costly transport. Infrastructure for H_2 use is still to be developed [23].

Given the different technologies for the production, storage, and transport of hydrogen, the TRL of each technology needs to be assessed individually [24].

- Production

The most mature technology for hydrogen production is electrolysis with an alkaline membrane (TRL 9). Other electrolysis technologies are being studied, such as Polymer electrolysis membrane (TRL 8), solid oxide electrolyser cell (TRL 7), and seawater electrolysis (TRL 3) [24].

Besides electrolysis, other processes are being studied, namely Biomass/waste gasification (TRL 7), Thermochemical water splitting (TRL 3), Chemical Looping (TRL 3), Coal gasification (TRL 4), Methane pyrolysis (TRL 6), Steam methane reforming (TRL 10), Natural Gas auto thermal reforming (TRL 10) [24].

- Storage

Hydrogen storage research focuses on three different methodologies, namely: Salt cavern storage (TRL 10), depleted oil and gas field, aquifer (TRL 3) and Storage tank (TRL 11) [24].

- Transport

Hydrogen transport can be done using three different methods: Pipeline (TRL 11), Hydrogen blending in the natural gas network (TRL 7), Liquid hydrogen tanker (TRL 6), and Liquid organic hydrogen carrier tank (TRL 5) [24].

3.5.3 - Electrochemical Energy Storage

3.5.3.1 - Lithium-ion Batteries

- IEA Guide TRL: 11
- IEA Importance of Li-ion batteries for net-zero emissions: Very High

The technology has been mastered and has reached the mass market. A problem is the high dependence on lithium and other rare minerals [23].

Development of this technology for the transport sector drives technology development towards higher densities, while power sector applications benefit from idling capacity or less-performing designs. Research in the post-Li-ion era is already underway with new systems such as lithium-sulphur, lithium-air, and sodium-ion batteries [24].

3.5.3.2 - Flow Batteries

- IEA Guide TRL: 8
- IEA Importance of Flow batteries for net-zero emissions: Very High

The major technological issue is the ageing effect on the electrodes. The high-cost fluctuation of Vanadium partly limits the use of Vanadium Redox Batteries in the broad market [23].

Several projects are underway. 2019 SoftBank invested USD 30 million in iron flow battery start-up ESS. RedT Energy has a 1 MW system in Australia. Avalon, Lockheed Martin, and U.S.

Vanadium are also advancing projects at different scales, but the need for longer-term storage durations is hampering progress [24].

3.5.4 - Thermal Energy Storage

3.5.4.1 - Sensible heat storage

- IEA Guide TRL: 8-9
- IEA Importance of Sensible heat storage for net-zero emissions: High

Regarding the business economic dimension of thermal energy storage systems, Molten Salt heat storage systems are more expensive than other sensible heat storage technologies, such as latent and Thermochemical heat storage. This disadvantage must be compensated by the operating costs, which in some cases is realistic due to a higher specific heat capacity and efficiency, depending on the application area. This is usually the case for the CSP application mainly because the suitability already results from the temperature range [23].

Since it is a clear advantage in solar plants to overcome the constraints on sunlight availability, solutions are being developed for standalone sensible heat storage. Storage concepts involve combining different storage units and optimising the charging and discharging performance and the storage capacity for the given power plant [24].

3.5.4.2 - Latent heat storage – High temperature

- IEA Guide TRL: 5-7
- IEA Importance of Latent heat storage (high temperature) for net-zero emissions: High

In CSP and Power Plant current applications, the latent heat storage technology is not yet fully mature or at an intermediate level of maturity.

Applications in the power sector are solar thermal power plants, allowing the plant to provide electricity after sunset. Salt hydrate and paraffin wax systems are partly commercialised for temperatures below 100ºC (TRL 6-8). High-temperature LHS with integrated finned-tube heat exchangers has been constructed and operated with variable phase-change temperatures between 140°C and 305°C (TRL 7) [24].

3.5.4.3 - Latent heat storage – Ice storage

- IEA Guide TRL: 9
- IEA Importance of Latent heat storage (Ice storage) for net-zero emissions: Moderate

For low-temperature storage, water (ice storage) and aqueous salt solutions (for temperatures below 0°C) have been commercialised and deployed on a large scale, e.g. the phase change of water at 0°C is used for storage of cold for air conditioning and supply of process cold. Many low-temperature products using latent heat technology in buildings, mini-storage for food, and cooling for medication have been commercialised (TRL 9).

The Paris La Défense business district is refrigerated from a centralised production and through a distribution network of cold water. Coupled with this production, a storage system allows for the modulation of production and consumption to increase the performance coefficient of refrigeration groups and improve the network's reliability [24].

3.5.4.4 - Thermochemical heat storage – Sorption process

- IEA Guide TRL: 5-7
- IEA Importance of Thermochemical heat storage (Sorption process) for net-zero emissions: High

The sorption principle can be applied for thermal energy storage and chemical heat pumps. Whereas sorption heat pumps are commercially available, sorption-based thermal energy storage with more than a 1-hour discharging cycle is still in research and development. Sorption storage systems are at a TRL 5-7, except for sorption heat pumps which have been fully commercialised (TRL 9) [24].

3.5.4.5 - Thermochemical heat storage – Chemical Reaction

- IEA Guide TRL: 3-4
- IEA Importance of Thermochemical heat storage (Chemical Reaction) for net-zero emissions: Moderate

TCS heat storage technology is not yet fully mature or at an intermediate level of maturity [23].

This thermochemical heat storage is based on gas-gas or gas-solid reactions by using thermal energy to dissociate compounds ("AB") into two reaction products ("A" and "B"). Upon subsequent recombination of the reactants, an exothermic reverse reaction occurs, and the previously stored heat of the reaction is released. This allows for the theoretically lossless storage of thermal energy. 95% of the installed systems are in R&D and have reached a TRL of 3-4 [24].

3.6 - Final decision and price evolution

By reviewing all the previously presented data summarised in Table 3.2, it is possible to observe that many energy storage technologies already show a mature state of development. Each of them has its shortcomings and advantages. However, for the context of the current dissertation, it was decided to use Li-ion batteries as the chosen technology for all investment calculations. Its high development level (TRL 11) and advantages such as high efficiency, high energy density, fast response time, long lifetime, and decreasing investment cost make this technology the most interesting for daily price arbitrage in the coming years.

When analysing the CAPEX price outlook for Li-ion batteries, the price reduction in the last years and the expected reduction for the following years are visible. The outlook of the battery capital cost of a Li-ion BESS is presented in Figure 3.14. For a 4-hour system, the CAPEX in 2020 was sitting at around 400€/kWh, which is expected to reduce to 150-250€/kWh by 2030 [26].

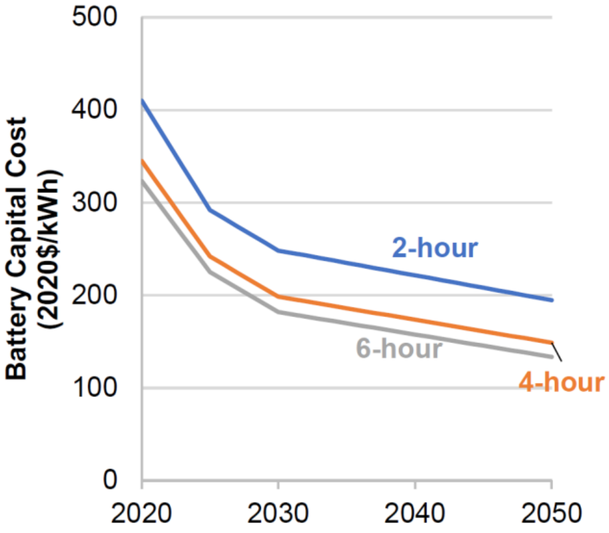


Figure 3.14 – Li-ion Batteries CAPEX expectation [26].

Chapter 4

Methodology

The main objectives of this dissertation were to study the economic viability of installing energy storage devices in the Portuguese electric grid and evaluate the impacts this might have on the electricity market price of MIBEL. To this end, python scripts were written to automatize this analysis.

The developed application must follow the requirements:

1. The user must be able to select the number of hours for charging and discharging.
2. The hours for each process must be consecutive.
3. Each day, the storage device must charge before discharging, and the processes must not overlap.

In the first phase, all the necessary data was downloaded from the OMIE website. This data was one ".zip" file for each year (data from 2017 until 2021 was available this way). For every year, a ".1" file for each hour of the year contained information about the purchase and sell bids, if the market operator accepted them or not, the amount of energy and price of the proposal, as well as to what countries were they accepted in (Portugal, Spain, or both). For 2022, the data was unavailable in a single ".zip" file, so a script was written to obtain the multiple files from the website, which is in Annex A.

After all the data was available on the root folder of the program, a second script called *obtain_curves* was developed for looping through all the ".1" files while preparing the data for the following processing by eliminating unnecessary data and outputting one comma-separated values file (".csv") for each year.

Once a file for each year was available, the main script was developed. In this script, the first step was to indicate for what year the analysis was conducted and the technical information about the storage system, namely the capacity, depth of discharge (DoD), efficiency, and the number of hours for charging and discharging.

Next, the program obtains the market price of each hour, corresponding to the price of the last accepted purchase bid. Then, using this information, the best hours for charging and discharging the storage system are obtained for each day of the year.

In the selected hours for charging and discharging, a function called *new_price* will be applied. This function uses a methodology of linear approximation to obtain the new market prices for those hours, including the bids for charging and discharging the storage system.

Once the new prices are obtained, the program will calculate the profit obtained by doing daily arbitrage for a given year using a specific storage device configuration. This profit will be the result that can later be used to evaluate the investment economically.

All the scripts and functions previously mentioned will be presented in greater detail throughout this chapter.

The developed python scripts are based on using the ‘pandas’ library. This is an open-source Python library used for data manipulation and analysis. It provides structures and functions for efficiently working with structured data, such as tabular data (similar to spreadsheets or SQL tables).

The primary data structure in pandas is the DataFrame, a two-dimensional data table with labelled rows and columns. DataFrames can hold different data types and allow easy indexing, filtering, grouping, and aggregating operations.

The pandas library provides various data cleaning, transformation, and exploration functionalities. It offers methods for handling missing data, merging, and joining datasets, reshaping data, and applying mathematical and statistical operations. It also integrates well with other libraries commonly used in the data science ecosystem, such as NumPy and Matplotlib.

4.1 - Market Price Estimation

A methodology based on linear approximation is applied to perform the new market price estimation.

The approach uses three points for each hour, shown in Figure 4.1. Point A will correspond to the point at the extreme right-hand side of the zero-price segment of the selling curve, point B will be associated with the point at the outer right side of the buying curve at the segment of the purchase curve with the highest amount of energy that is transacted, and C will correspond to the intersection point of both curves, which indicates the last accepted bid.

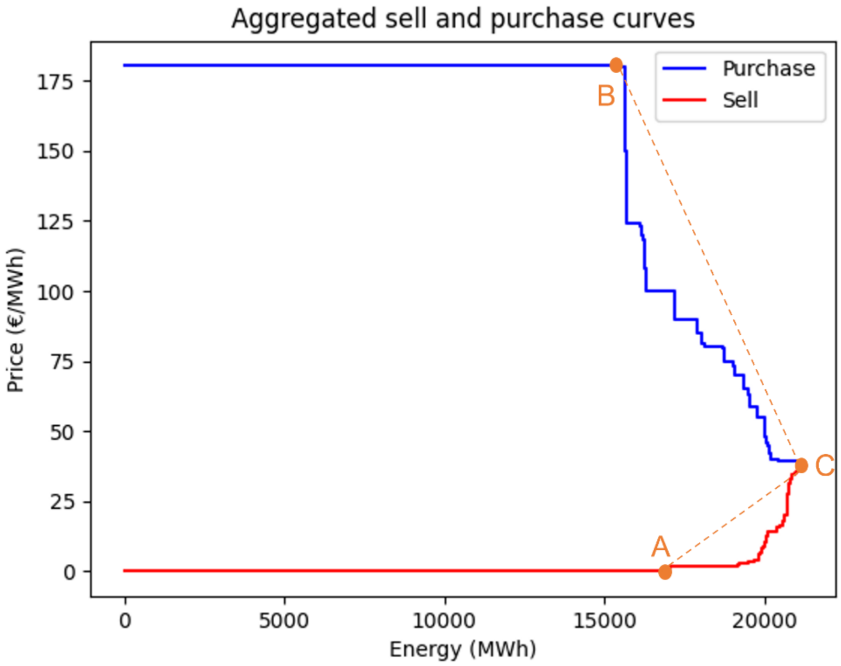


Figure 4.1 – Purchase and sell curves of the MIBEL Market for the 5th hour of 2nd of July 2021 with the representation of points A, B and C.

When a new selling bid is introduced (as for the discharging of the storage equipment), point A will move to the right side (point A'), and as a result, point C will also be moved downwards (point C'), leading to a new value for the market price, lower than the original. This effect can be observed in Figure 4.2.

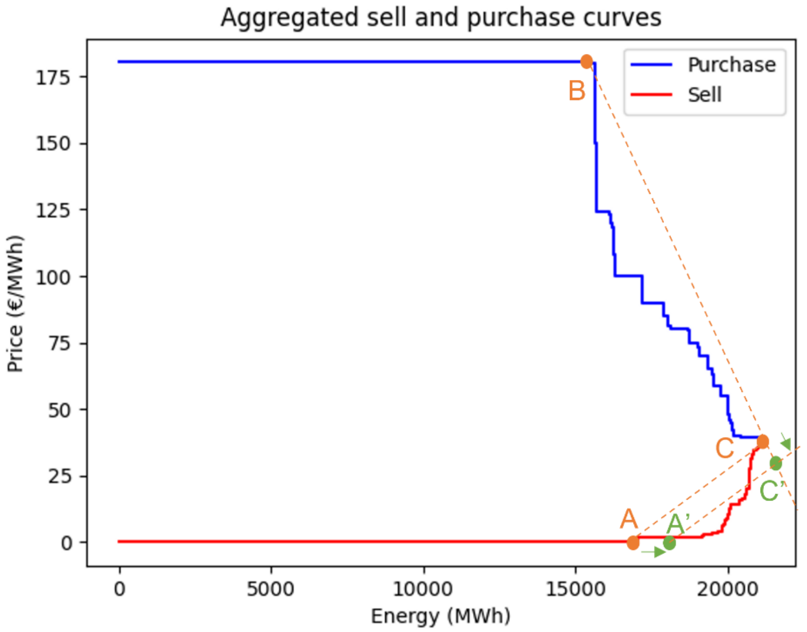


Figure 4.2 – Effect of adding new selling bids.

