Master's Thesis

EIT Innoenergy MSc. in Sustainable Energy Systems

Hybridization of Renewable Energy Systems with Battery Storage - A Techno-economic Optimization

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Abstract

The current energy landscape is one where renewables are finally in the right deployment stage to achieve the decarbonization of our energy systems and to limit climate change as per the current agreements. This is thanks to the learning rates of these technologies as well as policies in place. However, many projects now face regulation and permitting bottlenecks of several years plus uncertainties regarding wholesale market prices and possible curtailment. Hybrid Renewable Energy Systems (HRES) are seen as an alternative to these issues, as they can take advantage of regulations in place to bypass interconnection queues and can capture higher prices in the markets.

Throughout this work, a user-friendly optimization model is developed in collaboration with ODENRA, a Spanish project developer, to evaluate the profitability of hybridizing existing renewable power plants with battery energy storage systems (BESS), investigating the opportunity for energy arbitrage to maximize revenues while taking into account battery degradation. The model is implemented using Python and is then used in a case study for a representative 40MWp Solar PV plant in Spain, where it is found that hybridization is not profitable with the existing costs and revenue projections from arbitrage, so participation in other markets and new revenue mechanisms are needed to improve the business case of these projects and match them to the benefits provided to the system and consumers.

Resumen

Actualmente el sector energético se encuentra finalmente en la trayectoria correcta para decarbonizar los sistemas energéticos y limitar el cambio climático gracias al auge de las energías renovables. Se da este caso gracias a las curvas de aprendizaje de estas tecnologías, al igual que las políticas actuales. Sin embargo, varios proyectos se han encontrado con nuevos retos y cuellos de botella en lo que concierne a regulación y permisos de acceso a la red, al igual que riesgos por la volatilidad de precios en los mercados de electricidad y por congestiones en la red. Los sistemas híbridos de energías renovables son considerados como una alternativa para evitar los tiempos de espera en la obtención de permisos y para poder capturar mayores precios en los mercados.

A lo largo de esta tésis, un modelo de optimización amigable para el usuario es desarrollado en colaboración con ODENRA, empresa que desarrolla proyectos energéticos en España, con el objetivo de evaluar la rentabilidad de hibridar plantas de energía renovable con sistemas de almacenamiento de baterías, evaluando la oportunidad para realizar arbitraje de energía, maximizando los ingresos y considerando la degradación de las baterías. El modelo es implementado utilizando Python y es puesto a prueba con un caso de estudio de una planta solar fotovoltaica de 40MWp en España, donde el resultado no es favorable, al no ser rentable la hibridación considerando solo ingresos por arbitraje y con los costos actuales, por lo que son necesarios mecanismos de ingresos adicionales como la participación en otros mercados, para mejorar el caso de negocio de tal manera que sea una inversión atractiva para los inversores y no solo para el sistema y los consumidores.

Resum

Actualment el sector energètic es troba finalment en la trajectòria correcta para descarbonitzar els sistemes energètics i limitar el canvi climàtic gràcies a l'auge de les energies renovables. Es dona aquest cas gràcies a les corbes d'aprenentatge d'aquestes tecnologies, igual que les polítiques actuals. No obstant això, diversos projectes s'han trobat amb nous reptes i colls d'ampolla en el que concerneix regulació i permisos d'accés a la xarxa, igual que riscos per la volatilitat de preus en els mercats d'electricitat i per congestions en la xarxa. Els sistemes híbrids d'energies renovables són considerats com una alternativa per a evitar els temps d'espera en l'obtenció de permisos i per a poder capturar majors preus en els mercats.

Al llarg d'aquesta tesi, un model d'optimització amigable per a l'usuari és desenvolupat en col·laboració amb ODENRA, empresa que desenvolupa projectes energètics a Espanya, amb l'objectiu d'avaluar la rendibilitat d'hibridar plantes d'energia renovable amb sistemes d'emmagatzematge de bateries, avaluant l'oportunitat per a realitzar arbitratge d'energia, maximitzant els ingressos i considerant la degradació de les bateries. El model és implementat utilitzant Python i és posat a prova amb un cas d'estudi d'una planta solar fotovoltaica de 40MWp a Espanya, on el resultat no és favorable, al no ser rendible la hibridació considerant sol ingressos per arbitratge i amb els costos actuals, per la qual cosa són necessaris mecanismes d'ingressos addicionals com la participació en altres mercats, per a millorar el cas de negoci de tal manera que sigui una inversió atractiva per als inversors i no sols per al sistema i els consumidors.

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List of Abbreviations

BESS	Battery Energy Storage System
BNEF	Bloomberg New Energy Finance
CAGR	Compound Annual Growth Rate
CapEx	Capital Expenditures
DoD	Depth of Discharge
EPC	Engineering, Procurement and Construction
ESS	Energy Storage System
HRES	Hybrid Renewable Energy System
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LFP	Lithium Iron Phosphate
ML	Machine Learning
MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OpEx	Operating Expenditures
PPA	Power Purchase Agreement
RES	Renewable Energy System
SoC	State of Charge
SoE	State of Energy
SoH	State of Health

Chapter 1

Preface

The most important challenge of our generation is transitioning away from our fossil fuel based society into a sustainable system powered by renewables and other low emission sources. This challenge must be approached holistically, tackling issues in every sector of the economy, including: energy, industry, transportation, agriculture & information.

Renewable energy technologies, such as solar PV & wind are the clear way forward, as they do not pollute during their operation, and have achieved notable cost reductions during the last 20 years, with learning rates of 24% & 15%, as shown in Fig. 1.1. Detractors of this technologies often refer to the intermittency issue to downplay their role in the future energy system. That's where another core technology comes in, energy storage systems (ESS), as they enable the balancing of the variable behavior of renewable sources and distributed generation, the efficient supply of industrial and consumer loads, the electrification of transport, the development of near zero energy buildings and intelligent cities [1].

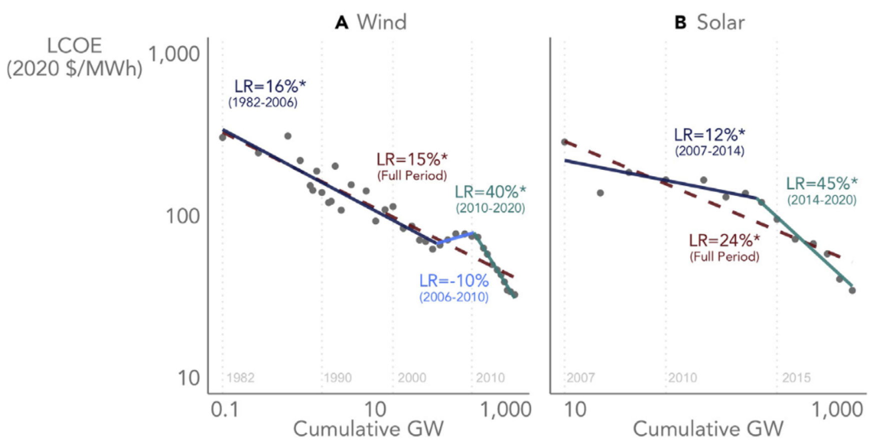

Figure 1.1: LCOE learning rate for solar & wind [2]

Based on how the energy is stored, the types of ESS include mechanical (compressed air, flywheel, pumped hydro), electrochemical (batteries), electromagnetic (capacitors), chemical (power to gas), and thermal. The current distribution by type is shown in Fig. 1.2. Each type has its own trade-offs to consider regarding costs, land, etc.

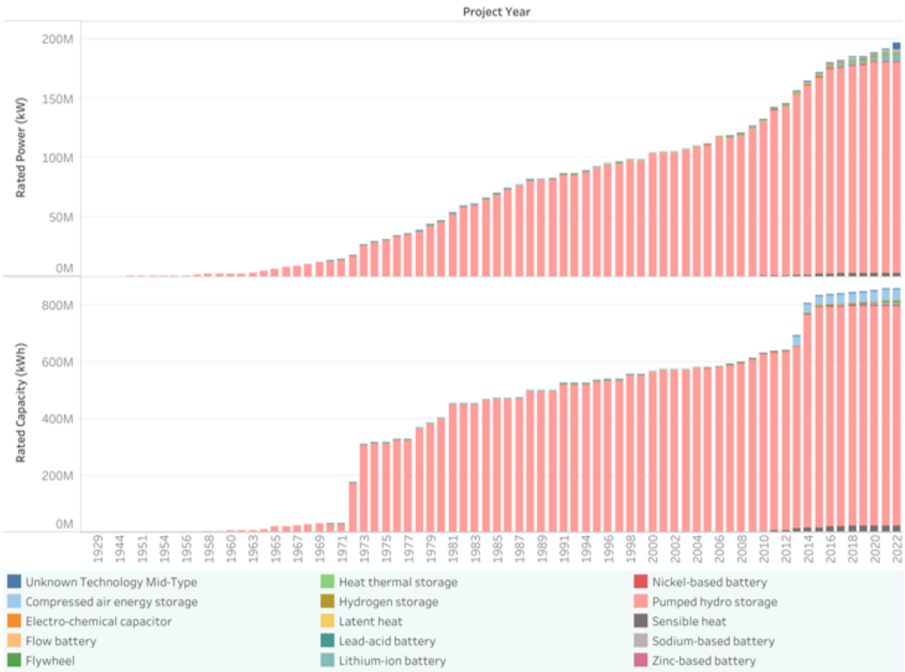

Figure 1.2: Cumulative ESS Deployment [3]

Today, the dominating type of storage is pumped hydro. However, Battery Energy Storage Systems (BESS) have gathered a lot of attention lately, thanks to their cost learning rate and services they can provide to the grid & consumers.

1.1 Motivation

The last few years, global energy markets have suffered disruptions, be it because of the COVID pandemic, extreme weather events, or war. This has translated to higher overall energy prices for consumers. The deployment of renewables and their negligible marginal cost has somewhat helped to alleviate those impacts, with 12% of global electricity now delivered by renewables [4]. However, current energy market designs also mean that as more renewables are deployed, the value captured by them decreases and additional complexity is added to the system. An example of this is the famous "duck curve" observed in the CAISO market, shown in Fig. 1.3, which requires fast ramping of dispatchable plants.

Different regulations have been proposed to deal with the additional complexity in the system, with the addition of storage seen as one of the most important solutions to deal with all the new renewables coming online.

Consequently, I decided for the topic of the present document to be on BESS, to investigate the value they provide and their economic feasibility on hybrid systems.

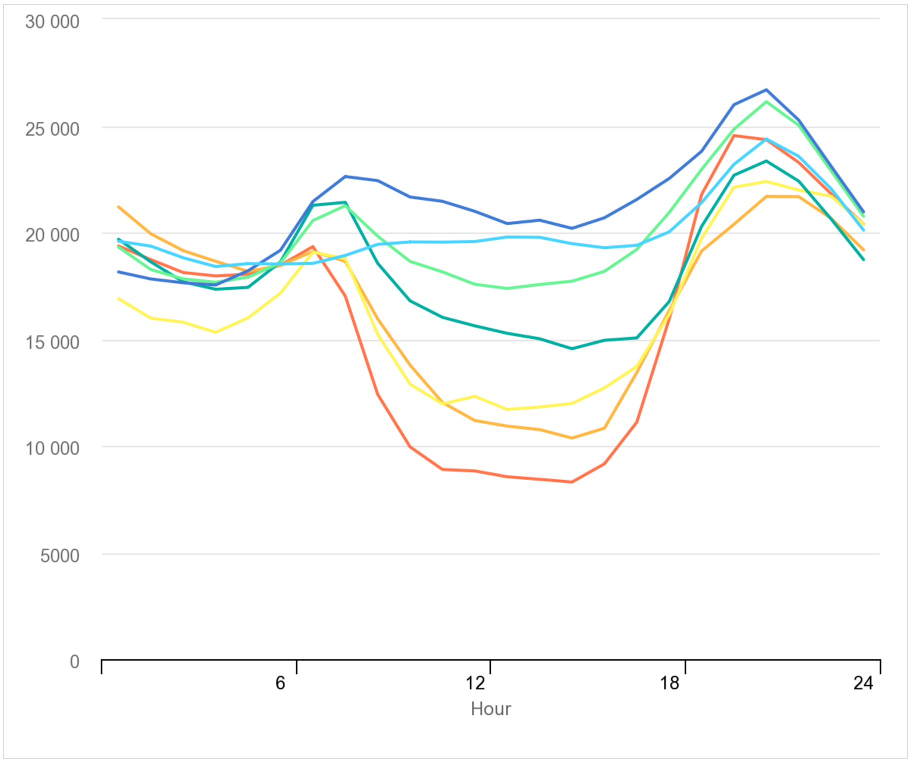

Figure 1.3: The California Duck Curve, net load (demand - renewable generation) [5]

1.2 Origin of the Project

The project is carried out in collaboration with ODENRA, as the Master Thesis for the EIT InnoEnergy MSc. in Sustainable Energy Systems.

Through an alumni of the MSc. program, I was approached by ODENRA, with the initial idea of modelling the economic feasibility of a hybrid PV plant with electrolyzers for H_2 production, which later was agreed to instead focus on hybrid PV/Wind + BESS modelling. The output of this project will allow the company to easily determine the profitability of adding BESS to existing PV/Wind installations.

ODENRA is a Spanish firm focused on the energy sector, including solar, wind, BESS & hydrogen. The services that it provides include renewables development, investment & advisory. Specifically they perform the following activities:

- Origination
- Business Intelligence
- Land Scouting
- Interconnection
- Development Services (Resource, Engineering, Permitting)
- Due Diligence

- Strategic Advisory (Technology choices, Contractual & Financial Structures)
- Power Purchase Agreements (PPAs) / Tenders / Auctions
- Engineering, Procurement and Construction (EPC)

They have developed more than 200 projects, equivalent to 10+ GW in 30 countries, with 20+ years of experience [6].

Chapter 2

Introduction

The present chapter first covers the main & specific objectives of the thesis, followed by its relevance to the literature and energy industry stakeholders. Next, the scope and research questions that guide the thesis are mentioned. Finally, an overview of the thesis chapters and structure is given.

2.1 Objectives

The aim of this thesis is to develop a tool that provides ODENRA with the necessary information on the possible profitability of hybridizing an existing RES with BESS, optimizing the size & operation schedule of the storage to perform energy arbitrage.

The specific objectives are:

- Review BESS role in the current and future energy system and its profitability.
- Research on the state of the art on HRES, their advantages and challenges.
- Develop a mathematical model that maximizes the return of the system, and translate the model to Pyomo (Python), providing a user friendly interface to input data and observe the results.
- Showcase a case study to assess the optimization tool developed.

2.2 Relevance

As mentioned in the preface, the deployment of solar and wind projects is now on an exponential scale, where their low cost and decarbonization policies are pushing them forward. However, this means that traditional utilities and system operators have to adapt the grid for the increasing penetration of renewables, and in many cases it is just not ready. There is congestion in the system and a lack of transmission, which means that many projects do not get the necessary permits and are left in the drawing board.

Different policies and regulations have been put in place to incentivize hybrid projects that make use of the existing points of connection, and can push forward projects that would have to wait years to get permits.

For project developers it is key to understand and assess the advantages and drawbacks of hybridizing existing installations with BESS. Thus, the thesis has a practical output that can provide value to stakeholders by creating a model that can calculate and optimize the size and operation of these installations.

2.3 Project Scope

The project gives an overview of several broad and complex topics such as energy markets, cannibalization, and valuation. These topics are framed within the research questions and the literature reviewed is focused on the practical aspects for the techno-economic optimization to be performed within the model developed.

The model considers certain design requirements and simplifications, regarding the constraints and uncertainties to be included, as requested by ODENRA:

- Perfect foresight of prices
- Perfect foresight of renewable resource
- Point of connection
- Cycles per year limit

2.4 Research Questions

The following questions are meant to serve as a guide for the literature review and the optimization model:

- What are the trade-offs of hybridizing a utility-scale RES?
- How to valuate storage? What are its possible revenue mechanisms?
- What are the implications of market price volatility for the economic assessment of projects?
- What is the impact of battery degradation for a BESS project business case?
- Is it viable to hybridize a plant based on arbitrage alone?

2.5 Thesis Structure

As for the structure of the thesis; the motivation & origin of the project were discussed in Chapter 1, while the objectives relevance and scope of the thesis have been explained in the current chapter.

The reader is then introduced to concepts regarding energy markets, hybridization, project valuation, renewables and storage in Chapter 3, concepts which are key for the model.

Next, the methodology carried to create the model is presented in Chapter 4, where the mathematical model developed, assumptions, software used and outputs are explained.

Afterwards, a case study is presented in Chapter 5 to show the output of the model for a PV plant in Spain, the results are discussed and a sensitivity analysis is performed.

A qualitative impact assessment for HRES projects is shown in Chapter 6, while the thesis planning and budget are explained in Chapter 7.

The final chapter gathers the conclusions and learning from the thesis.

Chapter 3

State of the Art

In this chapter the material that is needed to answer the research questions is covered. It is structured in four sections, first looking into the current situation and challenges in the electricity markets worldwide, next diving deep into BESS, afterwards looking into HRES projects, and finally covering energy projects valuation methods.

3.1 Energy Markets

3.1.1 Market Design

The general current energy market design (for most countries) follows a marginal pricing strategy, looking to maximize social welfare, where generators bid to provide a certain quantity of power at a certain price and are ranked from low to high price. On the demand side, industrial consumers and aggregators bid on the load that they need to match and are ranked from high to low price. The market operator then determines the clearing price and volume, which is where the ordered supply and demand curves meet, subject to technical restrictions from the TSO. The clearing price is the price that all generators will receive for each MW dispatched. Those bids that are below the clearing price are the ones that get dispatched, this is known as the merit order.

The bids are made based on each generator´s short-term marginal costs (fuel, labor, losses, etc), which in the case of renewables operating costs are almost negligible. Which means that as more renewables are deployed, the clearing price is reduced and generators with high short-term costs are pushed out [7]. This effect is illustrated in Fig. 3.1.

What was described before is scheduled in advance, as needed by the TSO to properly plan the necessities, in what is known as the Day-Ahead Market (DAM). In addition to the DAM, there are Intra-Day and Continuous Markets to balance out gaps in the forecasts made for both supply and demand. Lastly, Ancillary Markets exist to provide to ensure the reliability of the grid, through capacity and frequency regulation mechanisms.

In the case of Spain, the electricity market operator is OMIE, who is in charge of the Day-Ahead and Intra-day markets [8]. And Red Eléctrica is the TSO, in charge of the electricity system transmission, planning and operation [9].

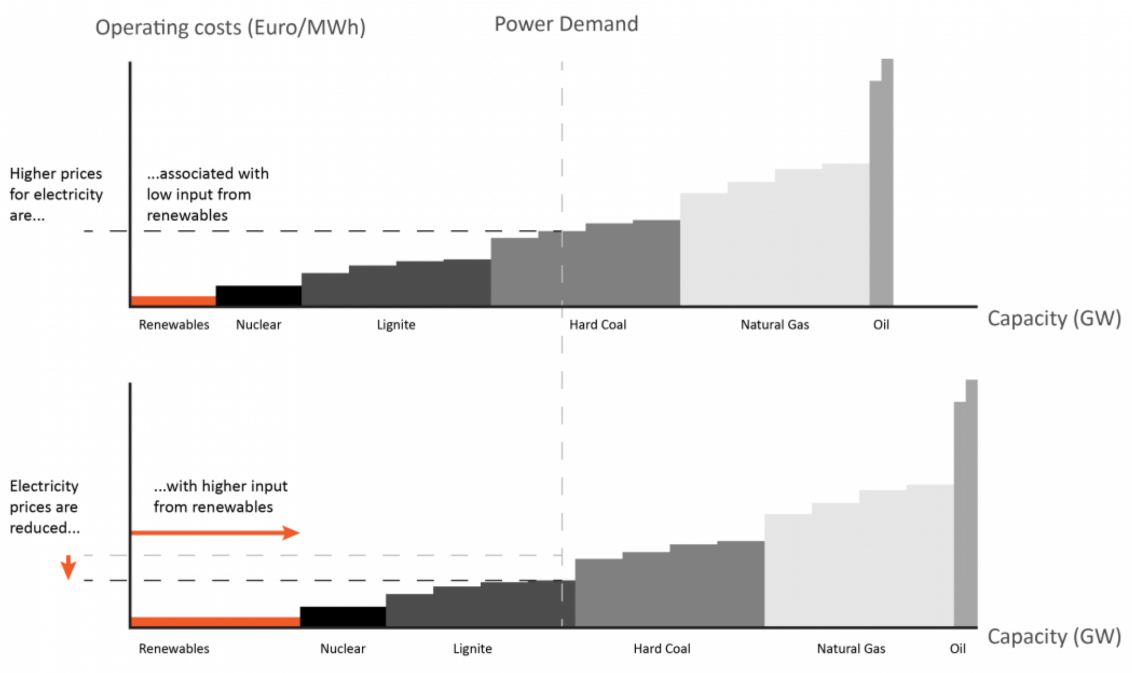

Figure 3.1: Merit order effect [7]

3.1.2 Renewables cannibalization

A key issue that energy markets face today is that of price volatility and renewables cannibalization, caused by the merit order effect explained in the previous section.

Fig. 3.2 shows the DAM prices for an example day during Spring in the Iberian Market, where prices were basically $0\frac{€}{MWh}$ for 8 hours. In this case, due to an oversupply of renewables seen that day.

So price risks become a problem for renewable projects that base their revenue mechanisms on the wholesale markets. It is specially the case for solar projects, that could end up having to pay in order to evacuate the energy they generated. This case mentioned corresponds to merchant projects, where other projects might chose to use PPAs to mitigate their risks.

The possible solutions to renewables cannibalization include:

1. Energy Storage
2. Grid Flexibility
3. Demand Response
4. Market Design

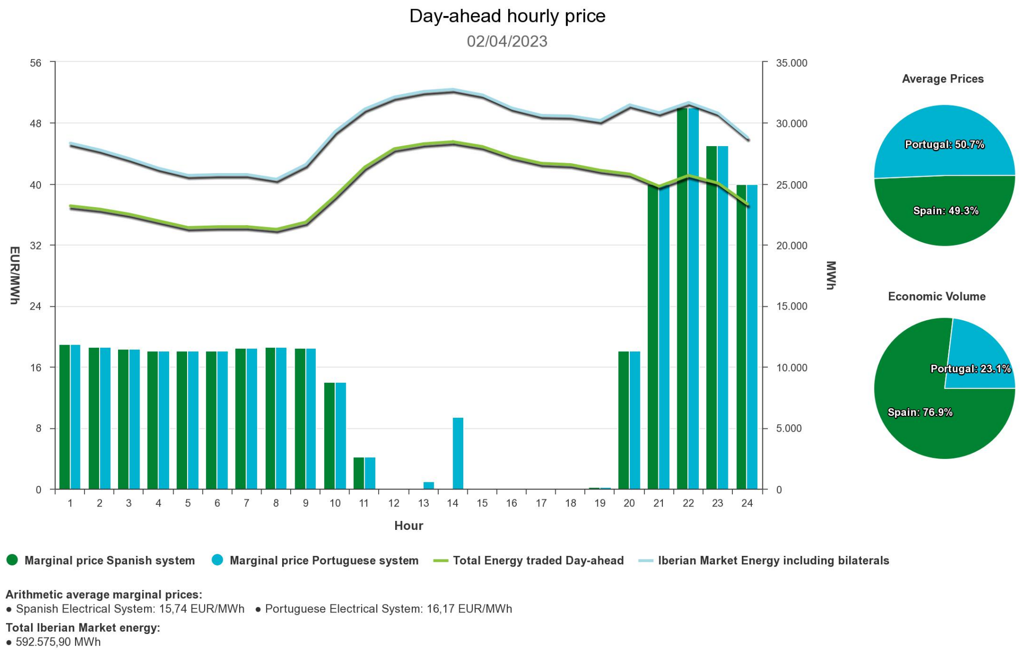

Figure 3.2: April 2, 2023 DAM prices for Spain & Portugal [8]

Hence, hybridization can be considered as a good risk hedging approach. By adding another type of generation or storage, the owners would get access to those higher prices, using different dispatching strategies. By adding storage such as BESS, the profitability of these assets can be improved.

3.2 Battery Energy Storage Systems

To correctly model the BESS optimization, it is necessary to delve into the revenue streams they can access by providing different services, together with the trends in CapEx and OpEx, plus the key parameters and challenges they face.

3.2.1 Services provided by storage

ESS have several applications in our current energy system, which can be classified by duration, which can range from seconds/minutes (power) to hours (energy) and, or by location, such as front of the meter (FTM) or behind the meter (BTM), or by purpose, with five categories that are described in Table 3.1.

Table 3.1: Services provided by ESS [10][11]

Application	Description
Bulk Energy Services	• Energy arbitrage: ESS can be used to buy electricity when prices are low and sell it when prices are high. • Renewable energy time-shift: ESS can move generation to peak hours, charging when energy generation is high and discharging during peak demand.
Ancillary Services	• Frequency regulation: ESS can charge or discharge to provide up/down regulation to help maintain the grid frequency. • Operating reserve: ESS can provide reserve capacity in the case of contingencies. • Frequency response and virtual inertia: ESS can help ensure minimize the imbalances between generation and load through frequency response services and emulated inertia. • Voltage support: ESS can provide voltage regulation by injecting reactive power to ensure that the voltage stays within limit. • Ramp support: where NG plants typically have to ramp up generation as solar production comes down, ESS could provide support to reduce the evening ramp needed • Black start and power system restoration: ESS can speed up the process of restoring the power system after a blackout thanks to their fast response time.
Transmission Services	• Transmission upgrade deferral: ESS can help in delaying transmission upgrades by through peak shaving, where the value of the deferral can provide a benefit compared to the upgrade cost. • Transmission congestion relief: ESS can be deployed in locations where the interconnections cannot provide the necessary energy during peak hours, or used to store curtailed energy from RES due to congested lines. • Stability damping control: ESS can provide damping for cases where specific generators present oscillations compared to other generators.
Distribution Services	• Peak shaving and upgrade deferral: ESS can help to ensure that distribution lines or transformers don´t exceed their rated capacity at peak hours. • Voltage regulation: as distributed generation increases, voltage issues arise in distribution networks. ESS can play a role regulating the voltage by injecting reactive power. • Resilience: ESS can play a role in reducing the both the time and impact of disruptive events such as natural disasters or extreme weather
End-user Services	• Time-of-use (TOU), demand charge and net-metering management: ESS provide flexibility for consumer to take advantage of TOU tariffs by shifting loads, by refucing peak demand charges and by selling energy back to the grid at higher prices. • Power quality: ESS provide protection of critical loads and mitigation of problems caused by harmonics and a low power factor

3.2.2 Revenue mechanisms

As mentioned in the previous section, BESS plants obtain revenues from different services. The U.K., which has deployed around 2.4 GW of BESS [12], serves as an example for projects to be deployed in the rest of Europe, where Fig. 3.3 shows how the plants' revenues distribution.