When new buying bids are added to the pool market (as for the charging of the storage equipment), point B will be altered (point B'), which causes point C to move and increase the market price (point C'). This effect is illustrated in Figure 4.3.

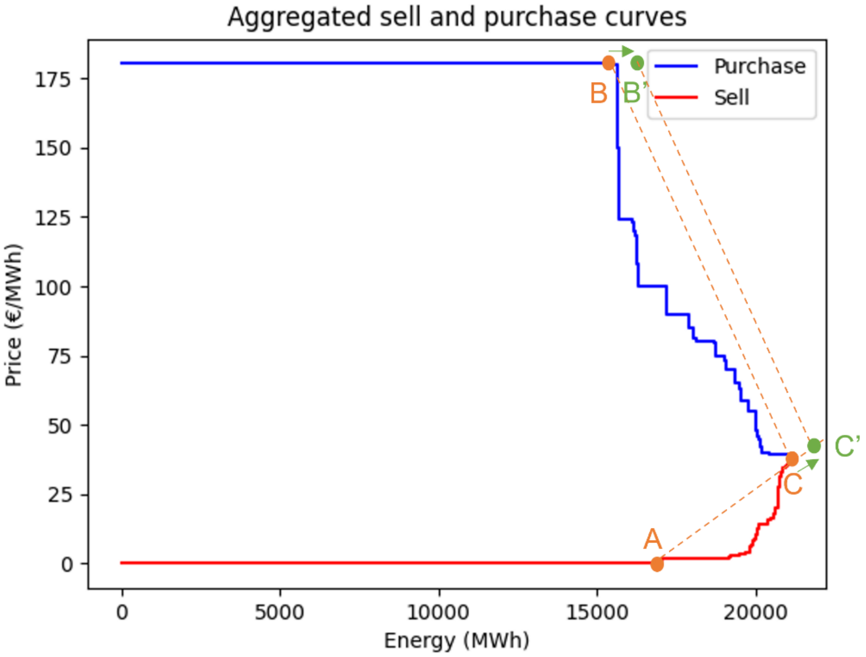


Figure 4.3 – Effect of adding new buying bids.

4.1.1 - Function *new_price*

The function new_price was written to implement the linear approximation methodology to obtain the new market prices in the hours when the storage system is charging or discharging.

This function requires as inputs: a DataFrame containing the purchase and sell bids for the hour under analysis, a string indicating the mode of operation (‘C’ if purchase, ‘D’ if sell), the amount of energy that is bought or sold in that hour, and the efficiency of the discharging process.

After separating the purchase and selling bids, they are ordered (purchase in descending order and selling in ascending order) and aggregated by price. The three points A, B and C are obtained as previously described.

If the mode of operation for that hour is of purchase (‘C’), then the quantities of new point B’ ($Q_{B'}$) is calculated using expression (4-1) by adding the amount of stored energy (Q_{stored}) to their original quantity (Q_B), but keeping the same price. Knowing that any straight line can be defined as y=mx+b, where m is the slope and b is the value of y when x=0, the next step is to calculate the values of m and b for the AC line, using expressions (4-2) and (4-3), where P_C and P_A are the prices of point C and A, and Q_C and Q_A are the quantities of point C and A. The slope of the line BC is also obtained with expression (4-4) since it will be the same as line B’C’. For the same line, b is calculated using expression (4-5). Finally, using expression (4-6), the point of intersection of lines B’C’ and AB will provide the new market Quantity for this situation.

$$Q_{B'} = Q_B + Q_{stored} \qquad \textbf{(4-1)}$$

$$m_{AC} = \frac{P_C - P_A}{Q_C - Q_A} \qquad \textbf{(4-2)}$$

$$b_{AC} = P_C - m_{AC} \times Q_C \qquad \textbf{(4-3)}$$

$$m_{B'C'} = m_{BC} = \frac{P_C - P_B}{Q_C - Q_B} \qquad \textbf{(4-4)}$$

$$b_{B'C'} = P_{B'} - m_{B'C'} \times Q_{B'} \qquad \textbf{(4-5)}$$

$$Q_{C'} = \frac{b_{AC} - b_{B'C'}}{m_{B'C'} - m_{AC}} \qquad \textbf{(4-6)}$$

The new price for point C’ ($P_{C'}$) can therefore be calculated using expression (4-7) and is used as the return value of this function.

$$P_{C'} = m_{AC} \times Q_{C'} + b_{AC} \qquad \textbf{(4-7)}$$

To avoid problems of dividing by 0, if P_C is less than 0.1, the line equation is not applied. Instead, the new price for C’ will be 0. This is appliable to hours when the final market price is zero, meaning that point A coincides with point C.

As for when the mode of operation is sell (‘D’), the new quantity of point A’ is obtained in a similar way using expression (4-8), except this time, the amount of stored energy will be multiplied by the efficiency (η) of the storing system, in order to take into account the losses of energy between the charging and discharging processes. The equation of line BC is obtained using expressions (4-9) and (4-10), and the equation of line A’C’ with expressions (4-11) and (4-12). The new market price for the hour is obtained using expressions (4-13) and (4-14).

$$Q_{A'} = Q_A + Q_{stored} * \eta \tag{4-8}$$

$$m_{BC} = \frac{P_C - P_B}{Q_C - Q_B} \tag{4-9}$$

$$b_{BC} = P_C - m_{BC} \times Q_C \tag{4-10}$$

$$m_{A'C'} = m_{AC} = \frac{P_C - P_A}{Q_C - Q_A} \tag{4-11}$$

$$b_{A'C'} = P_{A'} - m_{A'C'} \times Q_{A'} \tag{4-12}$$

$$Q_{C'} = \frac{b_{BC} - b_{A'C'}}{m_{A'C'} - m_{BC}} \tag{4-13}$$

$$P_{C'} = m_{BC} \times Q_{C'} + b_{BC} \tag{4-14}$$

The python script for this process is presented in Annex B.

4.2 - Program obtain_curves

In the *obtain_curves* script, the user must specify the variable *year* for which year the analysis should be conducted. The program will then obtain from the defined directory for that year the “.1” files referring to the market results for each hour of that year. For each file, it opens the file, reads the data, and skips the first three lines containing irrelevant information. All the information in each file is combined in a single DataFrame.

Some data cleaning is performed in the columns referring to “Quantity” and “Price” to convert the values into a numeric format. In the “Date” column, the data is converted to *datetime* format defined by ISO 8601 (yyyy-mm-dd).

Some filters are applied to reduce the amount of data by removing unnecessary information. Firstly, all the bids classified as “offered” are removed since only the “married” bids are relevant to the analysis. The column where this information is present is also dropped. The next applied filter aimed to remove all the offers that only apply to Spain, leaving only the ones marked as MIBEL or Portugal for further analysis. This is a way of ensuring that Market Splitting is considered.

Once all the data for one year has been appropriately filtered, they are saved in a single “.csv” file, where each line corresponds to one bid, and each column refers to Hour, Date, Country, Kind Bid, Quantity, and Price.

This program can be used for any year to analyse the available hourly market files in the correct directory.

The script for this program is present in Annex C.

4.3 - Program *main*

The *main* program requires the user to specify a series of parameters saved as variables. These parameters are the year of the analysis, the number of hours for charging and discharging, and the battery's energy capacity, efficiency, and Depth of Discharge (DoD). One other used parameter is the minimum daily SPREAD.

Using expression (4-15), the amount of energy stored in each charging hour is calculated.

$$stored\ amount = \frac{capacity \times DoD}{number\ hours} \tag{4-15}$$

Once all parameters are set, the ".csv" file corresponding to the year in the analysis is imported into a DataFrame. Using the *groupby* function of pandas, all the offers with the same price are aggregated for each hour, reducing the number of lines.

The next step is to obtain a DataFrame (*eq_prices*) with the final market price of each hour and the total quantity of energy negotiated. These are considered the price and accumulated quantity of the last purchase bid.

To *eq_prices*, two new columns are added, the 'Rolling Charging' and 'Rolling Discharge'. These are obtained using the *rolling* function of pandas, which allows calculating the mean of a window with size according to the number of hours for charging and discharging defined in the initial parameters. This way, it is possible to obtain the price of charging or discharging if the process starts at that respective hour.

To ensure that the discharge is done entirely inside the 24 hours of the day, for each day, the program selects the rows where the "Hour" column is greater than or equal to 24 minus the number of charging hours. It then assigns a null value to the "Rolling Charge" and "Rolling Discharge" columns in those rows, making them invalid.

The same applies to the first hours of the day on the "Rolling Discharge" column, ensuring that the discharge must be done after at least one charging cycle is completed.

By obtaining the maximum value of "Rolling Discharge" for each day, it is possible to obtain the hour for starting the discharge process where the revenue will be highest. This hour and the mean price will be saved in a DataFrame called *discharge_time*.

To guarantee that in each day the charging process occurs before the discharging, for each day, rows containing information about hours after the ones in *discharge_time* are deleted from *eq_prices*. On the remaining rows, the hour with a minimum "Rolling Charge" is selected as the time for the charging process to begin, leading to minimal charging costs. This hour and the mean price will be saved in a DataFrame called *charging_time*.

Using pandas' *merge* function, a new DataFrame called *operation_time* is built, obtaining a single table where each line corresponds to each day of the year, and contains the columns associated with the date, hour charging, value charging, hour discharge, and value discharge. A new column is added to this table showing SPREAD obtained each day, calculated using expression (4-16).

$$SPREAD = \frac{num.hours\ dis. \times price\ discharge \times efficiency}{num.hours\ char. \times price\ charging} \tag{4-16}$$

With the introduction of the parameter efficiency, there might be days in with the SPREAD is less than one since the price of sale is close to the price of purchase, and this does not provide enough revenue to overcome the energy loss. Using the parameter minimum SPREAD defined by the user in the beginning, all rows where the SPREAD is smaller than the user's specified value are removed from *operation_time*. This way, the program does not consider the days when the storage system keeps idle mode, not charging nor discharging.

Now that the hours for charging and discharging are selected for each day of the year, the next step will be to obtain the new market price at which energy will be commercialized in the designated hours by applying function *new_price* (explained in section 4.1.1 -) to each one of the hours.

At this point, there are two Dataframes called *chosen_times_discharge_extended* and *chosen_times_discharge_extended,* where each line corresponds to every hour in activity (discharging or charging, respectively) and a column with the new market price for that hour. With this information, it is possible to calculate the following results:

- Days of operation: number of days of the year in which the activity of arbitrage is economically viable (SPREAD > 1) – expression (4-17)

$$n.op.days = length(chosen\_times\_discharge\_extended)/(n.hours\ discharge) \quad \textbf{(4-17)}$$

- Revenue: revenue obtained with price arbitrage, considering the efficiency of the storage system – expression (4-18)

$$revenue = efficiency\ \times stored\ energy \times \sum New\ Price\ Discharge \quad \textbf{(4-18)}$$

- Cost: what was spent on buying energy for arbitrage – expression (4-19)

$$cost = stored\ energy \times \sum New\ Price\ Charging \quad \textbf{(4-19)}$$

- Profit: profit obtained for the year in study – expression (4-20)

$$profit = revenue - cost \quad \textbf{(4-20)}$$

- SPREAD: Obtained SPREAD for the year in analysis – expression (4-21)

$$SPREAD = revenue/cost \quad \textbf{(4-21)}$$

- Average difference: the mean difference between the price of purchase and the price of selling the energy in that year – expression (4-22)

$$Avg.Difference = \frac{\sum New\ Price\ Discharge - \sum New\ Price\ Charging}{n.op.days} \quad \textbf{(4-22)}$$

To further the analysis and study the impact of the *new_price* function on the results, revenue, cost, profit, and SPREAD are also calculated using the original market prices instead of the new prices – this considers the storage system as a Price Taker (PT), instead of a Price Maker (PM).

To obtain greater detail from this study, these parameters are calculated each month instead of the whole year.

After all calculations have been done, the program will output a report with the most important results about the year in the analysis. This report will be in Microsoft Excel format. The first sheet, called "Eq. Prices", contains the market clearing prices, the amount of energy negotiated, and the rolling averages for charging and discharging each hour. The second sheet, called "Hour Operation", presents all hours of the year, their market clearing prices and quantities, and the mode of operation (charging, discharging or idle). If the mode is charging or discharging, the new price and the price variation in percentage are presented.

As for the third sheet of the report ("Month Charging"), there is a monthly analysis of the charging mode, showing for each month the average hour selected for starting the charging, the old and new price, the percentage variation, and the number of days where the activity is performed. The fourth sheet ("Month Discharging") presents the same results for the discharging mode.

The fifth sheet ("Analysis - PM") contains an analysis for the whole year if the storage system is considered a price maker (using the new prices). It is presented the year under analysis, the number of days of operation, the revenue, cost, profit, SPREAD and average daily difference for that year. On the sixth sheet ("Analysis - PT"), the same analysis is presented but considering the device as a price taker (old prices). Sheets seven ("Analysis Monthly - PM") and eight ("Analysis Monthly - PT") present the same results as the previous ones organised by month.

Program main is presented in Annex D.

Chapter 5

Results

The results obtained by the methodology exposed in the previous chapter are presented and interpreted in the present chapter. Two case studies are considered, which differ only in the storage system's capacity. This storage system is based on Li-ion batteries, whose characteristics were based on the reported in [23].

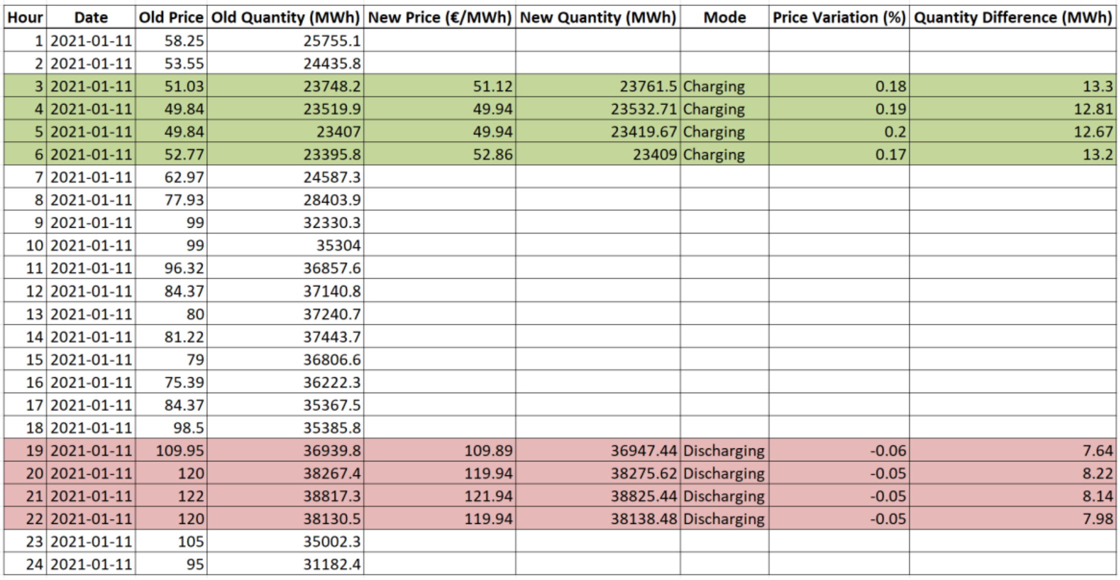
Case Study 1 considers 10 batteries with a capacity of 1 MWh each, using a DoD of 20%, an efficiency of 89%, and a charging and discharging time of 4 hours.