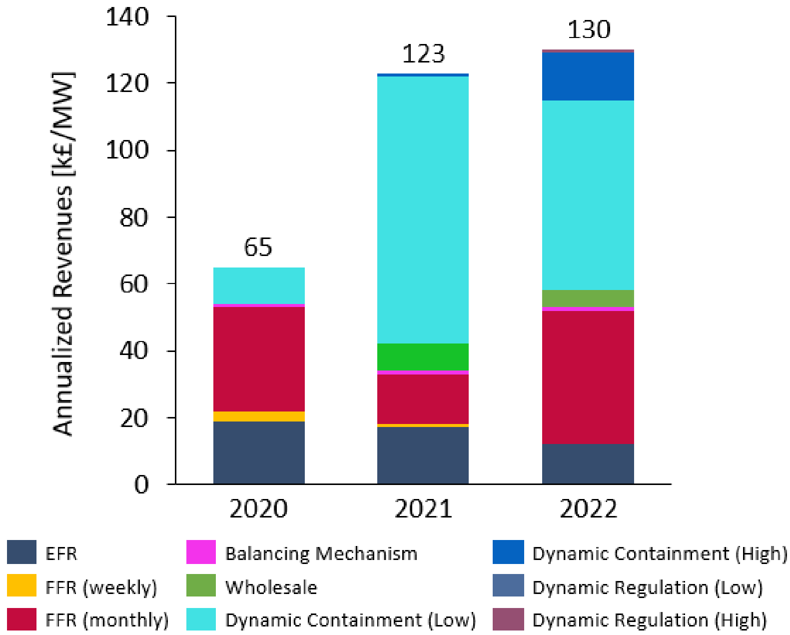

Figure 3.3: BESS Revenue Streams in the U.K. [13]

A BESS project can perform several of the mentioned grid services simultaneously in what is called value stacking. Given BESS current costs, stacking increases the prospects of a project being profitable, also considering that some of the grid services would only be needed for a few hours of scarcity or exceptional events. As the value provided depends on charging or discharging at the right time, this value stacking can then be formulated as an optimization problem [10].

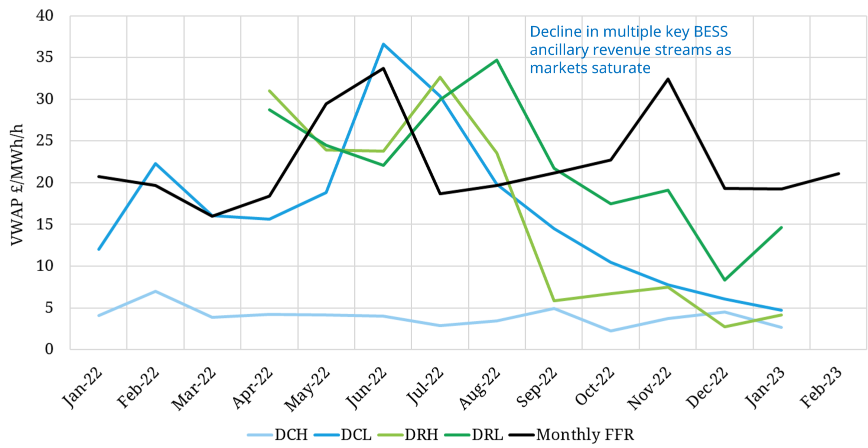

Figure 3.4: Ancillary services revenues in the U.K. [14]

Going back to the U.K example, Fig. 3.4 shows that participation in ancillary markets reaches a saturation point as there is now more capacity available than the one needed for capacity mechanisms, and leads to revenue cannibalization. Thus, assets are now pivoting towards arbitrage.

3.2.3 Costs

Battery technologies exhibit a similar behavior to that seen for wind and solar, thanks to learning rates as more of them are produced. Fig. 3.5 shows the cost reductions for lithium-ion cells and packs, with a CAGR of -16%. Prices rose in 2022 due to inflation and raw materials price increases, however, the expectation is that they will resume a downward trend to reach \$100/kWh by 2026, with increased adoption of LFP chemistry and new extraction and refining capacity coming online [15].

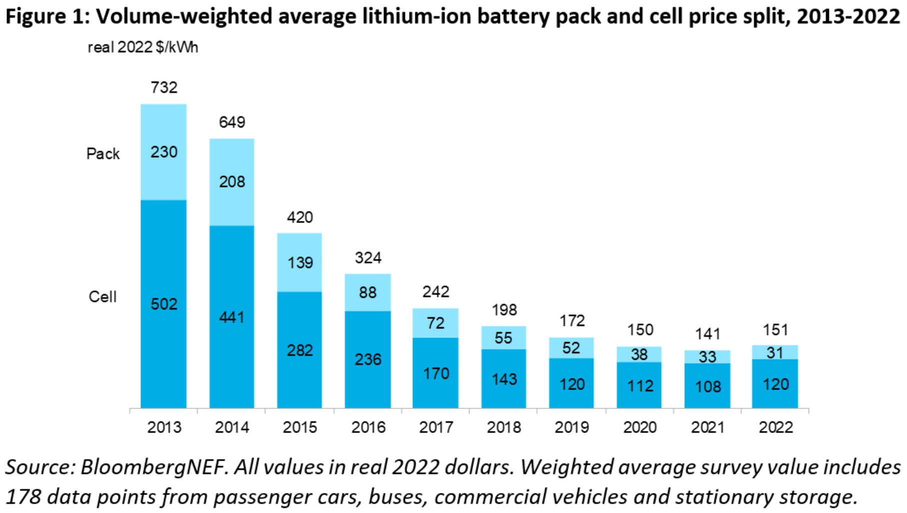

Figure 3.5: Lithium-ion batteries price [15]

Focusing specifically on utility-scale BESS costs, the National Renewable Energy Laboratory (NREL) publishes every year the Annual Technology Baseline (ATB), which provides cost and performance projections benchmarks for different generation technologies, using conservative, moderate & advanced scenarios [16].

Fig. 3.6 provides the CapEx projections that they NREL has modelled, where they estimate a reduction of 25-40% from 2030 to 2050. Included in the CapEx is [16]:

- Balance of System (BOS)
- Electrical Infrastructure & Interconnection (Power electronics, inverters, cabling, transformers, EMS, communications)
- Generation Equipment & Infrastructure (Battery packs and containers; battery, thermal, and fire suppression management systems; foundations, housing; construction)
- Installation (Labor, engineering, commissioning)
- Owner´s Costs (Development, studies, permitting, insurance, legal fees)

Regarding OpEx, NREL estimates it to be 2.5% per year of the CapEx cost, and it includes insurance, payments, taxes, maintenance , & the annualized augmentation costs (to recover the capacity lost to degradation) [17].

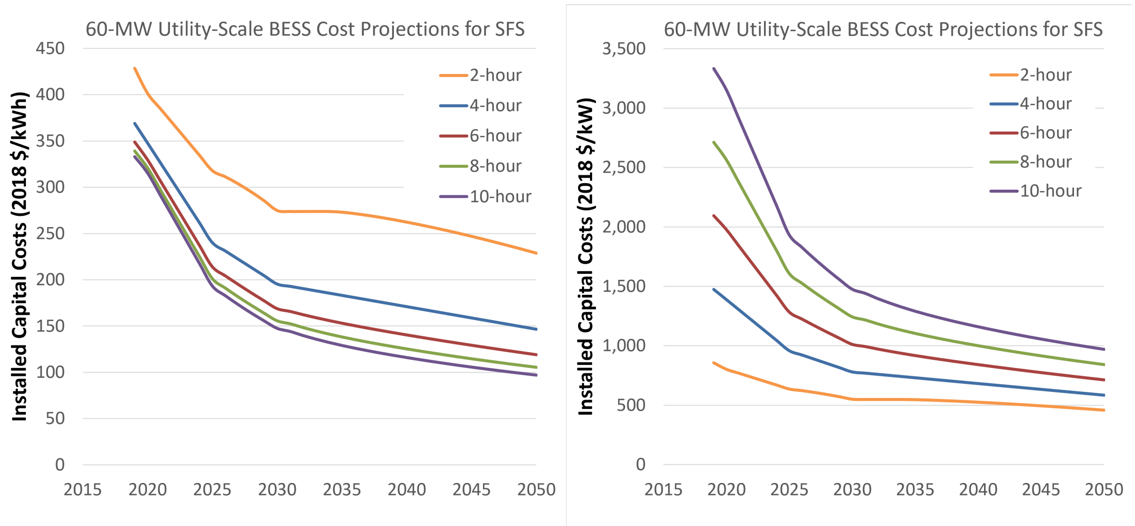

Figure 3.6: Utility-scale BESS Moderate Scenario cost projections, on a $US/kWh basis (left) and a $US/kW basis (right) [17]

3.2.4 Market Outlook

As for the growth expectations for BESS, IEA´s Net Zero Scenario (NZE) forecasts a need for 680GW of storage capacity by 2030, in order to meet flexibility needs in the future decarbonized system [18]. That translates to a required CAGR of 52% (considering 37GW deployed by the end of 2023), for which we are currently not on track. BNEF and GlobalData forecast 411GW & 354GW respectively [19]. These forecasts are shown in Fig. 3.7, while Fig. 3.8 shows the outlook by country, with the US and China clearly in a leading position.

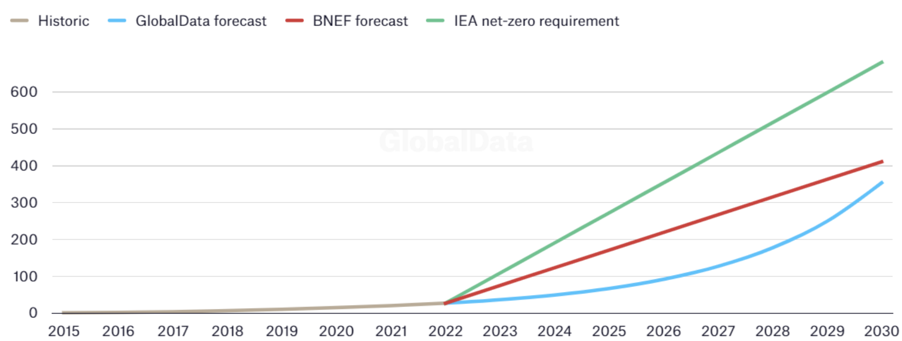

Figure 3.7: Different forecasts for grid-scale battery growth versus IEA net zero 2050 pathway requirement (GW) [19]

3.2.5 Key Parameters

Utility-scale BESS projects are typically described by both power and energy capacity, where the power part refers to the maximum charging or discharging at any time, that is

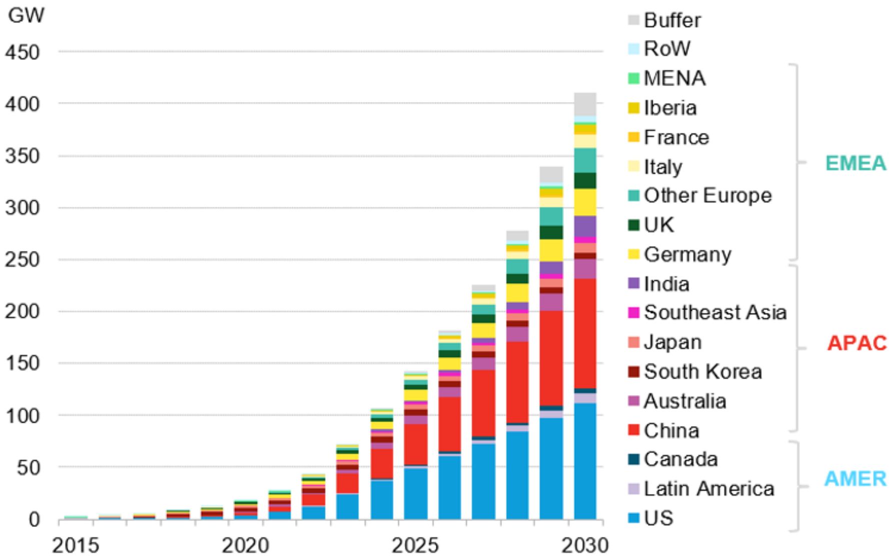

Figure 3.8: Global cumulative BESS installations, 2015-2030 [20]

the nameplate capacity. While the energy part refers to the actual storage capacity in the facility. For example, a facility would be described as 50MW/100MWh, or 50MW with a storage duration of 2 hours, where storage duration refers to the amount of hours at which the system can discharge at its full rated capacity. Other key parameters to consider when modelling a BESS include [21]:

- Cycle life: a cycle refers to the process of charging and discharging the battery, where it is not always fully charge/discharged. Batteries are typically rated to provide a certain number of cycles depending on the depth of discharge.
- Depth of Discharge (DoD): it refers to how deeply the battery is discharged, and it will vary depending on the battery chemistry.
- Roundtrip efficiency (RTE): it is the ratio between the energy provided to the battery and the energy delivered by the battery, expressed as a percentage, accounting for the losses.
- Roundtrip efficiency (RTE): it is the ratio between the energy provided to the battery and the energy delivered by the battery, expressed as a percentage, giving a sense of the losses.
- Self discharge: it refers to losses when batteries are not being discharged due to chemical reactions, it is expressed as a percentage, and varies based on the battery chemistry.
- State of charge (SoC): it refers to the available energy in the battery compared to the storage capacity, expressed as a percentage.

Table 3.2 gives an overview of the typical values for the parameters previously described for two battery chemistries: Lithium Iron Phosphate (LFP) & Nickel Manganese Cobalt (NMC).

Table 3.2: BESS performance parameters for different battery technologies, based on [22]

Parameter	Units	Technology	
		LFP	NMC
Round-trip efficiency	%	98	95
Self-discharge	%/day	0.02	0.02
DoD	%	90	90
Calendar life	years	12-20	13
Cycle life	cycles	6,000-10,000	4,500

3.2.6 Degradation

Electrochemical batteries suffer from degradation that is caused by parasitic reactions at the electrodes. This aging is divided into two types, the first one related to the useful life of the battery, known as calendar aging; and the second one related to the stress that occurs inside the battery during the charging and discharging processes, known as cycle aging. These aging mechanisms are independent and additive, where cyclic aging is mostly linear up to 60 to 80% of the original capacity [23].

The parameters that have an effect on the degradation mechanism of a battery and that can be controlled to reduce the aging process are the following: DoD, circulated current, cell ambient temperature and SoC. To keep track of said degradation, the State of Health (SoH) indicator is used to compare the current capacity with the nameplate capacity.

$$SoH = \frac{S_{actual}}{S_{rated}} \tag{3.1}$$

Different attempts to include the degradation in BESS operation optimization models have been considered in the literature, as shown in Fig. 3.9.

A constraint based approach uses inequalities or equalities to limit the search space by restricting the DoD or the energy throughput, ensuring reduced degradation in the optimal solution.

The cost of use approach introduces a degradation cost into the objective function of the optimization, which will look for solutions where the revenues are higher than the degradation cost. The cost can be related to the amortization of the investment, a battery replacement, an arbitrary number, or a changing cost throughout its lifetime.

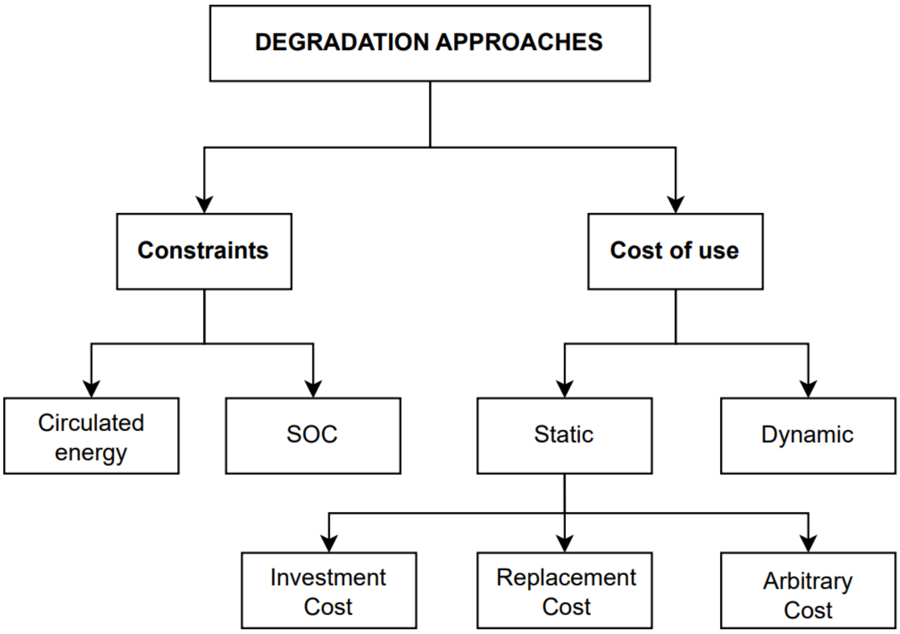

Figure 3.9: Possible options to model battery degradation [24]

3.3 Hybridization

A utility-scale HRES combines multiple types of renewable generation and/or storage with the objective of capturing more value in the markets or of sharing costs. These benefits for generators and the grid are detailed in Table 3.3.

There are several possible combinations that include VRES (solar, wind, run of river hydro), RES (geothermal, reservoir hydro), ESS (batteries, ultracapacitors, thermal) with different complementary behaviors. Due to all these possible combinations that these systems entail, it is a good practice to have a taxonomy to properly categorize them.

3.3.1 Taxonomy

In [26], three categories are proposed to differentiate HRES, as shown in Fig. 3.10, based on locational and operational linkages, and the benefits they provide:

- Co-located Resources: lower costs thanks to shared BOS and interconnection costs.
- Virtual Power Plants: additional revenues from coordinated operation of resources sited at their optimal location.
- Full Hybrids: additional benefits from the co-optimization of the technologies involved plus the use of shared components.

This taxonomy is put into practice in Fig. 3.11, where a PV+BESS project can fall into two categories, as each technology can optimize its own generation independently while just sharing an interconnection, or they can be co-optimized to yield a higher benefit.

Table 3.3: HRES Advantages [25]

Stakeholder	Advantages
Generators	• Dispatch capacity optimization • Savings in CapEx & OpEx thanks to installation and operation synergies • Savings in cost & time from permitting simplifications
System	• Lower environmental impact • Lower grid costs • Better supply quality and stability • Lower risk of overload and technical restrictions in the grid • Lower amount of access and connection points requests

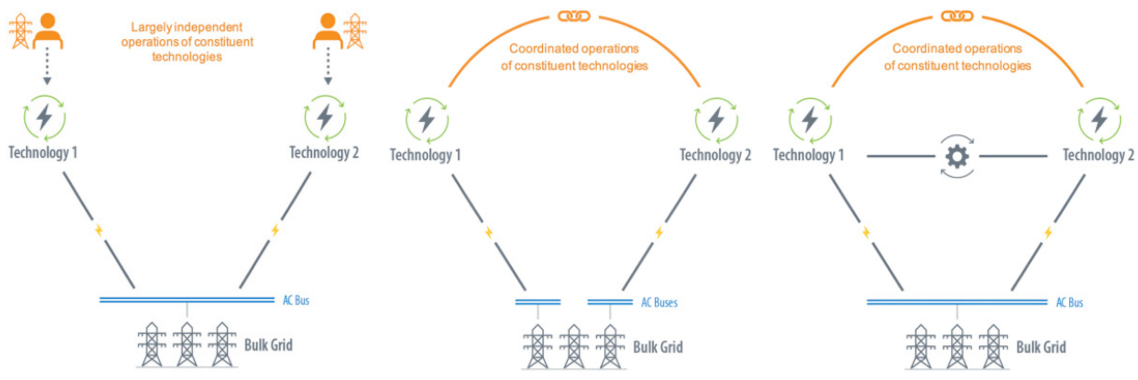

Figure 3.10: HRES categories in the taxonomy proposed in [26]: Co-located (left), Virtual Power Plants (middle), Full Hybrid (right)

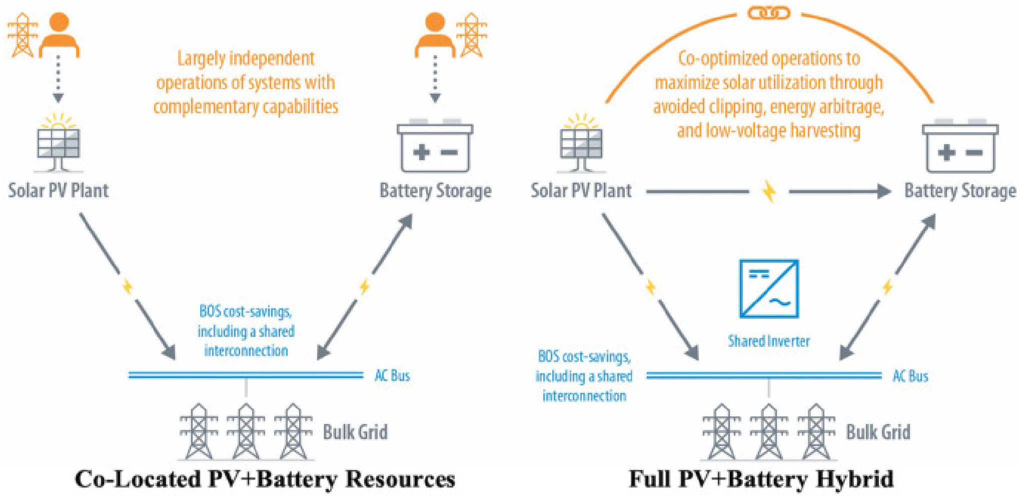

Figure 3.11: PV+BESS configurations [26]

3.3.2 Trends

Fig. 3.12 shows the evolution of the interconnections queues in the U.S., where an increasing trend in hybrid projects can be observed, due to both economics and regulations.

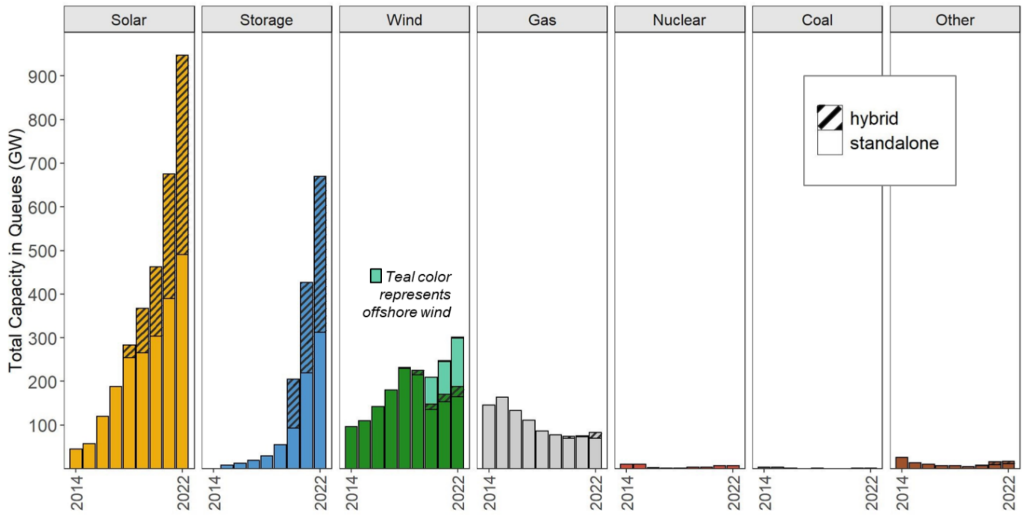

Figure 3.12: Capacity in interconnection queues as of the end of 2022 [27]

In the case of Spain, hybrid projects are gaining ground, thanks to a regulation that was set in motion in 2020 that provides incentives for hybridization, which is explained in the next section.

Examples of hybrid projects in Spain include [28] [29]:

- Cerro Calderón, Cerro del Palo & Cuesta Colorada wind farms, which will add 40,925 MWn solar PV to the existing 49,5 MW.
- Valdefuentes wind farm, which will add 27.83 MWn solar PV to the existing 28 MW.

- Carpio, Picón I, Picón II, Picón III, La Nava, Tabernas I & II solar PV farms, which will add 20MW, 40MWh of storage in each one.

3.3.3 Regulation

Focusing specifically in the regulations put in motion in Spain, the Article 27 on Chapter VIII of the Royal Decree 1183/2020 provides the detail on the regulation applied to the possible hybridization of power generation facilities [30].

The article mentions that power plant owners with granted and current permits can use the same connection point and capacity access previously granted if they hybridize their facility with either another renewable source or with storage. The permit holders must also obtain a positive resolution from the grid operator with regards to the following requirements for the hybrid plant:

a) In accordance with the technical access and connection criteria contemplated in the current law and to that established by the Comisión Nacional de los Mercados y Competencia

b) Granted access capacity is not increased

c) Fulfillment of technical requirements

d) Valid access and connection permit already in the owner´s possession

e) In no case should the installed capacity of the technology that possesses the access and connection permit shall be lower than 40% of the access capacity granted in the access permit

f) The new modules to incorporate in the installation fulfill the requirements set in the Law (UE) 2016/631

Also, for the hybridized facility to qualify for the renewables economic regime, the storage must be exclusively charged using the energy produced onsite. With another key factor being that the owner of the old generation facility and the storage must be the same one, due to the permit limits.

To stimulate the development of hybrid projects, the Spanish government announced in December 2022 that it would provide grants totalling €150M to help in the deployment of BESS systems hybridized with existing renewable projects, with the grants being able to cover 40 to 65% of the investment costs, and each project qualifying for a maximum €15M [31], as long as the storage capacity fulfills the size requirement of 40% of the plant capacity and does not go over 100% of the generation capacity.

3.4 Decision Metrics for Energy Projects

To assess if an HRES project is beneficial for the stakeholders, indicators are needed to analyze whether its expected benefits outweigh its costs, while considering the time value of money. In this section, four indicators widely used in the industry are addressed: the Net Present Value (NPV), the Internal Rate of Return (IRR), the Levelized Cost of Energy (LCOE), and the Levelized Cost of Storage (LCOS).