Case Study 2 considers 100 batteries with a capacity of 1 MWh each, using a DoD of 20%, an efficiency of 89%, and a charging and discharging time of 4 hours.

The data for the analysis was acquired from the OMIE website and processed by the developed algorithm. The main results will consider the data from the year 2021. However, an analysis will also be presented for all remaining years between 2017 and 2022.

As explained in Chapter 4, for each day, the consecutive hours with lower average prices are selected as the charging hours, and those with consecutive higher prices are the hours for discharging the energy. For hours with these operations, the new prices are calculated. Table 5.1 is an example of the program output for each hour of the 11th of November 2021 using Case Study 2. The operation hours are identified as ‘Charging’ and ‘Discharging’, and for those hours, the new prices in €/MWh are presented, as well as the percentage of price variation and the difference in the quantity of energy accepted by the simulated market.

Table 5.1 – Example of output of a day



Hour	Date	Old Price	Old Quantity (MWh)	New Price (€/MWh)	New Quantity (MWh)	Mode	Price Variation (%)	Quantity Difference (MWh)
1	2021-01-11	58.25	25755.1					
2	2021-01-11	53.55	24435.8					
3	2021-01-11	51.03	23748.2	51.12	23761.5	Charging	0.18	13.3
4	2021-01-11	49.84	23519.9	49.94	23532.71	Charging	0.19	12.81
5	2021-01-11	49.84	23407	49.94	23419.67	Charging	0.2	12.67
6	2021-01-11	52.77	23395.8	52.86	23409	Charging	0.17	13.2
7	2021-01-11	62.97	24587.3					
8	2021-01-11	77.93	28403.9					
9	2021-01-11	99	32330.3					
10	2021-01-11	99	35304					
11	2021-01-11	96.32	36857.6					
12	2021-01-11	84.37	37140.8					
13	2021-01-11	80	37240.7					
14	2021-01-11	81.22	37443.7					
15	2021-01-11	79	36806.6					
16	2021-01-11	75.39	36222.3					
17	2021-01-11	84.37	35367.5					
18	2021-01-11	98.5	35385.8					
19	2021-01-11	109.95	36939.8	109.89	36947.44	Discharging	-0.06	7.64
20	2021-01-11	120	38267.4	119.94	38275.62	Discharging	-0.05	8.22
21	2021-01-11	122	38817.3	121.94	38825.44	Discharging	-0.05	8.14
22	2021-01-11	120	38130.5	119.94	38138.48	Discharging	-0.05	7.98
23	2021-01-11	105	35002.3					
24	2021-01-11	95	31182.4					

From the data in this table, conclusions about the impact of the storage system can be determined, which will be analysed in the present chapter.

After obtaining the potential profit for each year, an investment analysis is conducted. The potential profit is used to calculate the cash flow for each year, along with the expected lifetime of the storage system. This methodology makes it possible to conclude if the project is economically viable.

5.1 - Case Study 1

For Case Study 1, the initial parameters are presented in Table 5.2.

Table 5.2 - Parameters for Case Study 1

Year	2021
Minimum SPREAD	1
Number Hours Charging	4
Number Hours Discharging	4
Efficiency	89%
Total Capacity	10 MWh
Depth of Discharge	20%

Table 5.3 presents the average prices in €/MWh in the charging and discharging hours before and after the introduction of the effect of the batteries, as well as the percentage variation of the price.

Table 5.3 - Old and New prices in €/MWh for each month of the year 2021

	Charging hours			***Discharging hours***		
Month	***Old Price (€/MWh)***	***New Price (€/MWh)***	***% Variation***	***Old Price (€/MWh)***	***New Price (€/MWh)***	***% Variation***
January	43.25	43.26	0.03%	78.1	78.1	-0.01%
February	14.21	14.21	0.03%	45.85	45.84	-0.02%
March	36.3	36.31	0.03%	59.21	59.2	-0.02%
April	55.44	55.45	0.02%	75.98	75.97	-0.01%
May	49	49.01	0.02%	80.11	80.1	-0.01%
June	69.48	69.5	0.02%	92.42	92.41	-0.01%
July	78.21	78.22	0.02%	101.69	101.68	-0.01%
August	88.97	88.99	0.02%	119.27	119.26	-0.01%
September	132.39	132.4	0.01%	174.7	174.69	0%
October	169.54	169.57	0.02%	240.38	240.36	-0.01%
November	161.87	161.9	0.02%	229.22	229.2	-0.01%
December	187.23	187.26	0.02%	285	284.98	-0.01%

As expected, it is possible to observe that introducing new purchase bids on the market during the hours of charging the storage system led to an increase in the final market price. The opposite effect is observed when new selling bids are added during discharging hours. The price remained unchanged for all remaining hours since no new bids were added. It should be highlighted that for the current capacity of 10 MWh, the maximum price variation obtained was 0.03%, revealing that this capacity has a minimal impact on the market.

Another relevant aspect is that the price variation is, on average, higher during charging hours than during discharging hours, which can be explained by the higher slope verified in the ordered purchase bids (line BC) than in the selling bids (line AC).

The number of operation days, the average purchase and selling prices, and the average price difference are presented in Table 5.4. All price values are in €/MWh. In 2021, the batteries operated for **322 days**, with an average purchase price of **92.28 €/MWh** for charging the batteries and **135.20 €/MWh** for selling the accumulated energy. This resulted in an average difference of **42.92 €/MWh**.

Regarding the number of days of operation, it is visible that during the winter months (January until March and October until December), the number of days where it is economically viable to operate the storage system is higher than in the remaining months. This effect is also reflected in the daily average difference column, where the value is lower during summer.

The winter months are generally characterized by higher renewable production, such as wind and hydro, which lead to higher price differences between different hours of the day, as can be observed. During summer, given the typically less windy and drier conditions, unsuitable for wind or hydroelectric production, the market prices are set by the non-renewable sources, for which the prices do not vary as much throughout the day.

Table 5.4 – Number of operation days, purchase and selling price, and daily average price difference for each month of 2021 in €/MWh.

Month	***Num. Operation days***	***Purchase price* (€/MWh)**	***Selling price* (€/MWh)**	***Daily Average Difference* (€/MWh)**
January	31	43.26	78.10	34.86
February	28	14.21	45.84	31.64
March	31	36.31	59.20	22.91
April	27	55.45	75.97	20.54
May	23	49.01	80.10	31.11
June	21	69.50	92.41	22.94
July	22	78.22	101.68	23.49
August	23	88.99	119.26	30.29
September	26	132.40	174.69	42.32
October	30	169.57	240.36	70.84
November	30	161.90	229.20	67.34
December	30	187.26	284.98	97.77
Total	322	92.28	135.20	42.92

Starting from August, there was a gradual increase in both the purchase and selling prices. However, the increase was sharper for the selling price, significantly increasing the daily average difference.

This price increase in 2021 can be attributed to the rising natural gas price observed during that year. Figure 5.1 presents the historical data for the reference natural gas price index in Europe, the Dutch Title Transfer Facility (TTF), where the price until August kept stable below 30 €/MWh. However, it starts increasing until the peak of around 180 €/MWh in December [27].

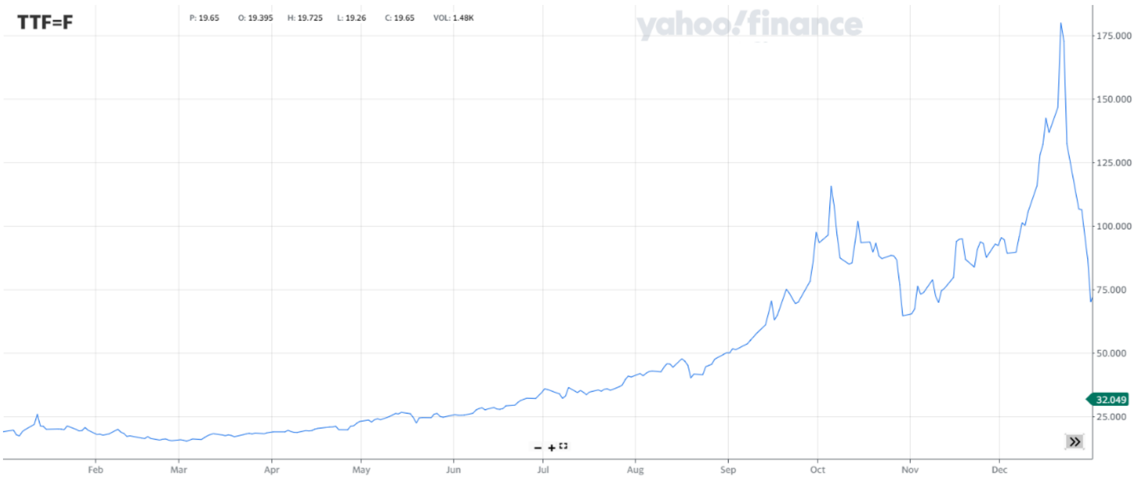


Figure 5.1 – Dutch TTF index evolution during 2021 [27].

Table 5.5 shows the total cost, revenue, and profit obtained each month of the year with the operation of the batteries during the selected hours. In total, **237 763.29 €** would be spent to charge de batteries, while **309 948.43 €** would be obtained by selling the accumulated energy, resulting in a yearly profit of 72 185.14 €. Note that these values relate only to purchasing and selling energy. They do not consider any aspect of investment or operational cost of the storage system.

Table 5.5 – Revenue, cost and profit obtained for Case Study 1.

Month	***Revenue***	***Cost***	***Profit***
January	17 237.58 €	10 727.63 €	6 509.95 €
February	9 139.22 €	3 183.84 €	5 955.38 €
March	13 066.27 €	9 005.05 €	4 061.22 €
April	14 603.82 €	11 977.07 €	2 626.75 €
May	13 116.95 €	9 018.14 €	4 098.81 €
June	13 817.46 €	11 675.26 €	2 142.20 €
July	15 927.53 €	13 766.66 €	2 160.87 €
August	19 529.47 €	16 373.59 €	3 155.88 €
September	32 339.49 €	27 539.64 €	4 799.85 €
October	51 340.96 €	40 696.69 €	10 644.27 €
November	48 957.00 €	38 856.61 €	10 100.39 €
December	60 872.68 €	44 943.11 €	15 929.57 €
Total	309 948.43 €	237 763.29 €	72 185.14 €

When comparing the daily average difference in Table 5.4, and the profit in Table 5.5, it is possible to observe a high correlation between the results. This can be observed in the graph in Figure 5.2, where these two variables follow the same pattern throughout the year. The minor differences are due to the number of operation days being different from month to month.

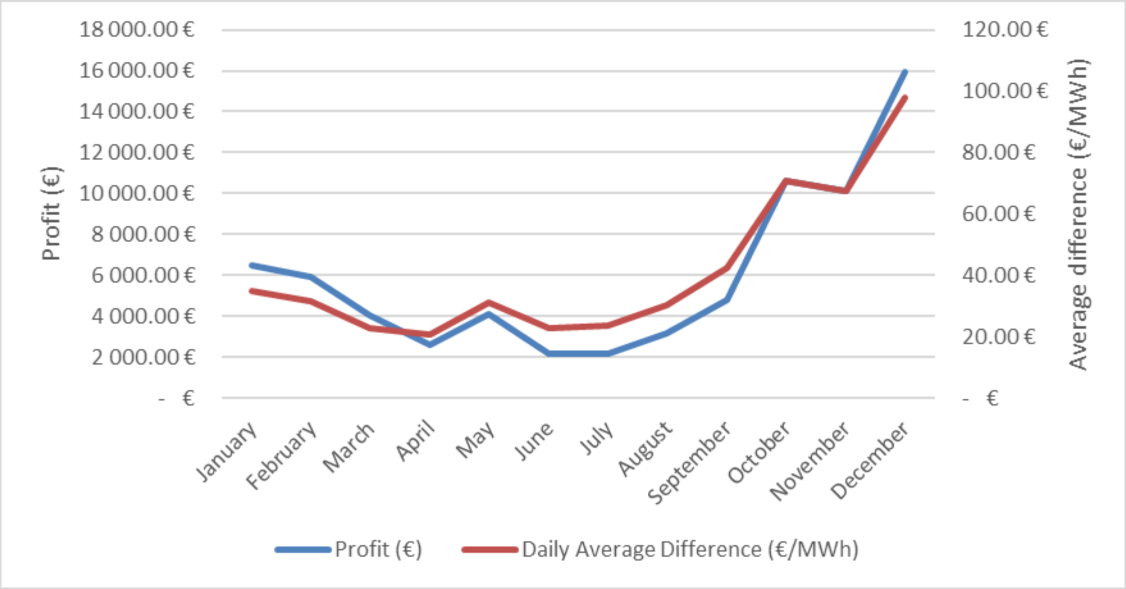


Figure 5.2 – Graph showing the monthly Profit and daily average difference in 2021.

The last performed analysis for this Case Study was to evaluate the impact of applying the linear approximation method to obtain new prices, considering the storage system as a Price Maker. Table 5.6 presents this storage system's revenue, cost, and profit as a Price Maker (PM) and a Price Taker (PT). Due to the small amount of energy necessary to charge the batteries, the impact on prices is small compared to the total amount of energy traded by the market. When considering the system as a PM, there is a reduction of the profit of **68.95 €** for the year 2021, which corresponds to a **0.1%** reduction against the PT case.

Table 5.6 – Revenue, Cost and Profit considering storage system as Price Maker (PM) or Price Taker (PT).