3.4.1 Net Present Value

The NPV is an indicator used for project evaluation that considers the value of the different cash flows over time, where the present has more importance, so the future values are converted using a discount factor. Its formula is shown in Eq. (3.2), and it is used to rank and make decisions on projects. A positive NPV means that the project provides a net benefit.

$$NPV = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+i)^t} - I_0 \tag{3.2}$$

Where:
R_t is the revenue in year t
C_t is the cost in year t
i is the discount rate
I_0 is the initial investment

3.4.2 Internal Rate of Return

The NPV is highly influenced by the choice of discount rate. An alternative approach used is that of the IRR, which involves finding the discount rate where the benefits equal the costs, that is, where the NPV is zero. Its formula is shown in Eq. (3.3), and a project will be considered as beneficial if the calculated IRR is above the market interest rate, or another predetermined rate. The IRR also serves as the limit of the acceptable cost of capital, where a project will be profitable as long as the cost of capital is less than the IRR [32].

$$\sum_{t=1}^{T} \frac{R_t - C_t}{(1+i)^t} = I_0 \tag{3.3}$$

However, there are two issues with the IRR that should be considered. First, in specific cases it could be possible to find multiple rates that yield a zero NPV. Second, the IRR assumes that the annual cash flow is reinvested at that same rate, which is not always the case [32].

3.4.3 Levelized Cost of Energy

The LCOE is a metric used to evaluate energy projects using a cost approach, where the NPV of both investment & operating costs is divided by the NPV of the lifetime energy production, as shown in Eq. (3.4), providing a way to compare projects on a cost per unit basis. The LCOE can also be defined as the minimum revenue needed per MWh delivered to break even or be profitable.

$$LCOE = \frac{I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+i)^t}} \tag{3.4}$$

3.4.4 Levelized Cost of Storage

The LCOS is a metric comparable to the LCOE, adapted so that different ESS can be compared, incorporating the charging cost, as shown in Eq. (3.5)[33].

$$LCOS = \frac{I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} + \sum_{t=1}^{T} \frac{C_{ch}}{(1+i)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+i)^t}} \tag{3.5}$$

Where
C_{ch} is the charging cost
E_t is the energy dispatched

Lazard conducted an analysis on the estimations for the LCOE and LCOS of several technologies to be able to compare their use cases and their learning rates [34]. The cost metrics that they calculated for utility-scale standalone BESS and hybrid PV/Wind+BESS projects are shown in Table 3.4, where the hybrid cases consider the net output from both technologies.

Table 3.4: Lazard´s LCOS comparison [34]

Case	**Capacity**	**Unsubsidized LCOS Range** [$\frac{\$US}{MWh}$]
Standalone	100MW, 1hr	249-323
Standalone	100MW, 2hr	215-285
Standalone	100MW, 4hr	200-257
PV+BESS	100MW + 50MW, 4hr	100-131
Wind+BESS	100MW + 50MW, 4hr	69-79

Chapter 4

Methodology

In this section, the methodology followed to develop the optimization model is developed. First, the optimization flow is explained. Second, the programming language, solver and interface used are mentioned. Next, the mathematical model is introduced, diving into the assumptions, parameters, variables, constraints, and optimization function. Afterwards, the post-processing of the model is elaborated on. And finally, limitations of the model are discussed.

4.1 Optimization flow

Fig. 4.1 shows a diagram with the inputs and outputs of the model, illustrating if Python or Excel is used. First, the mathematical model is loaded, considering the constraints & objective defined in Section 4.3. Second, the user must input the parameters: time series for market prices and power generation, battery specifications, cost parameters & economic parameters. Third, the optimization is run for one year, with the objective of maximizing the annual profit while computing battery degradation and changing market prices over the project lifespan, giving as an output the optimal storage size & scheduling. Then visualizations are generated, together with the calculation of the average price spread captured, NPV, IRR & LCOS. The last step is a check to see if the IRR is higher than the target discount rate provided by the user, if it is not the case then the user can provide a new input target value and calculate the missing money that would be needed using other revenue mechanisms or subsidies.

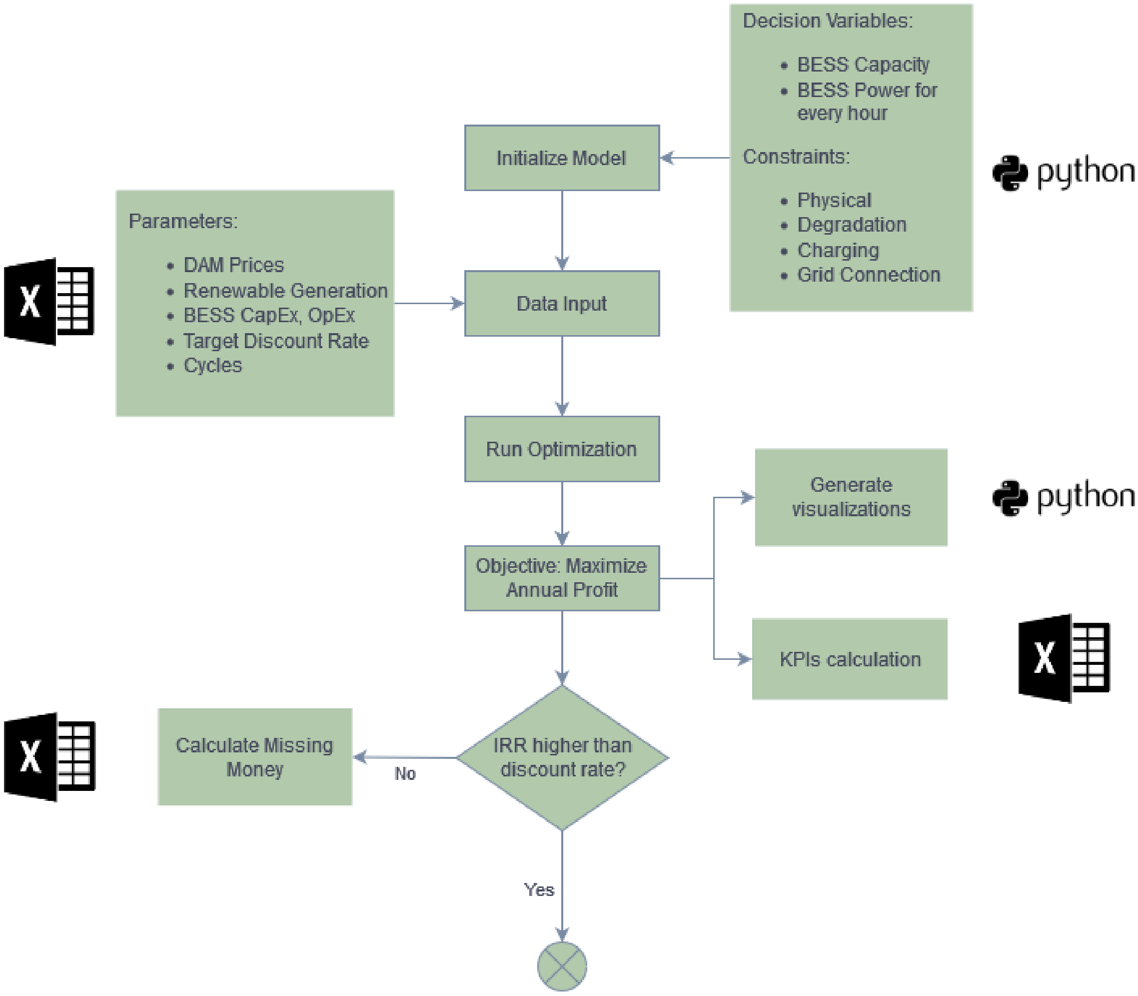

Figure 4.1: Optimization flow proposed

4.2 Software

The model is developed using Python and Excel. Python is used as it is powerful, flexible, and easy to use. Python was created in 1991 by Guido Van Rossum, and is now one of the most popular programming languages thanks to features such as [35]:

- Presence of third-party modules
- Extensive support libraries
- Open source and large active community base
- Versatile, easy to read, learn and write
- User-friendly data structures
- Object-oriented and procedural programming
- High efficiency
- Portability across operating systems

Packages & libraries used include: matplotlib, numpy, pandas, pyomo & xlwings. Matplotlib is used to create 2D visualizations [36]; numpy is used for numerical computations [37]; pandas is used for data analysis & manipulation [38]; Pyomo and xlwings will be explained in Subsections 4.2.1 & 4.2.3.

4.2.1 Optimization modelling language

Pyomo is an open-source software package for Python used for formulating, solving, and analyzing optimization models. It can be used to define general symbolic problems, create specific problem instances, and solve these instances using commercial and open-source solvers. [39, 40]

The following problem types are supported in Pyomo:

- Linear programming
- Quadratic programming
- Nonlinear programming
- Mixed-integer linear programming
- Mixed-integer quadratic programming
- Mixed-integer nonlinear programming
- Stochastic programming
- Generalized disjunctive programming

- Differential algebraic equations
- Bi-level programming
- Mathematical programs with equilibrium constraints

4.2.2 Solver

The solver used in the model is Gurobi, due to its performance and its ability to solve Mixed-Integer Programming (MIP) problems [41]. One drawback to this solver is that it is not open-source. However, an academic license is used.

4.2.3 User Interface

As mentioned in the objectives, one key factor for the model is that it is user friendly. To achieve this, the xlwings library is used. This library provides a connection between Python and Excel.

Xlwings is an open-source spreadsheet automation package, which serves as an alternative to VBA functions and PowerQuery, it is easy to deploy and provides a powerful file reader for Python. Xlwings has the following features [42]:

- Scripting: Excel automation
- UDFs: User-defined functions
- Interact with Excel from Jupyter notebooks
- Macros: RunPython function
- Custom Excel Ribbon Add-ins

An Excel macro-enabled file serves as the main window for the model, where the user is provided with three tabs: Input Parameters, Results & Graphs.

In the Input Parameters tab, the user can introduce the DAM prices, RE generation, grid constraint, costs, BESS specific technical parameters, and economic parameters. Once all the parameters are in place, a button is used to call the Python program using VBA, and run the optimization. This interface is shown in Fig. 4.2.

The Results tab (shown in Fig. 4.3) provides the optimal BESS size together with other KPIs including: NPV, IRR, average price spread, cycles. The time series for each of the decision variables is also provided, together with the cash flows for the project lifetime. The results are filled once the python script finds the optimal solution, and rewritten in case the user runs it again.

Finally, the Graphs tab provides visualizations of the BESS operation during the year, in addition to plots of the input prices and generation.

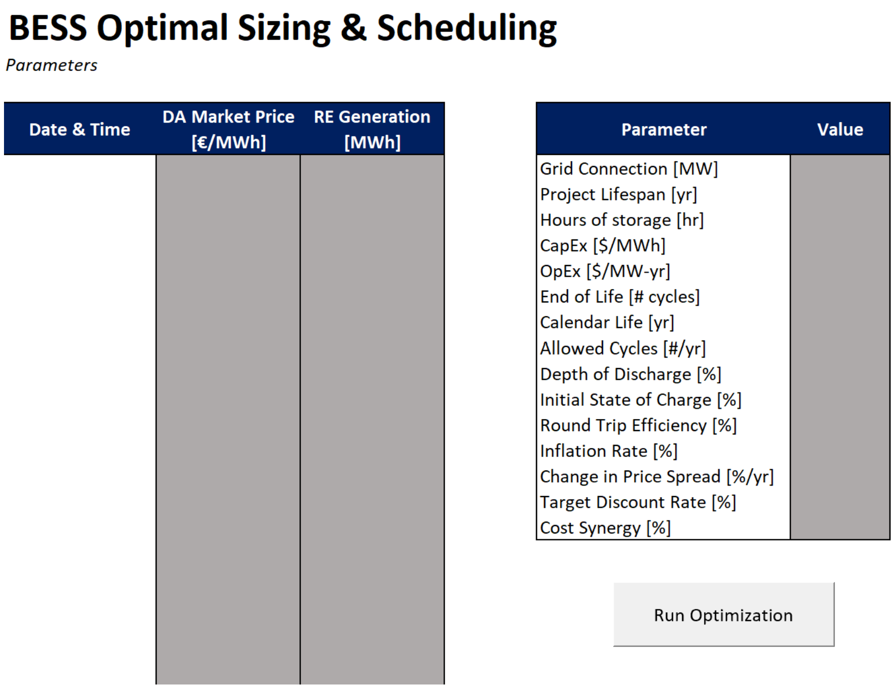

Figure 4.2: Input parameters tab

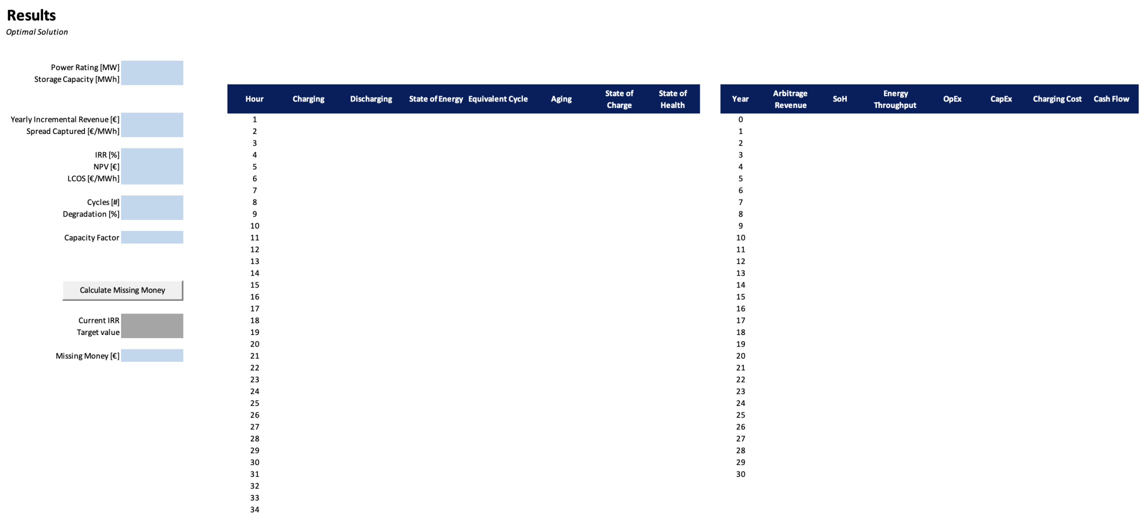

Figure 4.3: Results tab

4.3 Mathematical Model

The optimization is composed of two objectives, where the model must determine both the optimal size and the scheduling of the system, by maximizing the lifetime profits of the system. It is a Mixed Integer Quadratically Constrained Programming (MIQCP) problem, due to constraints that will be elaborated on Section 4.3.5.

4.3.1 Assumptions

The assumptions made for the model are:

- Hourly resolution, where renewable generation and BESS charging/discharging are considered as constant for the entire hour
- Perfect foresight of prices
- BESS cannot charge using electricity from the grid
- Power interconnection is capped based on connection permit
- BESS performs energy arbitrage, ancillary services are not modelled
- There is a cost synergy thanks to the shared site and OpEx.
- Negative DAM prices are not considered
- The BESS is considered to be a price taker
- The minimal size for the BESS is 50% of the connection permit, chosen arbitrarily to limit the boundaries, otherwise for negative NPV's the model would size the system at zero capacity.

4.3.2 Parameters

The parameters considered in the model are the following:

$T =$	Simulation time
$Y =$	Project lifespan
$\eta =$	Round-trip efficiency
$Lt_{cyc} =$	Storage cycle life
$Lt_{cal} =$	Storage calendar life
$P_G =$	Grid limit
$R_B =$	Hours of storage
$SoC_{max} =$	Maximum state of charge
$SoC_{min} =$	Minimum state of charge
$SoC_{ini} =$	Initial state of charge
$SoC_{SD} =$	Self-discharge
$Th_{max} =$	Allowed cycles
$C_{inv} =$	CapEx
$C_y =$	OpEx
$i_{disc} =$	Target discount rate
$i_{inf} =$	Inflation rate
$i_{spread} =$	Change in average price spread
$i_{syn} =$	Synergy rate
$M[t] =$	DAM price at hour t
$P_{RE}[t] =$	RE generation at hour t

4.3.3 Variables

The model variables are the following:

$S_B =$	BESS Storage Capacity
$P_B =$	BESS Rated Power
$P_C[t] =$	Charging at hour t
$P_D[t] =$	Discharging at hour t
$SoE[t] =$	State of energy at hour t
$FEC[t] =$	Full equivalent cycles
$SoH[t] =$	State of health at hour t

Where the decision variables are the BESS capacity plus the charging/discharging power at every hour, and the rest of the variables serve to track the state and degradation of the system.

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4.3.4 Objective Function

$$\text{maximize}\ \{\text{Revenues} - \text{Costs}\} \tag{4.1}$$

Where:

$$\text{Revenues} = \sum_{y=1}^{Y} \frac{(\sum_{t=1}^{T}(P_D[t] - P_C[t]) \cdot M[t]) \cdot (1 + i_{spread})^y}{(1 + i_{disc})^y} \tag{4.2}$$

$$\text{Costs} = \sum_{y=1}^{Y} (\frac{C_y \cdot (1 + i_{inf})^y}{(1 + i_{dic})^y} + C_{inv}) \cdot (1 - i_{syn}) \cdot S_B \tag{4.3}$$

The objective function for the proposed model looks to maximize the profit that can be obtained from adding the BESS to the RE plant. The revenues are calculated from the difference between the power charged and discharged, based on the price spread, with an additional parameter used to model the yearly change in captured prices. While the costs consider both the CapEx and the yearly OpEx, plus the additional parameter to consider cost synergies.

4.3.5 Constraints

Regulatory constraints

$$0.5 \cdot P_G \leq P_B \leq P_G \tag{4.4}$$

Eq. (4.4) bounds the storage power capacity, where the lower bound is chosen arbitrarily, to see the optimization results in case of a negative NPV. The upper bound is set according o the regulation seen in Section 3.3.3, based on the grid connection permit.

$$P_{RE}[t] + P_D[t] \leq P_G \ \ \forall\, t \in T \tag{4.5}$$

Eq. (4.5) ensures that the power injected to the grid at any time is equal or less than the contracted power interconnection.

Battery physical constraints

$$0 \leq P_C[t] \leq P_B \ \ \forall\, t \in T \tag{4.6}$$

$$0 \leq P_D[t] \leq P_B \ \ \forall\, t \in T \tag{4.7}$$

Eqs. (4.6) & (4.7) refer to the minimum & maximum power that can be absorbed or dispatched by the BESS at any time.

$$P_C[t] \cdot P_D[t] = 0 \ \ \forall\, t \in T \tag{4.8}$$

Eq. (4.8) ensures that the BESS cannot charge & discharge at the same time.

$$S_B = R_B \cdot P_B \tag{4.9}$$

Eq. (4.9) refers to the hours of storage that the BESS can hold at its rated power capacity.

Battery state of charge constraints

$$SoC_{min} \leq SoC[t] \leq SoC_{max} \cdot SoH[t] \ \ \forall\, t \in T \tag{4.10}$$

$$SoC[t] = \begin{cases} SoC_{ini} + \frac{(\sqrt{\eta} \cdot P_c[t] - \frac{P_d[t]}{\sqrt{\eta}})}{S_B} & \in t = 1 \\ SoC[t-1] \cdot (1 - SoC_{SD}) + \frac{\sqrt{\eta} \cdot P_c[t] - \frac{P_d[t]}{\sqrt{\eta}})}{S_B} & \in t = (2:8760) \end{cases} \tag{4.11}$$

Eq. (4.10) is used to bound the SoC to the total storage capacity that considers the SoH, and to the minimum that is required at any time based on the DoD. Eq. (4.11) defines the change in SoC at every time-step, considering both charging & discharging efficiencies.

Energy throughput constraint

$$FEC[t] = 0.5 \cdot \frac{\sum_{t=1}^{T} P_d[t] + P_c[t]}{S_B} \ \ \forall\, t \in T \tag{4.12}$$

$$\sum_{t=1}^{T} FEC[t] \leq Th_{max} \tag{4.13}$$

From the alternatives for degradation investigated in Section 3.2.6, the approach considered for the model is that of circulated energy, so that the computation time can be kept reasonable. Eq. (4.12) is computed to calculate the equivalent cycles at every time step, while Eq. (4.13) constrains the cycles per year.

Degradation tracking

$$aging_{cal} = \frac{1}{Lt_{cal} \cdot T} \tag{4.14}$$

$$aging_{cyc}[t] = \begin{cases} 0 & \in t = 1 \\ aging_{cyc}[t-1] + \frac{FEC[t]}{Lt_{cyc}} & \in t = (2, 8760) \end{cases} \tag{4.15}$$

$$SoH[t] = \begin{cases} 1 & \in t = 1 \\ SoH[t-1] - 0.2 \cdot (aging_{cal} + aging_{cyc}[t]) & \in t = (2, 8760) \end{cases} \tag{4.16}$$

Both degradation components are modeled based on the work done in [22]. Calendar aging is modeled linearly, as shown in Eq. (4.14) and has a constant value at every time step. Cyclic aging, shown in Eq. (4.15) considers the previous values and uses the equivalent cycles as input. The SoH is modeled by adding both aging types, as shown in Eq. (4.16).

4.3.6 Model Post-processing

The output from the optimization is then used to compute the NPV, IRR and LCOS, for which their formulas were described in Section 3.4. Other KPIs recorded are the degradation, the price spread captured, and the cycles for the year.

The final calculation is that of the missing money, where calculations are made based on an input target discount rate. To do this, a function is run using VBA to calculate the additional yearly revenues needed to attain the target discount rate. All these results are showcased in the Excel file, as shown in Fig. 4.3.

4.3.7 Model Limitations

The present model has been developed to provide an initial glimpse of the profitability of hybridizing a RE plant with BESS, and includes several assumptions that may on one hand overestimate the profitability of the asset, such as degradation & foresight, while other that may also underestimate it, such as price volatility & market design.

Another factor that is kept out of the scope is that of project finance, where debt, equity & taxes are not modelled. To get the complete picture of a project viability they need to be taken into account as one or two points of the Weighted Average Cost of Capital (WACC) can greatly affect the profitability.

A future energy system comprised of mostly renewables will be radically different, and will require different mechanisms to ensure the profitability of all assets. As mentioned in previous sections, many countries are experiencing several hours of negative prices & curtailment, that are only expected to increase as RE generation expands.

Chapter 5

Case Study

Using the model developed in the previous section, a solar PV plant will now be used as a case study to investigate the profitability of hybridizing the site by installing a BESS, optimizing the storage operation to maximize its revenues from energy arbitrage alone.

5.1 Case description

The site considered is located in Spain. The power output of the plant is shown in Fig. 5.1. The market prices used correspond to the Iberian DAM prices for the year 2022, and are shown in Fig. 5.2, with the daily arbitrage opportunity shown in Fig. 5.3.

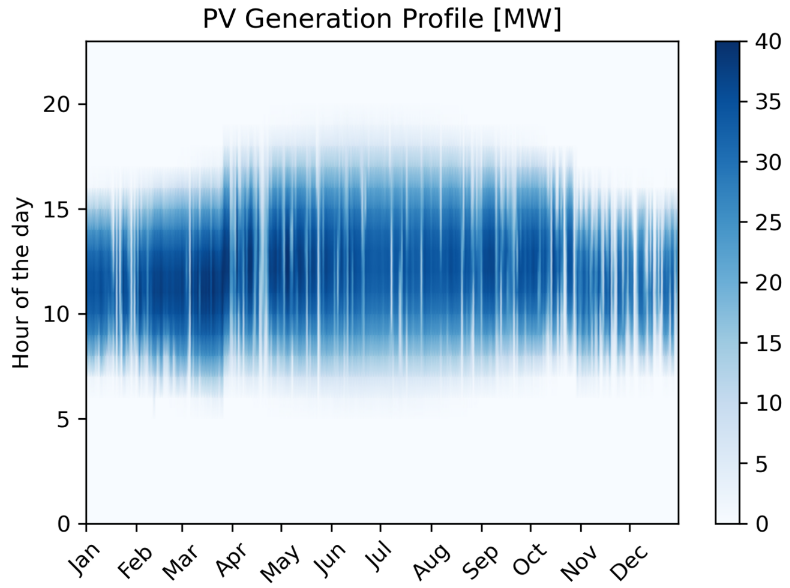


Figure 5.1: PV Generation (MW)

The cost, interconnection, and technical parameters used are shown in Table 5.1. The CapEx costs considered are based on [16], while the OpEx is based on current market costs.

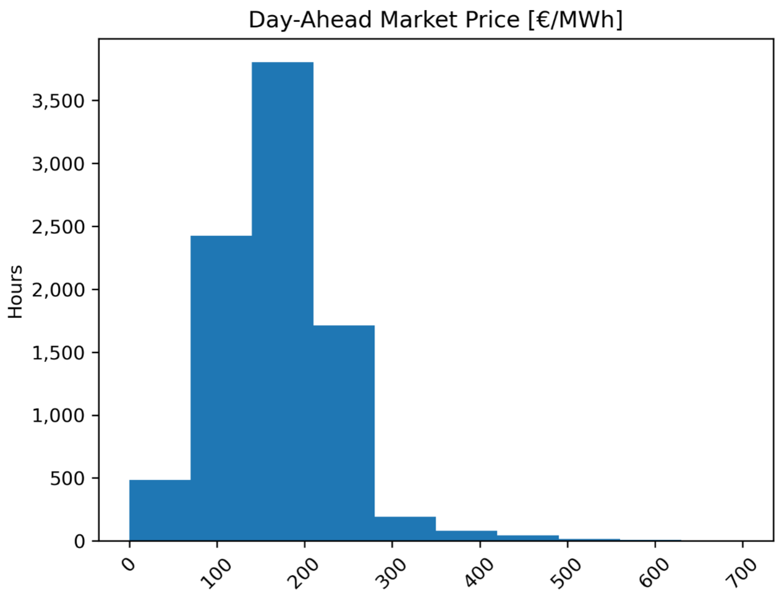


Figure 5.2: Day Ahead Market Price in Spain ($/MWh)

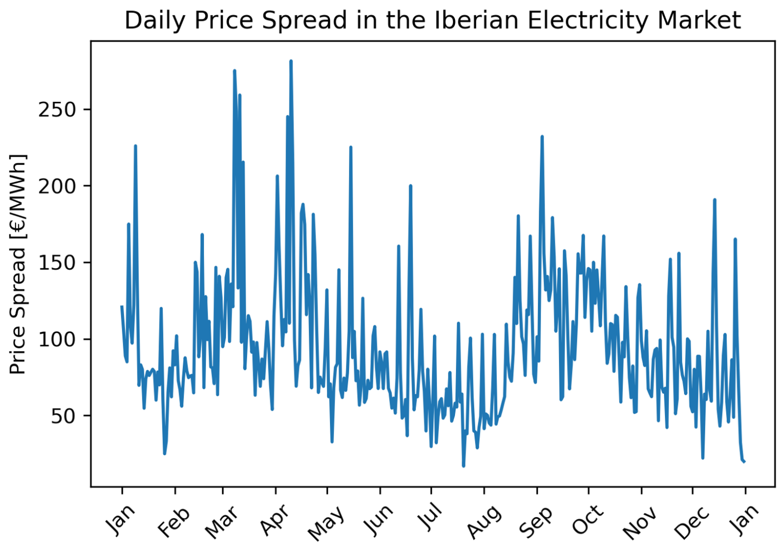


Figure 5.3: Daily Price Spread in Spain, for the year 2022 (€/MWh)

Table 5.1: Parameters considered for the case study

Parameter	Value	Units
Grid connection	40	MW
BESS CapEx	346,907	$\frac{€}{MWh}$
BESS OpEx	867	$\frac{€}{MWh \cdot yr}$
Hours of storage	2	hr
DoD	0.8	$p.u.$
Initial SoC	0.6	$p.u.$
Cycles	360	yr
Self discharge	0.02	$\frac{\%}{day}$
Inflation	2.0	%
Target discount rate	7.5	%
Cost synergy	5.0	%
Change in price capture	0.0	%

5.2 Results

The results obtained from the model are summarized in Table 5.2, where the capacity proposed for the system is the lower bound, due to a negative NPV. The LCOS shown in parenthesis corresponds to the one without considering the charging cost, to serve as a reference for hybrid systems. For more detail from the operation schedule & cash-flows refer to the appendix.