	PM	***PT***
Revenue	309 948.43 €	309 975.55 €
Cost	237 763.27 €	237 721.44 €
Profit	72 185.16 €	72 254.11 €

5.2 - Case Study 2

The parameters used for Case Study 2 are presented in Table 5.7. The difference from the previous case is using 100 MWh storage capacity instead of 10 MWh.

Table 5.7 - Parameters of Case Study 2

Year	2021
Minimum SPREAD	1
Number Hours Charging	4
Number Hours Discharging	4
Efficiency	89%
Total Capacity	100 MWh
Depth of Discharge	20%

Table 5.8 presents the average prices in €/MWh in the charging and discharging hours before and after the introduction of the effect of the batteries, as well as the percentage variation of the price.

Table 5.8 - Old and New prices in €/MWh for each month of the year 2021

	Charging hours			***Discharging hours***		
Month	***Old Price (€/MWh)***	***New Price (€/MWh)***	***% Variation***	***Old Price (€/MWh)***	***New Price (€/MWh)***	***% Variation***
January	43.25	43.36	0.26%	78.1	78.03	-0.10%
February	14.21	14.25	0.25%	45.85	45.78	-0.16%
March	36.3	36.42	0.33%	59.21	59.12	-0.16%
April	55.44	55.55	0.20%	75.98	75.88	-0.13%
May	49	49.12	0.25%	80.11	80	-0.14%
June	69.48	69.61	0.19%	92.42	92.33	-0.10%
July	78.21	78.35	0.18%	101.69	101.59	-0.10%
August	88.97	89.11	0.15%	119.27	119.17	-0.08%
September	132.39	132.54	0.12%	174.7	174.63	-0.04%
October	169.54	169.81	0.16%	240.38	240.17	-0.09%
November	161.87	162.16	0.18%	229.22	229.03	-0.08%
December	187.23	187.53	0.16%	285	284.83	-0.06%

Compared with Case Study 1 (Table 5.3), the prices show a more significant increase during the charging hours, while during the discharge hours, they show a more significant decrease. This effect was expected since more energy is purchased or sold each hour for Case Study 2.

Regarding the percentage variation, the same time pattern is observed in Case Study 1, with the first three months of the year displaying higher percentages of price increases during charging hours. The maximum price variation was **0.33%** in March, which is still a tiny difference from the original prices.

Table 5.9 presents the number of operation days, the average purchase and selling prices, and the average price difference. All price values are in €/MWh. In 2021, the batteries were operated for **322 days**, with an average purchase price of **92.45 €/MWh** for charging the batteries and **135.09 €/MWh** for selling the accumulated energy. This resulted in an average difference of **42.64 €/MWh**, slightly smaller than the one obtained for Case Study 1.

Table 5.9 – Number of operation days and average monthly price in €/MWh.

Month	***Num. Operation days***	***Purchase price* (€/MWh)**	***Selling price* (€/MWh)**	***Daily Average Difference* (€/MWh)**
January	31	43.36	78.03	34.67
February	28	14.25	45.78	31.53
March	31	36.42	59.12	22.70
April	27	55.55	75.88	20.33
May	23	49.12	80.00	30.88
June	21	69.61	92.33	22.72
July	22	78.35	101.59	23.24
August	23	89.11	119.17	30.06
September	26	132.54	174.63	42.09
October	30	169.81	240.17	70.36
November	30	162.16	229.03	66.87
December	30	187.53	284.83	97.30
Total	322	92.45	135.09	42.64

Table 5.10 shows the total cost, revenue, and profit obtained each month of the year with the operation of the batteries during the selected hours. In total, **3 097 042.73 €** would be spent to charge de batteries, while **2 381 406.36 €** would be obtained by selling the accumulated energy, resulting in a yearly profit of **715 636.37 €**.

Table 5.10 – Revenue, cost and profit obtained for Case Study 2.

Month	***Revenue***	***Cost***	***Profit***
January	172 222.63 €	107 523.49 €	64 699.14 €
February	91 260.89 €	31 910.56 €	59 350.33 €
March	130 478.69 €	90 317.52 €	40 161.17 €
April	145 865.81 €	119 990.83 €	25 874.98 €
May	131 000.42 €	90 384.58 €	40 615.84 €
June	138 047.23 €	116 950.81 €	21 096.42 €
July	159 130.99 €	137 891.29 €	21 239.70 €
August	195 147.46 €	163 962.01 €	31 185.45 €
September	323 280.24 €	275 689.35 €	47 590.89 €
October	512 999.32 €	407 543.32 €	105 456.00 €
November	489 217.85 €	389 178.99 €	100 038.86 €
December	608 391.20 €	450 063.61 €	158 327.59 €
Total	3 097 042.73 €	2 381 406.36 €	715 636.37 €

As in Case Study 1, one last analysis was performed to evaluate the impact of applying the linear approximation method to obtain new prices, this way considering the storage system as a Price Maker. Table 5.11 presents this storage system's revenue, cost, and profit as a Price Maker (PM) and Price Taker (PT). Given the relatively small amount of energy used to charge the batteries, the impact on prices is small compared to the total amount of energy commercialized by the market. When considering the system as a PM, there is a reduction of the profit of **6 904.78 €** for the year 2021, which corresponds to a **0.96%** reduction against the PT case. This reduction is higher than in Case Study 1 in absolute value and percentage.

Table 5.11 - Revenue, Cost and Profit for Case Study 2 considering storage system as Price Maker (PM) or Price Taker (PT).

	PM	***PT***
Revenue	3 097 042.73 €	3 099 755.55 €
Cost	2 381 406.36 €	2 377 214.40 €
Profit	715 636.37 €	722 541.15 €

To better visualize the effect of the price modification when more storage capacity is added, the results obtained using four different growing capacities are presented in Table 5.12. There it is possible to observe the effect of cannibalization when an excess of storage capacity is added to the system. When this happens, the prices for purchasing energy increase in the hours of charging and the prices for selling energy diminish in the hours of discharging the batteries. This effect must be considered when planning storage systems for an electricity grid.

Table 5.12 – Absolute difference and percentage of reduction in profit between the cases of Price Maker and Price Taker for different storage capacities.

Capacity	***Absolute difference***	***% reduction***
10 MWh	68.95 €	0.10%
100 MWh	6 904.78 €	0.96%
1000 MWh	690 567.27 €	9.56%
10000 MWh	69 057 626.89 €	95.58%

5.3 - Analysis 2017-2022

To assess how the results would vary throughout different years, the program was run for each year with data available on the OMIE website, which includes the years between 2017 and 2022. This was conducted using a storage configuration equal to the one in Case Study 2 (Table 5.7).

Figure 5.3 contains a graph showing the average price difference between each year's purchase and selling hours in analysis. Until 2020 this difference is slight, consistently below **17.05 €/MWh** observed in 2017. However, starting in 2021, there is an increase to more than double that value, reaching **49.53 €/MWh** in 2021 and **74.38 €/MWh** in 2022.

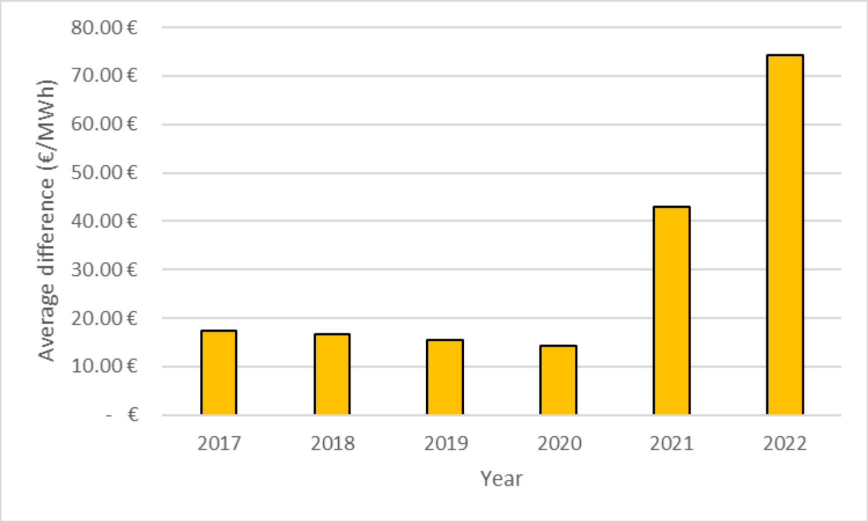


Figure 5.3 – Average daily difference for each year.

Two factors can explain this increase. The first is the price of natural gas, one of the primary fuels for electricity production that usually sets the market price in peak hours in the Iberian system, which are the preferable hours for selling the stored energy. As shown in Figure 5.4, until the middle of 2021, the prices of the TTF index were relatively stable, never going above 30 €/MWh. Starting in August 2021, the price sharply rises and maintains high values until the end of 2022, peaking in August 2022 at above 350 €/MWh [27].

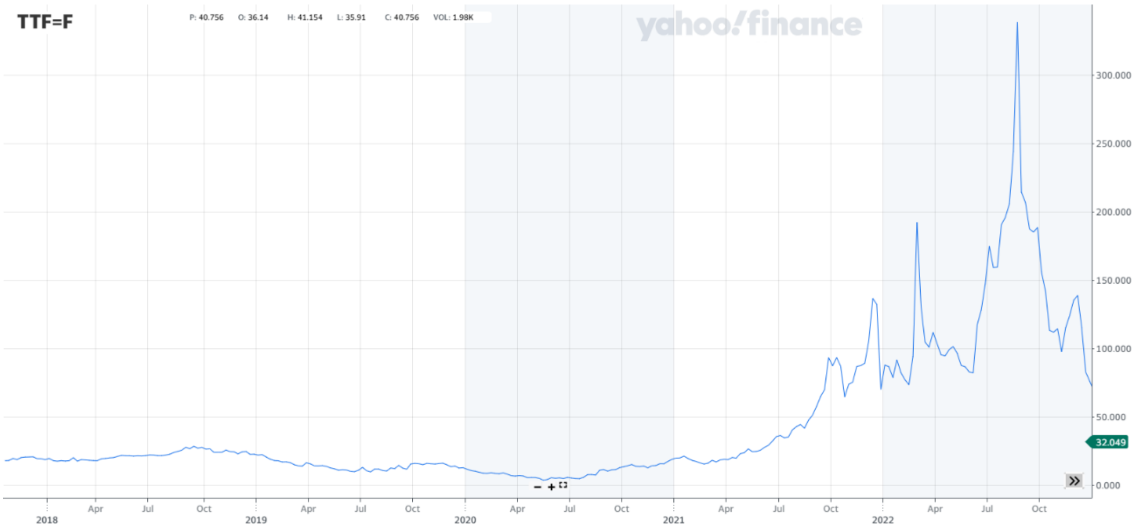


Figure 5.4 – Dutch TTF index evolution between 2017 and 2022 [27].

Another aspect that can explain the increasing difference in price between the purchasing and selling hours is the evolution of the electricity production sources that has been occurring in the Iberian power grid. The increase of installed capacity and power production of renewable power sources that have occurred as planned in the PNEC (Figure 2.6 and Figure 2.7), namely in solar and wind power, contribute to a lowering of the market prices during the hours of production from these renewable sources. This is especially relevant in solar power production, which generally reduces prices during peak production hours in the middle of the day.

Figure 5.5 represents the number of days it was profitable to operate the storage system each year. In this case, 2022 and 2020 are the years with more profitable days, **343** and **345**, respectively. This can be attributed to the integration of renewable power sources compared to previous years. However, other aspects connected to weather patterns can impact production. Periods with less wind, sunlight or periods of drought can impact renewable production during those periods, leading to smaller differences in prices throughout those days.

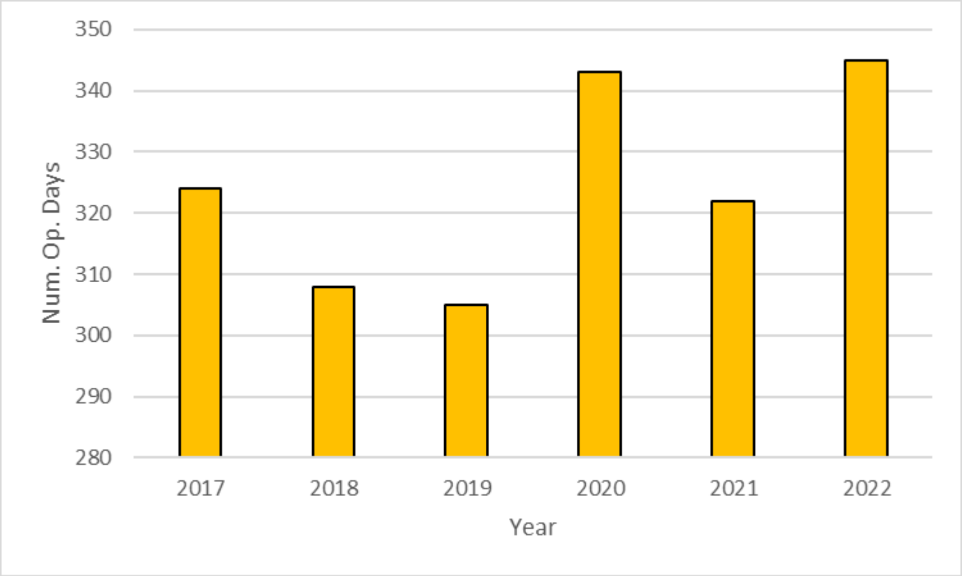


Figure 5.5 – Number of days of operation for each year.

The profits potentially obtained for each year are represented in Figure 5.6. This graph is similar to Figure 5.3, which is expected given the high correlation between the average daily difference and the potential profits, as explained in Chapter 5.1 - . The year 2022 presents the highest potential profits, at **1 403 925.27 €**, which is around double that of 2021, at **722 541.15 €**. In the years before these, the highest profit was in 2017 at **268 842.09 €**.

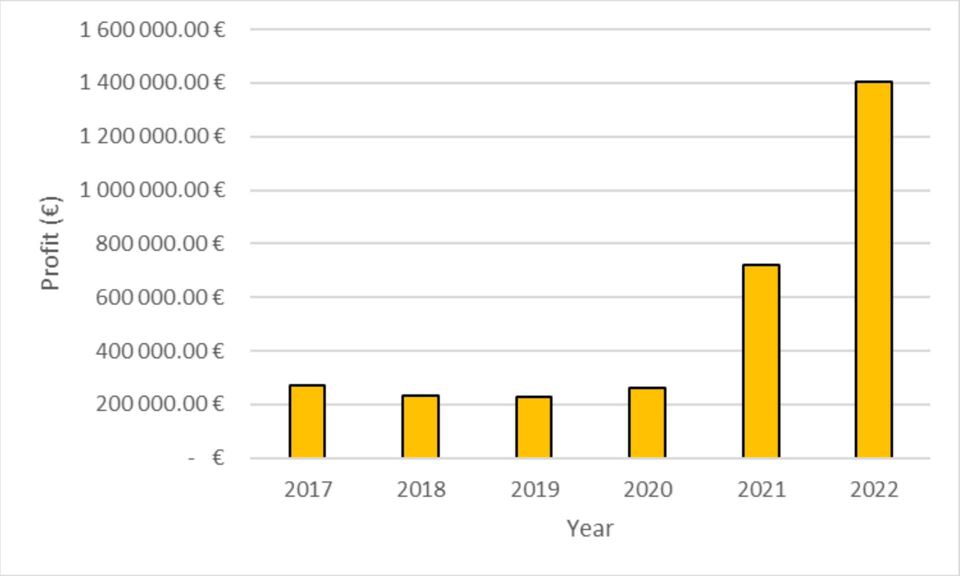


Figure 5.6 – Profits obtained for each year.

5.4 - Investment analysis

For an investment analysis of an energy storage system, the starting point is to obtain the project's Capital expenditure (CAPEX) and Operational expenditure (OPEX). Using the data contained in the report *Cost Projections for Utility-Scale Battery Storage: 2021 Update* compiled by the *National Renewable Energy Laboratory* (NREL), for the year 2025, the expected mid-scenario CAPEX for a 4-hour Li-ion storage system is 242 €/kWh. The OPEX is expected to be 1% of the CAPEX each year, which would mean 2.42 €/kWh each year [26].

The year selected for the start of operation was the beginning of 2025 to provide time to project and build the storage system.

The methodology applied to the investment evaluation is called Discounted Cash Flow (DCF), a valuation method that estimates the value of an investment using its expected future cash flows. DCF analysis attempts to determine the value of an investment today based on projections of how much money that investment will generate in the future [28], [29].

In a DCF analysis, an update rate must be defined to obtain the current value of future revenues. In the present context, the updated rate was the Weighted Average Cost of Capital (WACC) calculated using the expression (5-1).

$$WACC = K_e \times \frac{E}{E+D} + K_d \times \frac{D}{E+D} \times (1-T) \qquad \textbf{(5-1)}$$

Where:

- E - Own Capitals (Equity)
- D - Borrowed Capital (Debt)
- K_e - Cost of Equity
- K_d - Cost of Debt
- T - Tax on Profits (*Imposto sobre rendimento das Pessoas Coletivas - IRC*)

For the current analysis, the investment would be 50% equity and 50% debt. To obtain the cost of debt (K_d) expression (5-2) was used, where T is the current mean IRC (*Imposto sobre rendimento das Pessoas Coletivas*) rate of 21%, and k_d is the variable interest rate. For this value, it was selected the current savings certificate interest rate of 3.5%.

$$K_d = k_d \times (1-T) = 3.5\% \times (1-21\%) = 2.77\% \qquad \textbf{(5-2)}$$

To determine the cost of equity capital (K_e), it is assumed that the investor is risk-averse and, therefore, higher rates of return are required for higher levels of risk. Therefore, expression (5-4) is used, where R_f is the interest of a no-risk application (such as an interest rate of Portuguese public depth at 3 months - 3.5%), R_m is the expected market return that is obtained by adding R_f (3.5%) to the market risk premium of Portugal (3.29%), and β_l is the measure of systematic risk (the volatility) of the asset relative to the market and is calculated using expression (5-3), where β_u is the beta for Green and Renewable Energy industry, according to Damodaran and the New York University Beta Database - 0.84. Since this beta is less than 1, the asset is less volatile than the market [30].

$$\beta_l = \beta_u + \beta_u \times (1-T) \times \frac{E}{E+D} = 0.84 + 0.84 \times (1-3.5\%) \times \frac{50\%}{50\%+50\%} = 1.1718 \qquad \textbf{(5-3)}$$

$$K_e = R_f + (R_m - R_f) \times \beta_l = 3.5\% \times (6.79\% - 3.5\%) \times 1.1718 = 8.36\% \qquad \textbf{(5-4)}$$

Once all these intermediate values are calculated, the WACC can be obtained using expression (5-1), as shown in expression (5-5). The update rate used in this analysis was 5.27%.

$$WACC = 8.36\% \times \frac{50\%}{50\% + 50\%} + 2.77\% \times \frac{50\%}{50\% + 50\%} \times (1 - 3.5\%) = 5.27\% \qquad \textbf{(5-5)}$$

Besides the update rate, the other analysis that needs to be conducted is the Free Cash-flow of the project. This is the remaining value the company captures after paying all the expenses relative to the operational activity. A cash flow is calculated for each year of the project. The yearly cash flow is calculated following Table 5.13, where:

- EBITDA are the Earnings Before Interest, Taxes, Depreciation and Amortization
- EBIT is the Earnings Before Interest and Taxes
- The Profits are the expected profits from the storage system that were estimated by the developed Python program
- The operating costs are obtained from the yearly OPEX.
- The amortization is obtained by dividing the Investment cost by the number of years of the project
- The IRC is the *Imposto sobre rendimento das Pessoas Coletivas* (21%)
- The Fix Capital Investment is the CAPEX of the storage system.

Table 5.13 – Methodology for calculating the Free Cash-flow of the project.

EBITDA = Profits – Operating Costs
EBIT = EBITDA – Amortization
Theoretical Tax = IRC x EBIT
Operational Cash-flow = EBITDA – Theoretical Tax
Free Cash-flow = Operational Cash-flow - Fix Capital Investment

Once the Free Cash-flow of the project is obtained for each year, it is necessary to evaluate the project's profitability. This was done using the Net Present Value (NPV), a financial metric defined by the sum of all updated Free Cash-flows (FCF). NPV accounts for the time value of money and can be calculated using the expression (5-6).

$$NPV = \sum_{t=0}^{n} \frac{Free\ Cash\ flow_t}{(1+r)^t} \qquad \textbf{(5-6)}$$

Where:

- r - Update rate (WACC)
- t - period
- n - duration of the project in years

A project is profitable when the Net Present Value is positive at the reference discount rate. The net monetary flows generated by the implementation of the project make it possible to recover the capital invested and still leave a surplus that increases the investors' wealth.

The NPV is a criterion that meets the time value of money, valuing current cash flows more than future cash flows, and which assumes as an implicit hypothesis that the cash flows generated by the project are reinvested at the discount rate.

Another criterion that was used for the evaluation of the investment was the Rentability Index (RI), which was calculated using expression (5-7), where I_0 is the initial investment (initial cost of the project).

$$RI = \frac{\sum_{t=0}^{n} \frac{Free\ Cash\ Flow_t}{(1+r)^t}}{I_0} \qquad \textbf{(5-7)}$$

Suppose the Rentability Index is greater than 1. In that case, it indicates that the project is expected to be profitable, as the present value of the future cash flows exceeds the initial investment cost. A Rentability Index of less than 1 suggests that the project may not be profitable, as the present value of the future cash flows is less than the initial investment cost.

The described methodology was applied to both Case Studies to evaluate the financial feasibility of both storage system configurations considering two different profitability scenarios.

5.4.1 - Case Study 1

For Case Study 1, with a capacity of 10 MWh, considering a price of the Li-ion storage system of 242 €/kWh, the fixed investment cost will be 2 420 000 €, and the yearly operational costs 24 000 €. These operational costs need to be updated according to the annual inflation rate, which was considered as 2%.

The cash-flow analysis was conducted as described previously. The results for the investment year, the first two years of operation and the last two years are presented in Table 5.14. The complete table is presented in Annex E.1. In this scenario, it is considered that every year, the profits obtained by performing daily arbitrage are always the same as the ones obtained for this Case Study in 2021 (72 185.16 €).

Since the EBIT is negative yearly, there is no taxable profit, so the theoretical tax is always zero. The NPV was obtained by summing the discounted FCF of every year, resulting in **- 1 896 538.12 €**, which leads to the conclusion that the project is not viable in this scenario. Also, at this point, the Rentability Index is **19%**, which leads to the conclusion that at the final of the operation time of the storage system, only **19%** of the initial investment is recovered.

Table 5.14 – DCF for Case Study 1 using profits of 2021.

Year number	**0**	**1**	**2**	**...**	**15**	**16**
Year	2024	2025	2026	...	2039	2040
Price index		100	102	...	132	135
Profits		72 185.16 €	72 185.16 €	...	72 185.16 €	72 185.16 €
Adjusted Operating Costs		24 200.00 €	24 684.00 €	...	31 931.39 €	32 570.01 €
EBITDA		47 985.16 €	47 501.16 €	...	40 253.77 €	39 615.15 €
Amortization		151 250.00 €	151 250.00 €	...	151 250.00 €	151 250.00 €
EBIT		- 103 264.84 €	- 103 748.84 €	...	- 110 996.23 €	- 111 634.85 €
Theoretical Tax		- €	- €	...	- €	- €
Operational Cash-Flow		47 985.16 €	47 501.16 €	...	40 253.77 €	39 615.15 €
Fixed Capital Investment	2 420 000.00 €	- €	- €	...	- €	- €
Free Cash-flow (FCF)	- 2 420 000.00 €	47 985.16 €	47 501.16 €	...	40 253.77 €	39 615.15 €
Discount Factor	0.97	0.93	0.88	...	0.45	0.43
Discounted FCF	- 2 358 649.97 €	44 427.44 €	41 777.73 €	...	18 159.28 €	16 976.55 €
NPV	- 1 896 538.12 €					

Table 5.15 contains the same analysis but considers a more optimistic scenario, where the profits are higher (complete table in Annex E.2). These are the profits for 2022, which were **141 534.22 €** for this Case Study.

In this scenario, the NPV was reduced to **- 1 177 868.73 €**, and the Rentability Index increased to **44%**. The project is still considered not viable.

Table 5.15 - DCF for Case Study 1 using profits of 2022.

Year number	0	1	2	...	15	16
Year	2024	2025	2026	...	2039	2040
Price index		100	102	...	132	135
Profits		141 534.22 €	141 534.22 €	...	141 534.22 €	141 534.22 €
Adjusted Operating Costs		24 200.00 €	24 684.00 €	...	31 931.39 €	32 570.01 €
EBITDA		117 334.22 €	116 850.22 €	...	109 602.83 €	108 964.21 €
Amortization		151 250.00 €	151 250.00 €	...	151 250.00 €	151 250.00 €
EBIT		- 33 915.78 €	- 34 399.78 €	...	- 41 647.17 €	- 42 285.79 €
Theoretical Tax		- €	- €	...	- €	- €
Operational Cash-Flow		117 334.22 €	116 850.22 €	...	109 602.83 €	108 964.21 €
Fixed Capital Investment	2 420 000.00 €			...		
Free Cash-flow (FCF)	- 2 420 000.00 €	117 334.22 €	116 850.22 €	...	109 602.83 €	108 964.21 €
Discount Factor	0.97	0.93	0.88	...	0.45	0.43
Discounted FCF	- 2 358 649.97 €	108 634.83 €	102 770.91 €	...	49 444.02 €	46 695.19 €
NPV	- 1 177 868.73 €					

To observe the evolution of the Rentability Index through the years of activity and find the time frame that the system would need to obtain profit, Figure 5.7 presents this value for 40 years of activity, using the profits from both 2021 and 2022. It is possible to observe that in this time frame, the maximum Rentability Index is still **27%** for the profits from 2021 and **66%** for the profits from 2022.

It is also observable a reduction of the increase of the RI yearly. This is because the Operating Costs increase yearly due to inflation, while the discount factor is smaller yearly to reflect the time-value relation of money. For this investment to be viable, many more years would be necessary for the RI to be above 100%.

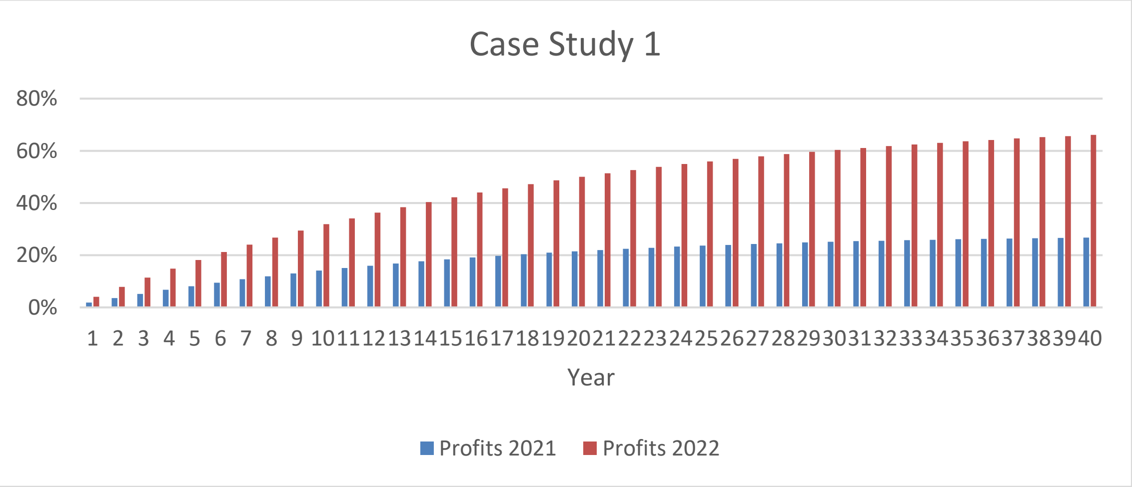


Figure 5.7 - Rentability Index (in %) for Case Study 1.

5.4.2 - Case Study 2

In Case Study 2, the proposed capacity for the storage system is 100 MWh, which translates to a fixed investment cost of 24 200 000 €, and a yearly operating cost of 242 000 €.

Table 5.16 contains the DCF analysis using the profits obtained for Case Study 1 for 2021 (complete table in Annex E.3). The NPV obtained was **- 18 958 235.34 €**, which translates into the projects not being financially viable**.** The RI for this case is **19%**.

Table 5.16 - DCF for Case Study 2 using profits of 2021.