Table 5.2: Case Study Results

Output	Value	Units
Rated Power	20	MW
Storage Capacity	40	MWh
NPV	-6,154,132	€
IRR	1.8	%
LCOS	250.6 (113.2)	$\frac{€}{MWh}$
Equivalent Cycles	360	$\frac{\#}{year}$
Degradation	1.9	%
Incremental Revenues	774,074	€
Price Spread Captured	82.0	$\frac{€}{MWh}$
Capacity Factor	9.4	%

Fig. 5.4 illustrates the operation of the BESS over the simulated year, where it is clearly seen that charging takes place around noon (11:00 to 14:00) and the energy is dispatched mostly at peak hours (20:00 to 23:00).

Fig. 5.5 provides a glimpse to the scheduling of the BESS over a representative week, it shows how the charging/discharging is triggered by the changing DAM prices.

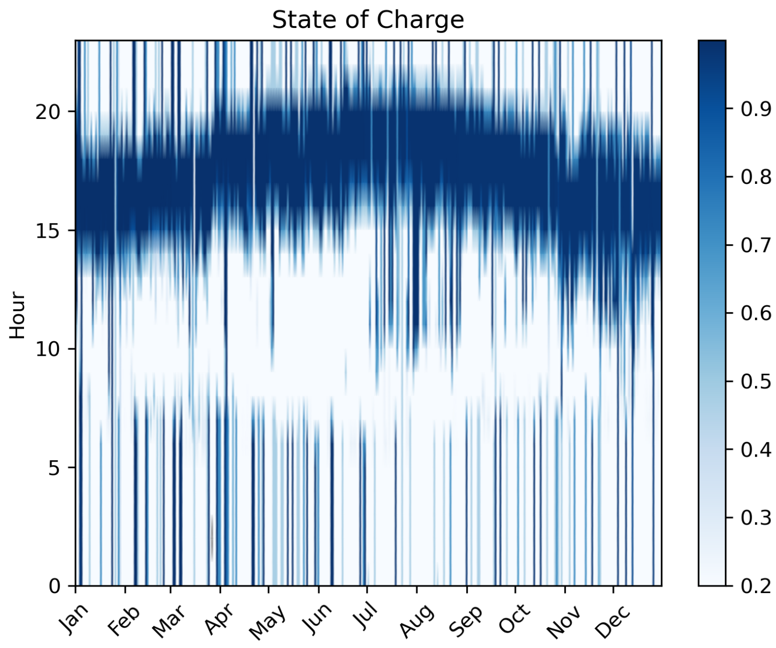


Figure 5.4: BESS SoC throughout the year

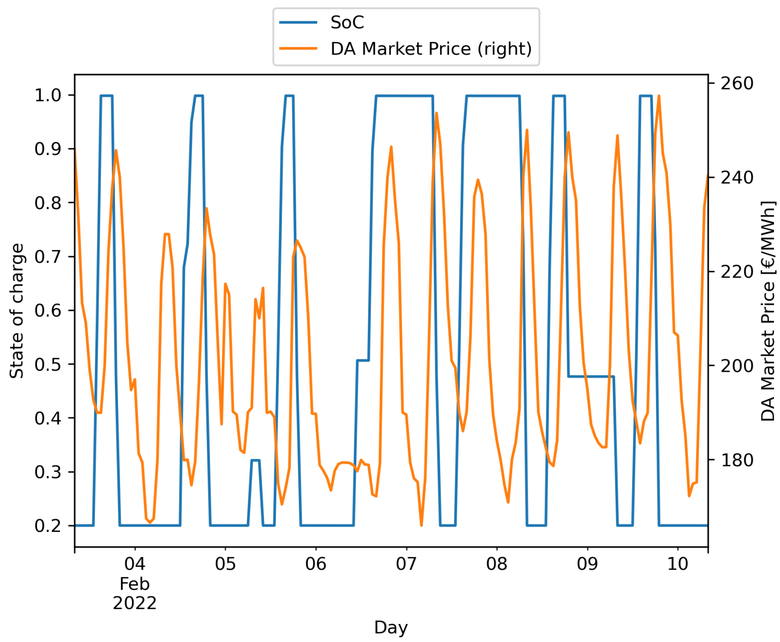


Figure 5.5: BESS operation for one week

Based on the model results, arbitrage alone does not yield enough revenues to obtain a profitable project. The results observed are in line with [43], who found that BESS projects that obtain revenues in short-term markets are not profitable under the current regulatory framework in Spain and that support mechanisms such as capacity payments, capacity auctions or direct subsidies are needed to cover the gap that they found in revenues, in the order of 54-62%.

A study done by [44] also found that the current and expected revenue streams are not enough to attract the 20 GW target volume in storage by 2030 as contemplated by the Spanish government in the National Energy and Climate Plan. They propose new regulatory mechanisms around capacity markets where value is given to security of supply and integration of renewables, and where a division is made between short and long duration technologies.

5.3 Sensitivity Analysis

A sensitivity analysis is performed to test the model for the following variables: CapEx projections, hours of storage, price spread, cost synergy, discount rate and inflation rate. The values considered for each variable are shown in Table 5.3. The main results from testing the model with these variables are shown in Figs. 5.6, 5.7 & 5.8. The rest of the sensitivity results are found the appendix.

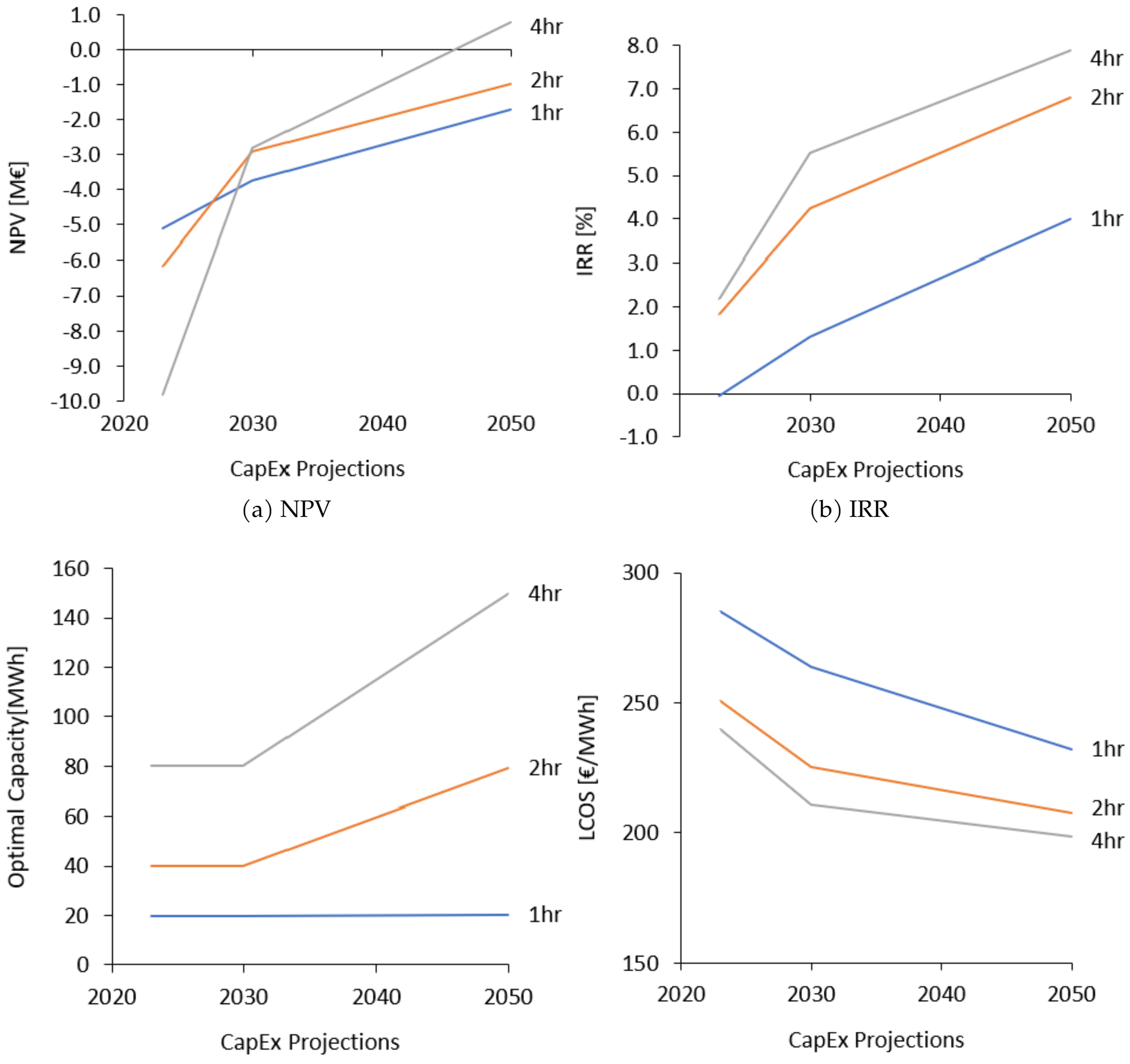
Table 5.3: Variables used to test the model´s sensitivity

Variable	Units	Low	Base	High
Storage	hr	1	2	4
Price Spread	%	-2.0	0.0	2.0
Cost Synergy	%	0.0	5.0	10.0
Discount Rate	%	5.0	7.5	10.0
Inflation Rate	%	0.0	2.0	4.0

By changing the CapEx in the model it is seen that systems with 1hr and 2hr of storage would still not yield a positive NPV by 2050 when considering EA alone, with the 4hr system being the only one to achieve a favorable NPV, with an optimal capacity at the upper bound, at 160MWh.

The sensitivity test for cost synergy shows that a 5% variation leads to a 12.4% increase in NPV and 0.5pp in IRR. Meanwhile, a 2.5pp change in discount rate leads to an improvement of up to 32.1% in NPV, which is to be expected as it is quite sensitive to a change in discount rate.

Another input parameter that greatly affects the output from the model is the market prices. The model was based on the prices for 2022, so to test the sensitivity the prices for 2019, 2020 and 2021 are also used. Fig. 5.9 depicts the comparison between the daily price spreads for the different years, while Fig. 5.10 shows the change in NPV and LCOS values depending on the year used for the market prices. It is observed that the years 2019 and 2020 had relatively low volatility compared to 2021 and 2022, which leads to a worse NPV and a better LCOS thanks to lower charging costs.



(a) NPV (b) IRR

(c) Capacity (d) LCOS

Figure 5.6: Model sensitivity results to storage capacity and CapEx projections

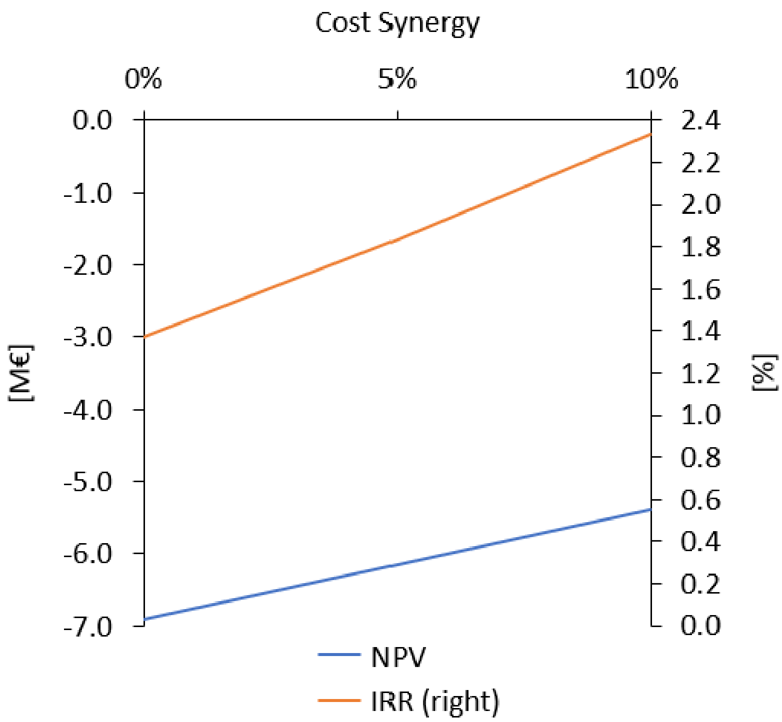


Figure 5.7: Model sensitivity to changes in cost synergies

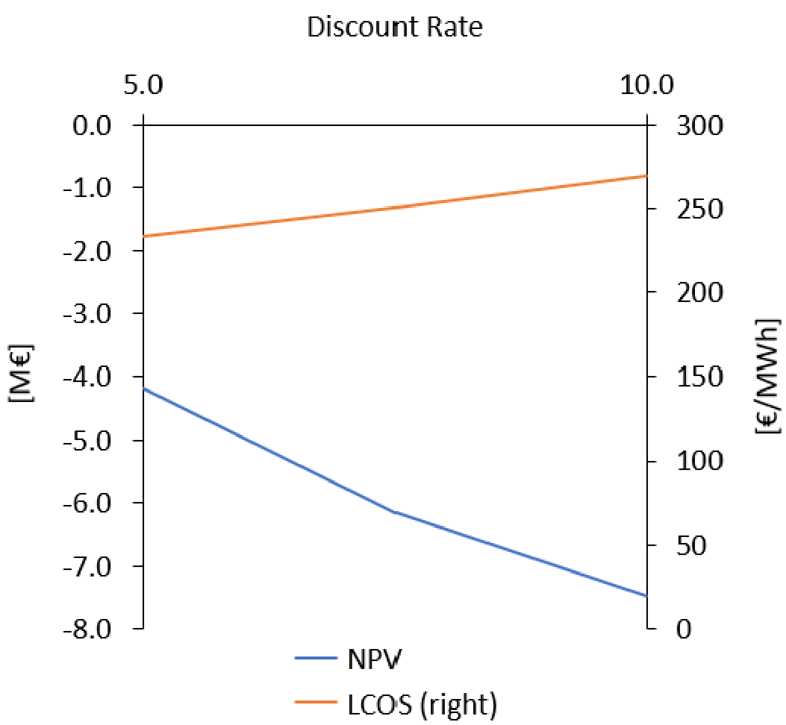


Figure 5.8: Model sensitivity to changes in discount rate

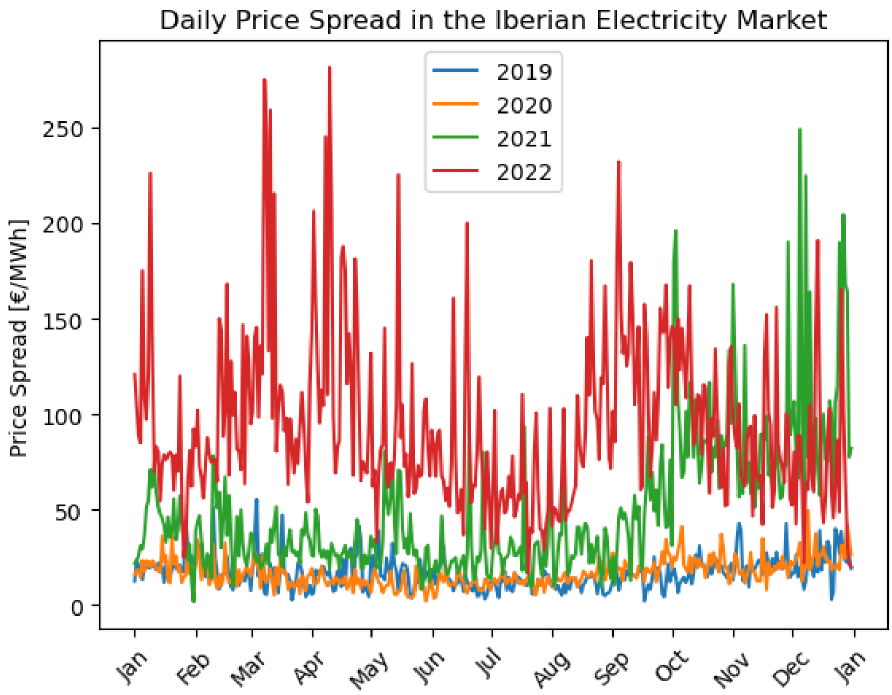


Figure 5.9: Daily price spread for the last 4 years

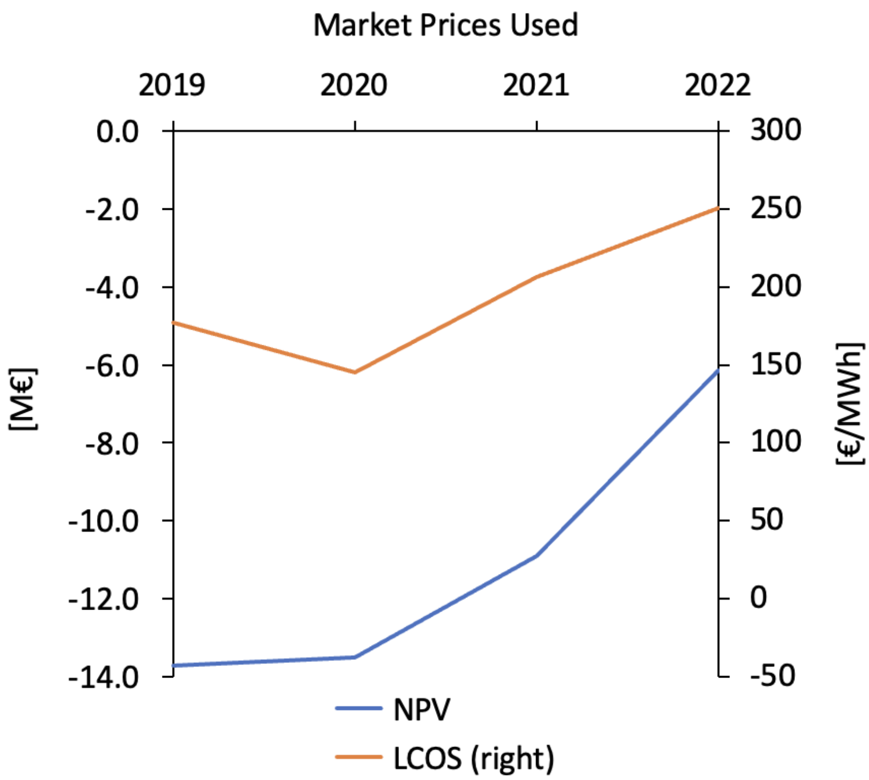


Figure 5.10: Model sensitivity to year chosen for the optimization

Chapter 6

Project Impacts

While the theme of the thesis focuses mostly on the techno-economic aspects, it is important to also assess the direct/indirect impacts for the present work in other aspects, including environmental, social and gender aspects. Each of these impacts are addressed in this chapter.

6.1 Environmental Impact

The model proposed in this thesis has a direct impact on the environment, as hybridizing a renewable plant with storage provides it with dispatchability, so that the solar/wind energy can be dispatched during peak times and avoid curtailment, leading to a phaseout of fossil peaker plants. Thus, reducing emissions and contributing to the decarbonization of the grid.

A quantification of this impact is out of the scope of the project. However, a Life Cycle Assessment (LCA) was conducted in [45] to quantify the environmental impact of using BESS instead of Combined Cycle Gas Turbines (CCGT) in the U.K., and they found it would lead to a reduction of 87% of GHGs emissions (1.98 $MtCO_2eq$) by 2035. Likewise, in a study conducted for California [46], it was found that implementing BESS to replace CCGTs for backing up solar would reduce the state´s electricity sector CO_2eq emissions up to 8% by 2030.

6.2 Social Impact

Utility-scale hybrid renewable projects provide value to the communities where they are built, by creating new revenue streams such as jobs and land leasing, providing a net economic benefit.

Another key impact of hybrid and renewable projects in general is that they drive down electricity costs, thanks to their low short-term marginal costs as mentioned in Section 3.1.1, and this trend will continue thanks to the learning rates observed for Solar, Wind, and Batteries. Therefore, providing a benefit for consumers by lowering their bills.

On the other side, utility-scale renewable projects have a large footprint that can be seen negatively by certain communities, as the land could have been used for other purposes, i.e. agriculture. However, hybrid projects make up for this, by increasing the power output and keeping a lower footprint.

6.3 Gender Impact

Regarding gender impacts, a study conducted on gender perspectives in the energy sector found that women make up 32% of the renewable energy workforce, compared to 22% of the oil & gas industry workforce [47]. It shows that the renewables sector is getting closer to the gender parity. However, many opportunities remain to improve, and to bring more perspectives into the fold.

Actions that can be taken by the renewables industry to close this gap include:

- Training - hiring local women and close the skills gap by training them, promoting inclusion.
- Gender mainstreaming - considering the needs of women and others throughout the different project phases.
- Empowerment - making sure that voices of minorities are heard, for example through consultations

Overall, a good practice for utility-scale project developers, and in line with the SDGs, is to conduct gender assessments and to engage with the local communities women, so that the projects can be tailored accordingly.

Chapter 7

Project Budget and Planning

7.1 Budget

The budget for the present thesis is calculated based on the labor, equipment, and software costs. The final budget is shown in Table 7.1, including the breakdown of each part.

Table 7.1: Thesis costs

Concept	**Time [hr]**	**Cost [€]**
Software Tutorials	80	640.00
Literature Research	220	1,760.00
Methodology	80	640.00
Programming	80	640.00
Case Study	50	400.00
Writing	250	2,000.00
Value Added Tax (21%)		1,276.80
Equipment		1.10
Total	760	7,357.90

For the labor cost an hourly wage of 8 € is considered as it is the minimum wage in the UPC's rules for project & internship work.

For the equipment cost, the thesis is developed using my own laptop, with a battery capacity of 56Wh, for which a charging cost of 0.1360 €/kWh (based on my current electricity rate) is considered.

The software cost is negligible as open-source software was used, with the exception of the solver (academic license).

Based on the estimations made, the total cost for the thesis is 7,357.90 €.

7.2 Planning

The project's Gantt chart is shown in Fig. 7.1, following the same concepts described in Table 7.1, where it is shown that February and March were mostly focused on investigating on the state of the art and learning to use Pyomo and the other software packages used. Then in April, the focus shifted to building the model and translating it into Python, while May and June were mostly focused on obtaining the results of the case study and writing the document.

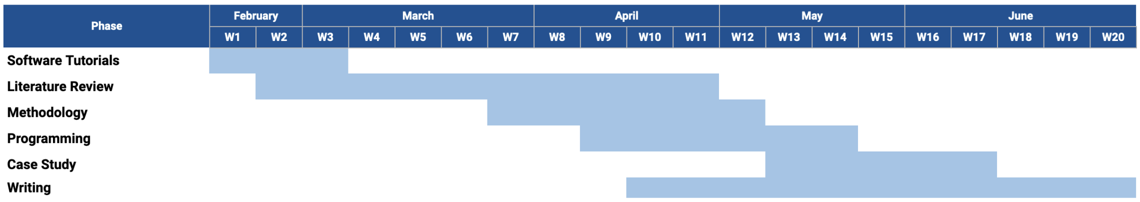


Figure 7.1: Project Planning

Conclusions

An optimization model was designed for ODENRA to assess the profitability of hybridizing existing renewable power plants with BESS.

The model developed was put into practice through a case study, for a 40MW solar plant, where the optimal BESS to hybridize the plant was found to be 20MW/40MWh with an NPV of $-6,154,132$ €, an IRR of 1.8%, and a LCOS of $250.6\frac{€}{MWh}$. A sensitivity analysis was carried to test the results by changing the values of storage capacity, CapEx, synergies, and YoY rates.

While the model showed that hybridizing a PV plant with a BESS is not profitable today when used only for energy arbitrage, there are more revenue mechanisms that can be used to obtain that missing money, including ancillary markets, capacity payments or subsidies. It should also be noted that with the projected learning rates, the CapEx costs are expected to decrease 15 to 45% by 2030.

Overall, it is seen that HRES provide a good alternative to the uncertainties faced by project developers, thanks to favorable regulations, such as the Royal Decree 1183/2020, in Spain; also due to cost synergies and the ability to capture a higher price in the energy markets.

It is important to note that as more merchant BESS are implemented, their possible revenue streams will also be affected, in a similar manner to merchant solar/wind plants, where the low marginal costs will saturate and depress capture prices in wholesale & ancillary markets. Changes in market design & regulatory frameworks will be needed for a power system dominated by renewables, to ensure that the proper investments needed are made.

Regarding future work, suggestions to further refine this model include:

- Allowing revenue stacking, by modelling ancillary markets.
- Model more hybridization possibilities, i.e. solar PV + Wind + BESS.
- Incorporating Machine Learning (ML) forecasts to predict market prices or generation deviations.
- Using dynamic programming, and setting a time horizon of 24/48hr to further reflect how these assets operate in the market.

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I would like to thank first my parents and brothers, who pushed me throughout the thesis duration to make sure I delivered in time and form.

I also specially thank Miguel Eguizabal for allowing me to undertake this thesis project at ODENRA and providing guidance as to what are the metrics and special considerations to take into account as a project developer.

I want to thank my supervisor Oriol Gomis, as it is through his class on Integration of Renewables to the Grid that I acquired further interest in modelling energy systems.

Finally, I want to thank all my professors, classmates and friends that I have had throughout this two-year journey at the EIT InnoEnergy master program, undertaken in Stockholm and Barcelona.

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