Year number	0	1	2	...	15	16
Year	2024	2025	2026	...	2039	2040
Price index		100	102	...	132	135
Profits		722 541.15 €	722 541.15 €	...	722 541.15 €	722 541.15 €
Adjusted Operating Costs		242 000.00 €	246 840.00 €	...	319 313.86 €	325 700.14 €
EBITDA		480 541.15 €	475 701.15 €	...	403 227.29 €	396 841.01 €
Amortization		1 512 500.00 €	1 512 500.00 €	...	1 512 500.00 €	1 512 500.00 €
EBIT		-1 031 958.85 €	-1 036 798.85 €	...	- 1 109 272.71 €	- 1 115 658.99 €
Theoretical Tax		- €	- €	...	- €	- €
Operational Cash-Flow		480 541.15 €	475 701.15 €	...	403 227.29 €	396 841.01 €
Fixed Capital Investment	24 200 000.00 €			...		
Free Cash-flow (FCF)	-24 200 000.00 €	480 541.15 €	475 701.15 €	...	403 227.29 €	396 841.01 €
Discount Factor	0.97	0.93	0.88	...	0.45	0.43
Discounted FCF	-23 586 499.74 €	444 912.87 €	418 383.79 €	...	181 903.87 €	170 061.04 €
NPV	-18 958 235.34 €					

Using a more optimistic scenario, Table 5.17 presents the same Case Study but with the profits obtained for 2022. Although smaller, the NPV is still negative (**- 11 897 001.77 €**), and the RI is **44%**, so the project is not financially viable.

Table 5.17 - DCF for Case Study 2 using profits of 2022.

Year number	0	1	2	...	15	16
Year	2024	2025	2026	...	2039	2040
Price index		100	102	...	132	135
Profits		1 403 925.27 €	1 403 925.27 €	...	1 403 925.27 €	1 403 925.27 €
Adjusted Operating Costs		242 000.00 €	246 840.00 €	...	319 313.86 €	325 700.14 €
EBITDA		1 161 925.27 €	1 157 085.27 €	...	1 084 611.41 €	1 078 225.13 €
Amortization		1 512 500.00 €	1 512 500.00 €	...	1 512 500.00 €	1 512 500.00 €
EBIT		- 350 574.73 €	- 355 414.73 €	...	- 427 888.59 €	- 434 274.87 €
Theoretical Tax		- €	- €	...	- €	- €
Operational Cash-Flow		1 161 925.27 €	1 157 085.27 €	...	1 084 611.41 €	1 078 225.13 €
Fixed Capital Investment	24 200 000.00 €			...		
Free Cash-flow (FCF)	- 24 200 000.00 €	1 161 925.27 €	1 157 085.27 €	...	1 084 611.41 €	1 078 225.13 €
Discount Factor	0.97	0.93	0.88	...	0.45	0.43
Discounted FCF	- 23 586 499.74 €	1 075 777.82 €	1 017 667.76 €	...	489 289.84 €	462 059.32 €
NPV	- 11 897 001.77 €					

The evolution of the Rentability Index for 40 years of operation is presented in Figure 5.8. It again demonstrates that in both these scenarios, the investment is still not recovered in this time frame, being at **27%** for the Profits of 2021 and **65%** for the profits of 2022. These values are very similar to the ones obtained for Case Study 1.

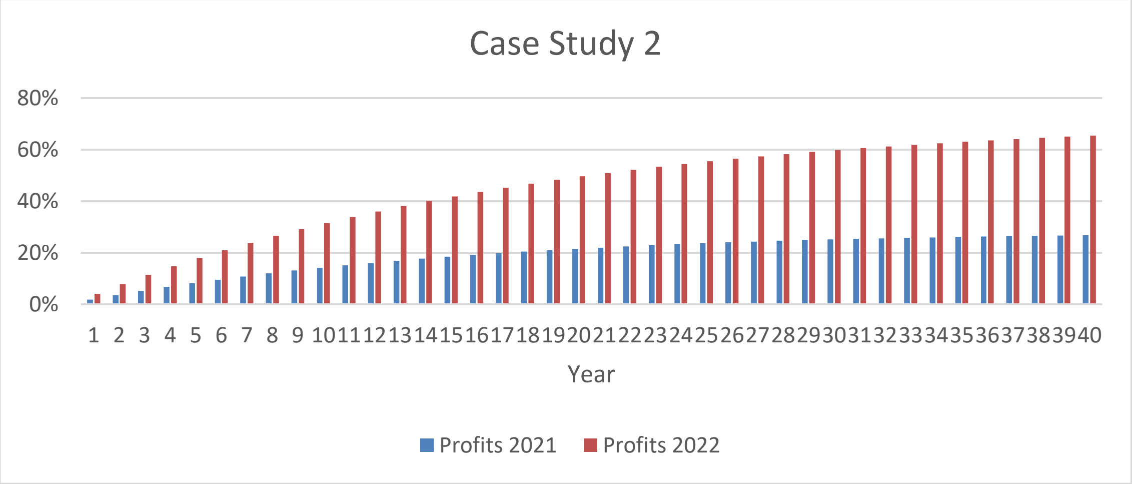


Figure 5.8 – Rentability Index (in %) for Case Study 2.

As previously stated, the difference in profits between 2021 and 2022 can be explained by the increase in the price of Natural Gas throughout 2022, which led to a surge in the selling prices and the average daily difference. This explains why the RI is much higher if the years for which the storage system will operate are closer to what is observed during 2022 than during 2021.

From the goals expressed in PNEC (Chapter 2.2 -), a significant increase in Photovoltaic capacity is foreseeable. This fact could lead to that during the sunny hours of the day, the price of electricity decreases, providing opportunities to fill the storage system with lower-cost energy, which could then be used at the end of the day when the photovoltaic production is down, the demand is higher, and the price of electricity is also higher.

Chapter 6

Final Considerations

6.1 - Conclusion

This dissertation aimed to evaluate the potential impacts of integrating storage systems for daily arbitrage in the Portuguese electrical grid and to assess the investment case for such systems. Through the Linear Approximation methodology, it was observed that the introduction of new purchase and selling bids in the MIBEL market had an impact on market prices during charging and discharging hours which was related to the capacity of the storage device. This methodology proved to be an effective tool for evaluating the impact of storage systems on the final market price in a balanced pool model.

The developed program allowed for customized analysis, considering different years and storage system characteristics. The results demonstrated that the average daily price difference between energy purchase and selling was crucial in determining potential profits from daily arbitrage. Recent years, like 2021 and 2022, exhibited higher profit potentials due to increased renewable energy production and rising natural gas prices during discharging hours. Additionally, the storage system's capacity influenced profits, as higher capacities resulted in cannibalization effects and reduced the average daily price difference.

However, the investment analysis of the case studies revealed that relying solely on Li-ion batteries for daily price arbitrage is currently not economically viable in the studied scenarios (profits from 2021 and profits from 2022). Alternative strategies, such as selling accumulated energy on the ancillary services markets, should be considered to complement or replace this use. Nevertheless, considering the expected growth of photovoltaic energy production in Portugal throughout the decade, the profitability of daily arbitrage could increase, especially when coupled with the anticipated reduction in Li-ion battery system CAPEX prices.

Furthermore, the lifetime of batteries emerged as a critical factor in the investment analysis. If the battery lifetime surpasses the expected break-even point, the associated project risk is reduced, and the system's feasibility is enhanced.

In summary, this research contributes to the understanding of integrating storage systems for daily arbitrage in the Portuguese electrical grid. While current economic viability is limited, future developments in renewable energy production and decreasing battery costs hold the potential for increased profitability. Further exploration of complementary strategies and continuous evaluation of market dynamics and technology advancements are recommended for future research.

6.2 - Future Projects

To further develop the work in this dissertation, one of the most relevant aspects would be to include the possibility of allowing more than one cycle of charging and discharging per day on days when it would be beneficial. Also, another optimization mechanism could be added by allowing the storage system to be charged in one day and discharged in the next. Both these options could increase the possible obtained profits for the year in the analysis.

In the investment analysis, one aspect that could be improved would be to implement a long-term price forecast mechanism to obtain the expected prices for the years of operation of the storage system. This could be done by considering the information in PNEC and its Spanish equivalent (PNIEC - *Plan Nacional Integrado de Energía y Clima*), which outline the expected changes in the electricity production system. By obtaining these prices, the expected profits could be calculated for each year and improve the cash-flow analysis, allowing a more informed decision on the viability of the investment.

The study's Depth of Discharge was set at 80%. However, an additional revenue stream can be explored by commercializing the remaining 20% of unused capacity on the ancillary services markets during hours when the storage device is neither charging nor discharging. This approach provides an opportunity to diversify revenue sources and further enhance the system's profitability. By leveraging the untapped potential of the storage system during idle periods, it becomes possible to maximize its value and optimize overall financial returns.

In addition to the economic analysis presented, conducting an environmental impact assessment is crucial to comprehensively evaluate the environmental implications of storage systems for daily arbitrage. This assessment would assess factors such as greenhouse gas emissions, resource consumption, and potential environmental impacts throughout the lifecycle of the storage device. Understanding these systems' environmental benefits and trade-offs is essential for informed decision-making and aligning with national goals and international commitments. By quantifying and analysing the environmental footprint of storage systems, policymakers can better assess their role in promoting sustainable energy practices and contribute to global efforts to mitigate climate change and achieve environmental targets. Such insights would be invaluable in shaping energy policies and regulations to foster a greener and more sustainable energy landscape.

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Annex A - Script for extracting data from the OMIE website.

```
import requests
from bs4 import BeautifulSoup

url = 'https://www.omie.es/pt/file-access-list?parents%5B0%5D=/&parents%5B1%5D=%20Mercado%20Di%C3%A1rio&parents%5B2%5D=3.%20Curvas&dir=Curvas%20de%20oferta%20e%20demanda%20agregadas%20do%20mercado%20di%C3%A1rio&realdir=curva_pbc'

response = requests.get(url)

soup = BeautifulSoup(response.content, 'html.parser')

# Find all links that start with "curva_pbc_2022"
links = soup.find_all('a', href=lambda href: href and href.startswith('/pt/file-download'))

# Download each file
for link in links:
    file_url = 'https://www.omie.es' + link['href']
    filename = link.text
    if filename.startswith('curva_pbc_2022'):
        file_content = requests.get(file_url).content
        with open(filename, 'wb') as f:
            f.write(file_content)
```

Annex B - Function to calculate new estimated price

```
def new_price(df: pd.DataFrame, modo: str, q_armazenada: float, efficiency:
float, ano: str):

    # Separate Purchase and sell bids
    agregado_oferta_compra = df.loc[df['Kind Bid'] == 'C', ['Quantity',
'Price']]
    agregado_oferta_venda = df.loc[df['Kind Bid'] == 'V', ['Quantity',
'Price']]

    # Order bids
    agregado_oferta_compra =
agregado_oferta_compra.sort_values(by=['Price'],
ascending=False).reset_index(drop=True)
    agregado_oferta_venda = agregado_oferta_venda.sort_values(by=['Price'],
ascending=True).reset_index(drop=True)

    # Cumulative quantity
    agregado_oferta_compra['C_Quantity'] =
agregado_oferta_compra['Quantity'].cumsum()
    agregado_oferta_venda['C_Quantity'] =
agregado_oferta_venda['Quantity'].cumsum()

    # Point C
    ponto_c = agregado_oferta_compra.iloc[-1]

    # Point A
    ponto_a = agregado_oferta_venda.loc[agregado_oferta_venda['Price'] == 0]

    # Point B
    ponto_b =
agregado_oferta_compra.loc[agregado_oferta_compra['Quantity'].idxmax()]

    # Get new points
    ponto_a_new = ponto_a.copy()
    ponto_b_new = ponto_b.copy()
    ponto_c_new = ponto_c.copy()

    if modo == 'C':
        if ponto_c['Price'] < 0.1:
            ponto_c_new['Price'] = 0
        else:
            # line AC
            mAC = (ponto_c['Price'] - ponto_a['Price']) /
(ponto_c['C_Quantity'] - ponto_a['C_Quantity'])
            bAC = ponto_c['Price'] - mAC * ponto_c['C_Quantity']
            # line BC
            mBC = (ponto_c['Price'] - ponto_b['Price']) /
(ponto_c['C_Quantity'] - ponto_b['C_Quantity'])
            # New point B
            ponto_b_new['C_Quantity'] = ponto_b_new['C_Quantity'] +
q_armazenada
            # line BnCn
            mBnCn = mBC
            bBnCn = ponto_b_new['Price'] - mBnCn * ponto_b_new['C_Quantity']
            # Interseption of BnCn and AC
            ponto_c_new['C_Quantity'] = (bAC - bBnCn) / (mBnCn - mAC)
            # find new price
            ponto_c_new['Price'] = mAC * ponto_c_new['C_Quantity'] + bAC

    if modo == 'D':
        # line AC
        mAC = (ponto_c['Price'] - ponto_a['Price']) / (ponto_c['C_Quantity']
- ponto_a['C_Quantity'])
        # line BC
        mBC = (ponto_c['Price'] - ponto_b['Price']) / (ponto_c['C_Quantity']
- ponto_b['C_Quantity'])
        bBC = ponto_c['Price'] - mBC * ponto_c['C_Quantity']
```

```
        # New point A
        ponto_a_new['C_Quantity'] = ponto_a_new['C_Quantity'] + q_armazenada
* efficiency
        # line AnCn
        mAnCn = mAC
        bAnCn = ponto_a_new['Price'] - mAnCn * ponto_a_new['C_Quantity']
        # Interseption of BnCn and AC
        ponto_c_new['C_Quantity'] = (bBC - bAnCn) / (mAnCn - mBC)
        # find new price
        ponto_c_new['Price'] = mBC * ponto_c_new['C_Quantity'] + bBC

    return ponto_c_new['Price']
```

Annex C - Script to obtain curves from OMIE data

```
ano = '2022'

# Define the directory where the .1 files are located
directory = f'Curvas/curva_pbc_{ano}/'

# Define the output CSV file name
output_file = f"Curvas/curvas_temp.csv"

# Define the headers for the output CSV file
headers = ["Hour", "Date", "Country", "Unit", "Kind Bid", "Quantity",
"Price", "Offered/Married"]

# Initialize the output CSV file
with open(output_file, "w", newline="") as csv_file:
    writer = csv.writer(csv_file, delimiter=",")
    writer.writerow(headers)

    # Loop through each .1 file in the directory
    for filename in os.listdir(directory):
        if filename.endswith(".1"):
            file_path = os.path.join(directory, filename)
            # Open the .1 file and read the data, skipping the first 3 lines
            with open(file_path, "r") as data_file:
                data = data_file.readlines()[3:]

            # Write the data to the output CSV file
            for line in data:
                row = line.strip().split(";")
                writer.writerow(row)

df = pd.read_csv('Curvas/curvas_temp.csv', delimiter=",", index_col=False)
print(df.dtypes)
df["Quantity"] = df["Quantity"].str.replace(".", "")
df["Quantity"] = df["Quantity"].str.replace(",", ".")
df["Quantity"] = pd.to_numeric(df["Quantity"])
df["Price"] = df["Price"].str.replace(".", "")
df["Price"] = df["Price"].str.replace(",", ".")
df["Price"] = pd.to_numeric(df["Price"])
df = df.drop('Unit', axis=1)
print(df)

df["Date"] = pd.to_datetime(df["Date"], format='%d/%m/%Y')
print(df.dtypes)

# Select only married offers
df_casadas = df.loc[df["Offered/Married"] == 'C']
df_casadas = df_casadas.drop("Offered/Married", axis=1)
print(df_casadas)

# Select only offers for MIBEL and Portugal
df_casadas_PT = df_casadas.loc[df_casadas["Country"].isin(['MI', 'PT'])]
print(df_casadas_PT)

df_casadas_PT.to_csv(f'Curvas/curvas_casadas_PT_{ano}.csv', index=False)
```

Annex D - Script main

```
import numpy as np
import pandas as pd
from new_price import new_price

# Year in analysis
ano = '2021'
# Control variables
spread_minimo = 1
# Number of hours charging
n_hours_ch = 4
# number of hours discharging
n_hours_dis = 4
# Efficiency of discharging (0 to 1)
efficiency = 0.89
# Total Energy Capacity (MWh)
capacity = 100
# Depth of discharge (0 to 1)
DoD = 0.8

# Energy stored in each hour (MWh)
q_armazenada = (capacity * DoD) / n_hours_ch

# create ExcelWriter object
writer = pd.ExcelWriter(f'Relatórios Anuais/{n_hours_ch}h
{capacity}MWh/Relatório {ano}.xlsx', engine='xlsxwriter')

df = pd.read_csv(f'Curvas/curvas_casadas_PT_{ano}.csv')

df["Date"] = pd.to_datetime(df["Date"])
print(df)
print(df.dtypes)

df_aggregate = df.groupby(['Hour', 'Date', 'Country', 'Kind Bid',
'Price'])['Quantity'].sum().reset_index()
print(df_aggregate)

eq_prices = df[df['Kind Bid'] == 'C'].groupby(['Hour',
'Date']).agg({'Price': 'min', 'Quantity': 'sum'}).reset_index()
eq_prices = eq_prices.sort_values(['Date', 'Hour'])
eq_prices_total = eq_prices.copy()
print(eq_prices)
# eq_prices_total.to_excel(f'Preços equilibrio_{ano}.xlsx',
index=False)

# Create columns with rolling averages
eq_prices['Rolling Charge'] =
eq_prices.groupby(['Date'])['Price'].rolling(window=n_hours_ch,
min_periods=n_hours_ch).mean().reset_index(level=0, drop=True)
eq_prices['Rolling Discharge'] =
eq_prices.groupby(['Date'])['Price'].rolling(window=n_hours_dis,
min_periods=n_hours_dis).mean().reset_index(level=0, drop=True)

# Perform shift
eq_prices['Rolling Charge'] = eq_prices.groupby('Date')['Rolling
Charge'].transform(lambda x: x.shift(-(n_hours_ch-1)))
eq_prices['Rolling Discharge'] = eq_prices.groupby('Date')['Rolling
Discharge'].transform(lambda x: x.shift(-(n_hours_dis - 1)))

# Invalidate final hours of the day
```

```
eq_prices.loc[eq_prices['Hour'] >= 24-(n_hours_ch - 2), 'Rolling Charge'] = np.nan
eq_prices.loc[eq_prices['Hour'] >= 24-(n_hours_dis - 2), 'Rolling Discharge'] = np.nan

# Invalidate initial hours of the day for discharging
eq_prices.loc[eq_prices['Hour'] <= n_hours_ch, 'Rolling Discharge'] = np.nan
eq_prices_excel = eq_prices.copy()
eq_prices_excel['Date'] = eq_prices_excel['Date'].dt.date
eq_prices_excel.to_excel(writer, sheet_name='Eq. Prices', index=False)

# Obtain discharge time for each day
discharge_time = eq_prices.groupby('Date')['Rolling Discharge'].agg(['idxmax', 'max']).reset_index()
discharge_time.columns = ['Date', 'Hour', 'Value']
discharge_time['Hour'] = eq_prices.loc[discharge_time['Hour'], 'Hour'].values

# Discharge can't start until charging is completed
eq_prices = pd.merge(eq_prices, discharge_time[['Date', 'Hour']], on='Date', how='left')
eq_prices = eq_prices.loc[eq_prices['Hour_x'] <= eq_prices['Hour_y']-n_hours_ch].drop(columns=['Hour_y'])
eq_prices = eq_prices.rename(columns={'Hour_x': 'Hour'}).drop_duplicates(subset=['Date', 'Hour'])

# Obtain charging time for each day
charging_time = eq_prices.groupby('Date')['Rolling Charge'].agg(['idxmin', 'min']).reset_index()
charging_time.columns = ['Date', 'Hour', 'Value']
charging_time['Hour'] = eq_prices.loc[charging_time['Hour'], 'Hour'].values

# Unite both tables, obtaining one where each line corresponds to a day, and shows the price for charging and discharging
operation_time = pd.merge(charging_time, discharge_time, on='Date', how='outer')
operation_time = operation_time[['Date', 'Hour_x', 'Value_x', 'Hour_y', 'Value_y']]
operation_time.columns = ['Date', 'Hour Charging', 'Value Charging', 'Hour Discharge', 'Value Discharge']
operation_time = operation_time.sort_values('Date')

# Obtain profit
operation_time['Profit (€/MW)'] = n_hours_dis * operation_time['Value Discharge'] * efficiency - n_hours_ch * operation_time['Value Charging']

# Obtain SPREAD
operation_time['SPREAD'] = (n_hours_dis * operation_time['Value Discharge'] * efficiency) / (n_hours_ch * operation_time['Value Charging'])
print(operation_time)

# Remove lines where SPREAD < min_SPREAD
chosen_times = operation_time.loc[operation_time['SPREAD'] > spread_minimo].drop(columns=['Profit (€/MW)', 'SPREAD'])
print(chosen_times)
```

```
chosen_times_charging = chosen_times.drop(columns=['Value Charging', 'Value Discharge', 'Hour Discharge']).reset_index(drop=True)
chosen_times_discharge = chosen_times.drop(columns=['Value Charging', 'Value Discharge', 'Hour Charging']).reset_index(drop=True)
print(chosen_times_charging)
print(chosen_times_discharge)

# Add all hours charging instead of only the first
rows_to_concat = []
for i, row in chosen_times_charging.iterrows():
    # Get the Hour Charging value
    hour_charging = row['Hour Charging']
    for j in range(1, n_hours_ch):
        new_row = {'Date': row['Date'], 'Hour Charging': hour_charging + j}
        rows_to_concat.append(new_row)
chosen_times_charging_extended = pd.concat([chosen_times_charging, pd.DataFrame(rows_to_concat)], ignore_index=True)
chosen_times_charging_extended = chosen_times_charging_extended.sort_values(['Date', 'Hour Charging']).reset_index(drop=True)
print(chosen_times_charging_extended)

# Add all hours discharging instead of only the first
rows_to_concat = []
for i, row in chosen_times_discharge.iterrows():
    # Get the Hour Charging value
    hour_discharge = row['Hour Discharge']
    for j in range(1, n_hours_dis):
        new_row = {'Date': row['Date'], 'Hour Discharge': hour_discharge + j}
        rows_to_concat.append(new_row)
chosen_times_discharge_extended = pd.concat([chosen_times_discharge, pd.DataFrame(rows_to_concat)], ignore_index=True)
chosen_times_discharge_extended = chosen_times_discharge_extended.sort_values(['Date', 'Hour Discharge']).reset_index(drop=True)
print(chosen_times_discharge_extended)

# New prices in charging hours
new_prices = []
for i, row in chosen_times_charging_extended.iterrows():
    # Extract the hour and day from the Date column
    hour = row['Hour Charging']
    date = row['Date']

    # Filter df_aggregate based on the hour and day
    filtered_data = df_aggregate[(df_aggregate['Date'] == date) & (df_aggregate['Hour'] == hour)]

    # Pass the filtered data to the new_price function to obtain the new price
    price = new_price(filtered_data, 'C', q_armazenada, efficiency, ano)

    # Append the new price to the list
    new_prices.append(price)

chosen_times_charging_extended['New Price'] = new_prices
```

```
chosen_times_charging_extended =
chosen_times_charging_extended.rename(columns={'Hour Charging':
'Hour'})
chosen_times_charging_extended['Old Price'] =
pd.merge(chosen_times_charging_extended, eq_prices_total[['Date',
'Hour', 'Price']], on=['Date', 'Hour'], how='left')['Price']
print(chosen_times_charging_extended)
# chosen_times_charging_extended.to_excel(f'Novos preços
Carregamento {ano}.xlsx', index=False)

# New prices in discharging hours
new_prices = []
for i, row in chosen_times_discharge_extended.iterrows():
    # Extract the hour and day from the Date column
    hour = row['Hour Discharge']
    date = row['Date']

    # Filter df_aggregate based on the hour and day
    filtered_data = df_aggregate[(df_aggregate['Date'] == date) &
(df_aggregate['Hour'] == hour)]

    # Pass the filtered data to the new_price function to obtain the
new price
    price = new_price(filtered_data, 'D', q_armazenada, efficiency,
ano)

    # Append the new price to the list
    new_prices.append(price)

chosen_times_discharge_extended['New Price'] = new_prices
chosen_times_discharge_extended =
chosen_times_discharge_extended.rename(columns={'Hour Discharge':
'Hour'})
chosen_times_discharge_extended['Old Price'] =
pd.merge(chosen_times_discharge_extended, eq_prices_total[['Date',
'Hour', 'Price']], on=['Date', 'Hour'], how='left')['Price']
print(chosen_times_discharge_extended)
# chosen_times_discharge_extended.to_excel(f'Novos preços
Descarregamento {ano}.xlsx', index=False)

# Num. Operation days
n_operation_days = chosen_times_discharge_extended.shape[0] /
n_hours_dis
print(f'Número de dias de operação: {round(n_operation_days,0)}\n')

# Obtain revenue
revenue = efficiency * q_armazenada *
chosen_times_discharge_extended['New Price'].sum()
print(f'Receita: {round(revenue, 2)} €\n')

# Obtain cost
cost = q_armazenada * chosen_times_charging_extended['New
Price'].sum()
print(f'Custo: {round(cost, 2)} €\n')

# Obtain profit
profit = revenue - cost
print(f'Lucro em {ano}: {round(profit,2)} €\n')

# Obtain SPREAD
spread = revenue / cost
```

```
print(f'SPREAD em {ano}: {round(spread,3)}\n')

# Obtain average difference
chosen_times['Dif'] = chosen_times['Value Discharge'] -
chosen_times['Value Charging']
dif_med = chosen_times['Dif'].mean()
print(f'Diferença média de preços: {round(dif_med,2)}')

# Add all hours to table
chosen_times_discharge_extended['Mode'] = 'Discharging'
chosen_times_charging_extended['Mode'] = 'Charging'
every_hour = pd.concat([chosen_times_charging_extended,
chosen_times_discharge_extended], axis=0).reset_index()
every_hour = every_hour.sort_values(['Date', 'Hour'])
eq_prices_total = eq_prices_total.rename(columns={'Price': 'Old
Price'})


# merge the two data frames based on the common columns 'Date' and
'Hour'
merged_df = eq_prices_total.merge(every_hour[['Date', 'Hour', 'New
Price', 'Mode']], on=['Date', 'Hour'], how='left')


merged_df['Price Variation (%)'] = round(((merged_df['New Price']-
merged_df['Old Price'])/merged_df['Old Price']) * 100, 2)
merged_df_excel = merged_df.copy()
merged_df_excel['New Price'] = round(merged_df_excel['New Price'],
2)
merged_df_excel['Date'] = merged_df_excel['Date'].dt.date
merged_df_excel.to_excel(writer, sheet_name='Hour Operation',
index=False)

# Obtain revenue if price taker
revenue_old = efficiency * q_armazenada *
chosen_times_discharge_extended['Old Price'].sum()

# Obtain cost if price taker
cost_old = q_armazenada * chosen_times_charging_extended['Old
Price'].sum()

# Obtain profit if price taker
profit_old = revenue_old - cost_old
print(f'Lucro em {ano} se PT: {round(profit_old,2)} €\n')

# Obtain SPREAD if price taker
spread_old = revenue_old / cost_old
print(f'SPREAD em {ano} se PT: {round(spread_old,3)}\n')

# Group by month
# set Date column as index
chosen_times_discharge_extended =
chosen_times_discharge_extended.set_index('Date')
chosen_times_charging_extended =
chosen_times_charging_extended.set_index('Date')

# group by month and calculate mean
discharge_monthly =
chosen_times_discharge_extended.resample('M').mean()
discharge_monthly_size =
chosen_times_discharge_extended.resample('M').size()
```

```
charging_monthly =
chosen_times_charging_extended.resample('M').mean()
charging_monthly_size =
chosen_times_charging_extended.resample('M').size()

# Change index to display month names
discharge_monthly.index = discharge_monthly.index.strftime('%B')
discharge_monthly_size.index =
discharge_monthly_size.index.strftime('%B')
charging_monthly.index = charging_monthly.index.strftime('%B')
charging_monthly_size.index =
charging_monthly_size.index.strftime('%B')

# Obtain number of days in activity
discharge_monthly['Num. Days'] = discharge_monthly_size/n_hours_dis
charging_monthly['Num. Days'] = charging_monthly_size/n_hours_ch

# Obtain variation
discharge_monthly['% Variation'] = ((discharge_monthly['New Price']-
discharge_monthly['Old Price'])/discharge_monthly['Old Price'])*100
charging_monthly['% Variation'] = ((charging_monthly['New Price']-
charging_monthly['Old Price'])/charging_monthly['Old Price'])*100

discharge_monthly = discharge_monthly.round(2)
discharge_monthly['Num. Days'] = discharge_monthly['Num.
Days'].astype(int)
charging_monthly = charging_monthly.round(2)
charging_monthly['Num. Days'] = charging_monthly['Num.
Days'].astype(int)

charging_monthly.to_excel(writer, sheet_name='Month Charging')
discharge_monthly.to_excel(writer, sheet_name='Month Discharging')
print(charging_monthly)
print(discharge_monthly)

# Create Analysis sheet
df_analysis_total = pd.DataFrame({
    'Year': [int(ano)],
    'Num. Operation days': [n_operation_days],
    'Revenue (€)': [round(revenue, 2)],
    'Cost (€)': [round(cost, 2)],
    'Profit (€)': [round(profit, 2)],
    'SPREAD': [round(spread, 2)],
    'Daily Average Difference (€)': [round(dif_med, 2)]
})
df_analysis_total = df_analysis_total.transpose()

df_analysis_total.to_excel(writer, sheet_name='Analysis - PM')

df_analysis_PT = pd.DataFrame({
    'Year': [int(ano)],
    'Num. Operation days': [n_operation_days],
    'Revenue (€)': [round(revenue_old, 2)],
    'Cost (€)': [round(cost_old, 2)],
    'Profit (€)': [round(profit_old, 2)],
    'SPREAD': [round(spread_old, 2)],
    'Daily Average Difference (€)': [round(dif_med, 2)]
})
df_analysis_PT = df_analysis_PT.transpose()

df_analysis_PT.to_excel(writer, sheet_name='Analysis - PT')
```

```
# Analysis by month
# group by month and calculate sum
monthly_analysis_discharge =
chosen_times_discharge_extended.resample('M').sum()
monthly_analysis_charging =
chosen_times_charging_extended.resample('M').sum()
chosen_times_analysis = chosen_times.set_index('Date')
monthly_analysis_diffmed =
chosen_times_analysis.resample('M').mean()

monthly_analysis_discharge.index =
monthly_analysis_discharge.index.strftime('%B')
monthly_analysis_charging.index =
monthly_analysis_charging.index.strftime('%B')
monthly_analysis_diffmed.index =
monthly_analysis_diffmed.index.strftime('%B')

monthly_analysis = pd.DataFrame()

monthly_analysis['Num. Operation days'] = discharge_monthly['Num.
Days']
monthly_analysis['Revenue (€)'] = round(efficiency * q_armazenada *
monthly_analysis_discharge['New Price'], 2)
monthly_analysis['Cost (€)'] = round(q_armazenada *
monthly_analysis_charging['New Price'], 2)
monthly_analysis['Profit (€)'] = monthly_analysis['Revenue (€)'] -
monthly_analysis['Cost (€)']
monthly_analysis['SPREAD'] = monthly_analysis['Revenue (€)'] /
monthly_analysis['Cost (€)']
monthly_analysis['SPREAD'] = round(monthly_analysis['SPREAD'], 2)
monthly_analysis['Daily Average Difference (€)'] =
round(monthly_analysis_diffmed['Dif'], 2)

monthly_analysis.to_excel(writer, sheet_name='Analysis Monthly -
PM')

monthly_analysis_PT = pd.DataFrame()

monthly_analysis_PT['Num. Operation days'] = discharge_monthly['Num.
Days']
monthly_analysis_PT['Revenue (€)'] = round(efficiency * q_armazenada
* monthly_analysis_discharge['Old Price'], 2)
monthly_analysis_PT['Cost (€)'] = round(q_armazenada *
monthly_analysis_charging['Old Price'], 2)
monthly_analysis_PT['Profit (€)'] = monthly_analysis_PT['Revenue
(€)'] - monthly_analysis_PT['Cost (€)']
monthly_analysis_PT['SPREAD'] = monthly_analysis_PT['Revenue (€)'] /
monthly_analysis_PT['Cost (€)']
monthly_analysis_PT['SPREAD'] = round(monthly_analysis_PT['SPREAD'],
2)
monthly_analysis_PT['Daily Average Difference (€)'] =
round(monthly_analysis_diffmed['Dif'], 2)

monthly_analysis_PT.to_excel(writer, sheet_name='Analysis Monthly -
PT')

writer.save()
```

Annex E

E.1 – DCF for Case Study 1 using a scenario with profits from 2021.

Year number	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Price index		100	102	104	106	108	110	113	115	117	120	122	124	127	129	132	135
Profits		72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €	72 185.16 €
Adjusted Operating Costs		24 200.00 €	24 684.00 €	25 177.68 €	25 681.23 €	26 194.86 €	26 718.76 €	27 253.13 €	27 798.19 €	28 354.16 €	28 921.24 €	29 499.66 €	30 089.66 €	30 691.45 €	31 305.28 €	31 931.39 €	32 570.01 €
EBITDA		47 985.16 €	47 501.16 €	47 007.48 €	46 503.93 €	45 990.30 €	45 466.40 €	44 932.03 €	44 386.97 €	43 831.00 €	43 263.92 €	42 685.50 €	42 095.50 €	41 493.71 €	40 879.88 €	40 253.77 €	39 615.15 €
Amortization		151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €
EBIT		- 103 264.84 €	- 103 748.84 €	- 104 242.52 €	- 104 746.07 €	- 105 259.70 €	- 105 783.60 €	- 106 317.97 €	- 106 863.03 €	- 107 419.00 €	- 107 986.08 €	- 108 564.50 €	- 109 154.50 €	- 109 756.29 €	- 110 370.12 €	- 110 996.23 €	- 111 634.85 €
Theoretical Tax		- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Operational Cash-Flow		47 985.16 €	47 501.16 €	47 007.48 €	46 503.93 €	45 990.30 €	45 466.40 €	44 932.03 €	44 386.97 €	43 831.00 €	43 263.92 €	42 685.50 €	42 095.50 €	41 493.71 €	40 879.88 €	40 253.77 €	39 615.15 €
Fixed Capital Investment	2 420 000.00 €																
Free Cash-Flow	- 2 420 000.00 €	47 985.16 €	47 501.16 €	47 007.48 €	46 503.93 €	45 990.30 €	45 466.40 €	44 932.03 €	44 386.97 €	43 831.00 €	43 263.92 €	42 685.50 €	42 095.50 €	41 493.71 €	40 879.88 €	40 253.77 €	39 615.15 €
Discount Factor	0.97	0.93	0.88	0.84	0.79	0.75	0.72	0.68	0.65	0.61	0.58	0.55	0.53	0.50	0.47	0.45	0.43
Discounted FCF	- 2 358 649.97 €	44 427.44 €	41 777.73 €	39 273.89 €	36 908.19 €	34 673.34 €	32 562.39 €	30 568.77 €	28 686.24 €	26 908.90 €	25 231.12 €	23 647.61 €	22 153.33 €	20 743.49 €	19 413.57 €	18 159.28 €	16 976.55 €
NPV	- 1 896 538.12 €																

E.2 - DCF for Case Study 1 using a scenario with profits from 2022.

Year number	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Price index		100	102	104	106	108	110	113	115	117	120	122	124	127	129	132	135
Profits		141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €	141 534.22 €
Adjusted Operating Costs		24 200.00 €	24 684.00 €	25 177.68 €	25 681.23 €	26 194.86 €	26 718.76 €	27 253.13 €	27 798.19 €	28 354.16 €	28 921.24 €	29 499.66 €	30 089.66 €	30 691.45 €	31 305.28 €	31 931.39 €	32 570.01 €
EBITDA		117 334.22 €	116 850.22 €	116 356.54 €	115 852.99 €	115 339.36 €	114 815.46 €	114 281.09 €	113 736.03 €	113 180.06 €	112 612.98 €	112 034.56 €	111 444.56 €	110 842.77 €	110 228.94 €	109 602.83 €	108 964.21 €
Amortization		151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €	151 250.00 €
EBIT		- 33 915.78 €	- 34 399.78 €	- 34 893.46 €	- 35 397.01 €	- 35 910.64 €	- 36 434.54 €	- 36 968.91 €	- 37 513.97 €	- 38 069.94 €	- 38 637.02 €	- 39 215.44 €	- 39 805.44 €	- 40 407.23 €	- 41 021.06 €	- 41 647.17 €	- 42 285.79 €
Theoretical Tax		- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Operational Cash-Flow		117 334.22 €	116 850.22 €	116 356.54 €	115 852.99 €	115 339.36 €	114 815.46 €	114 281.09 €	113 736.03 €	113 180.06 €	112 612.98 €	112 034.56 €	111 444.56 €	110 842.77 €	110 228.94 €	109 602.83 €	108 964.21 €
Fixed Capital Investment	2 420 000.00 €																
Free Cash-Flow	- 2 420 000.00 €	117 334.22 €	116 850.22 €	116 356.54 €	115 852.99 €	115 339.36 €	114 815.46 €	114 281.09 €	113 736.03 €	113 180.06 €	112 612.98 €	112 034.56 €	111 444.56 €	110 842.77 €	110 228.94 €	109 602.83 €	108 964.21 €
Discount Factor	0.97	0.93	0.88	0.84	0.79	0.75	0.72	0.68	0.65	0.61	0.58	0.55	0.53	0.50	0.47	0.45	0.43
Discounted FCF	- 2 358 649.97 €	108 634.83 €	102 770.91 €	97 213.75 €	91 947.60 €	86 957.49 €	82 229.20 €	77 749.27 €	73 504.90 €	69 483.93 €	65 674.86 €	62 066.75 €	58 649.21 €	55 412.39 €	52 346.95 €	49 444.02 €	46 695.19 €
NPV	- 1 177 868.73 €																

E.3 - DCF for Case Study 2 using a scenario with profits from 2021.

Year number	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Price index		100	102	104	106	108	110	113	115	117	120	122	124	127	129	132	135
Profits		722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €	722 541.15 €
Adjusted Operating Costs		242 000.00 €	246 840.00 €	251 776.80 €	256 812.34 €	261 948.58 €	267 187.55 €	272 531.31 €	277 981.93 €	283 541.57 €	289 212.40 €	294 996.65 €	300 896.58 €	306 914.51 €	313 052.80 €	319 313.86 €	325 700.14 €
EBITDA		480 541.15 €	475 701.15 €	470 764.35 €	465 728.81 €	460 592.57 €	455 353.60 €	450 009.84 €	444 559.22 €	438 999.58 €	433 328.75 €	427 544.50 €	421 644.57 €	415 626.64 €	409 488.35 €	403 227.29 €	396 841.01 €
Amortization		1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €
EBIT		- 1 031 958.85 €	- 1 036 798.85 €	- 1 041 735.65 €	- 1 046 771.19 €	- 1 051 907.43 €	- 1 057 146.40 €	- 1 062 490.16 €	- 1 067 940.78 €	- 1 073 500.42 €	- 1 079 171.25 €	- 1 084 955.50 €	- 1 090 855.43 €	- 1 096 873.36 €	- 1 103 011.65 €	- 1 109 272.71 €	- 1 115 658.99 €
Theoretical Tax		- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Operational Cash-Flow		480 541.15 €	475 701.15 €	470 764.35 €	465 728.81 €	460 592.57 €	455 353.60 €	450 009.84 €	444 559.22 €	438 999.58 €	433 328.75 €	427 544.50 €	421 644.57 €	415 626.64 €	409 488.35 €	403 227.29 €	396 841.01 €
Fixed Capital Investment	24 200 000.00 €																
Free Cash-Flow	- 24 200 000.00 €	480 541.15 €	475 701.15 €	470 764.35 €	465 728.81 €	460 592.57 €	455 353.60 €	450 009.84 €	444 559.22 €	438 999.58 €	433 328.75 €	427 544.50 €	421 644.57 €	415 626.64 €	409 488.35 €	403 227.29 €	396 841.01 €
Discount Factor	0.97	0.93	0.88	0.84	0.79	0.75	0.72	0.68	0.65	0.61	0.58	0.55	0.53	0.50	0.47	0.45	0.43
Discounted FCF	- 23 586 499.74 €	444 912.87 €	418 383.79 €	393 314.97 €	369 629.20 €	347 253.28 €	326 117.77 €	306 156.84 €	287 308.07 €	269 512.29 €	252 713.38 €	236 858.14 €	221 896.15 €	207 779.59 €	194 463.15 €	181 903.87 €	170 061.04 €
NPV	- 18 958 235.34 €																

E.4 – DCF for Case Study 2 using a scenario with profits from 2022.

Year number	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Price index		100	102	104	106	108	110	113	115	117	120	122	124	127	129	132	135
Profits		1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €	1 403 925.27 €
Adjusted Operating Costs		242 000.00 €	246 840.00 €	251 776.80 €	256 812.34 €	261 948.58 €	267 187.55 €	272 531.31 €	277 981.93 €	283 541.57 €	289 212.40 €	294 996.65 €	300 896.58 €	306 914.51 €	313 052.80 €	319 313.86 €	325 700.14 €
EBITDA		1 161 925.27 €	1 157 085.27 €	1 152 148.47 €	1 147 112.93 €	1 141 976.69 €	1 136 737.72 €	1 131 393.96 €	1 125 943.34 €	1 120 383.70 €	1 114 712.87 €	1 108 928.62 €	1 103 028.69 €	1 097 010.76 €	1 090 872.47 €	1 084 611.41 €	1 078 225.13 €
Amortization		1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €	1 512 500.00 €
EBIT		- 350 574.73 €	- 355 414.73 €	- 360 351.53 €	- 365 387.07 €	- 370 523.31 €	- 375 762.28 €	- 381 106.04 €	- 386 556.66 €	- 392 116.30 €	- 397 787.13 €	- 403 571.38 €	- 409 471.31 €	- 415 489.24 €	- 421 627.53 €	- 427 888.59 €	- 434 274.87 €
Theoretical Tax		- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €	- €
Operational Cash-Flow		1 161 925.27 €	1 157 085.27 €	1 152 148.47 €	1 147 112.93 €	1 141 976.69 €	1 136 737.72 €	1 131 393.96 €	1 125 943.34 €	1 120 383.70 €	1 114 712.87 €	1 108 928.62 €	1 103 028.69 €	1 097 010.76 €	1 090 872.47 €	1 084 611.41 €	1 078 225.13 €
Fixed Capital Investment	24 200 000.00 €																
Free Cash-Flow	- 24 200 000.00 €	1 161 925.27 €	1 157 085.27 €	1 152 148.47 €	1 147 112.93 €	1 141 976.69 €	1 136 737.72 €	1 131 393.96 €	1 125 943.34 €	1 120 383.70 €	1 114 712.87 €	1 108 928.62 €	1 103 028.69 €	1 097 010.76 €	1 090 872.47 €	1 084 611.41 €	1 078 225.13 €
Discount Factor	0.97	0.93	0.88	0.84	0.79	0.75	0.72	0.68	0.65	0.61	0.58	0.55	0.53	0.50	0.47	0.45	0.43
Discounted FCF	- 23 586 499.74 €	1 075 777.82 €	1 017 667.76 €	962 598.89 €	910 414.88 €	860 967.32 €	814 115.38 €	769 725.38 €	727 670.46 €	687 830.22 €	650 090.39 €	614 342.53 €	580 483.74 €	548 416.35 €	518 047.70 €	489 289.84 €	462 059.32 €
NPV	- 11 897 001.77 €																