Master Thesis

Techno-Economic Analysis of Battery Operation in the Spanish Electricity Market

Author: Pablo Florit Siles [1]
Supervisor: Valentín García[2]

[1] Universidad Pontificia Comillas (ICAI); 202308669@alu.comillas.edu
[2] Arup, valentin.garcia@arup.com

Abstract: The increasing share of renewable energy in the Spanish power system highlights the need for flexible resources capable of ensuring stability and market efficiency. Battery Energy Storage Systems (BESS) emerge as a strategic option, but their deployment is still limited by regulatory, technical, and economic barriers. This Master's Thesis develops a techno-economic simulation tool designed in Excel-VBA to evaluate the profitability of BESS projects in the Spanish electricity market. The model integrates hourly wholesale prices (OMIE), regulated charges, and key technical parameters of batteries such as efficiency, equivalent cycles, degradation, and lifetime. It allows the user to define operating thresholds and strategies, generating energy and financial results over a 20-year horizon. The analysis demonstrates that pure arbitrage under current conditions results in negative Net Present Value (NPV), although it enables a clear comparison between technologies and scenarios. Results show that increasing battery size or varying operation thresholds can significantly change equivalent cycles and captured spreads, while the choice of technology (e.g., LFP versus NCA) influences operational costs and long-term viability. Although current profitability remains limited, the tool proves valuable for assessing different configurations, understanding key sensitivities, and supporting decision-making in the early stages of BESS project development in Spain.

Keywords: Battery Energy Storage Systems; arbitrage; techno-economic analysis; Spanish electricity market; Excel simulation

1. Introduction

The global energy transition is driving profound changes in power systems, with a growing integration of renewable sources that, while reducing emissions, introduce significant challenges in terms of stability, flexibility, and demand management. In this context, Battery Energy Storage Systems (BESS) are positioned as a key technology to enable a more resilient, efficient, and decarbonized electricity grid. At the international level, reports from the International Energy Agency confirm that installed storage capacity is expected to multiply by more than ten by 2030, driven by falling costs and technological progress [1].

In Spain, the National Integrated Energy and Climate Plan (PNIEC) and the Energy Storage Strategy set ambitious targets of reaching 20 GW of storage capacity by 2030 and up to 30 GW by 2050 [2]. However, several barriers still limit large-scale deployment, including double charging of network tariffs, the absence of capacity markets, and an evolving regulatory framework [3]. These elements create what national reports have described as a "technical-regulatory gap" [4], which hinders investment and slows down the consolidation of viable business models.

This Master's Thesis addresses these challenges by developing a techno-economic simulation tool capable of evaluating the performance and profitability of BESS in the Spanish electricity market. The model, built in Excel-VBA, integrates real wholesale market prices (OMIE), regulated costs, and battery technical parameters to replicate operating strategies such as arbitrage, time shifting, or participation in future capacity schemes.

The main aim of the work is to provide a practical and transparent tool to assess BESS projects under realistic conditions, allowing the comparison of technologies and configurations, and supporting decision-making in early investment stages. The results demonstrate that, although pure arbitrage currently leads to negative Net Present Value (NPV), the model highlights the sensitivity of profitability to factors such as battery size, technology choice, or operating thresholds. Ultimately, the work contributes to clarifying the current limitations and potential of BESS in Spain, offering insights for both technical evaluation and strategic planning.

2. State of the Art

Battery Energy Storage Systems (BESS) have become one of the most relevant technologies to support the energy transition. Their value lies in the ability to provide flexibility, stability, and efficiency to electricity systems increasingly dominated by variable renewable sources. At the international level, the International Energy Agency projects that global storage capacity will multiply by more than ten by 2030, driven by declining investment costs and accelerated technological progress [1].

In Spain, energy storage has only recently been explicitly integrated into the regulatory framework. The National Energy Storage Strategy, approved in 2021, sets ambitious targets of reaching 20 GW of capacity by 2030 and up to 30 GW by 2050 [2]. Royal Decree 1183/2020 regulated access and connection to the networks for generation, consumption, and storage installations, granting storage assets a status comparable to generation plants [3]. Despite these advances, deployment remains limited, and several barriers continue to constrain the real participation of BESS in the electricity market.

Among the most critical challenges is the so-called "double charging" of tariffs: batteries must pay network charges when consuming electricity from the grid and are not exempted when reinjecting it. This reduces arbitrage margins and penalizes BESS compared to other technologies [3]. Another structural limitation is the absence of a fully developed capacity market, which prevents batteries from monetizing their value as providers of firm capacity. In addition, administrative procedures for grid access remain complex and often discourage new investments [3].

From a technological perspective, lithium-ion batteries dominate the stationary storage market, thanks to their high efficiency, scalability, and decreasing costs. Within this family, LFP (lithium iron phosphate) chemistry has consolidated as the most common solution in large stationary applications, offering a balance between cost, efficiency, and durability. By contrast, NMC and NCA chemistries, although more energy dense, involve shorter lifetimes and higher costs, making them less attractive for long-duration stationary use. Other chemistries such as LTO (lithium titanate) or high-temperature technologies (NaS, $NaNiCl_2$) remain relevant only in specific niches due to their high cost or lower commercial maturity [1,4].

Despite their technical maturity, the economic viability of BESS in Spain is still constrained. Pure price arbitrage in the wholesale market, the most direct business model, tends to produce limited margins and often negative Net Present Value (NPV). Studies by IDAE highlight that current profitability remains insufficient without complementary income sources [4]. This is consistent with the findings of this Master's Thesis, which shows that under current cost structures, arbitrage alone cannot guarantee investment recovery. However, BESS have significant potential in other applications: frequency regulation, voltage control, and participation in future balancing or capacity markets [5].

Another controversial aspect is the uncertainty about future price signals. While battery costs have been decreasing globally, electricity prices in Spain have become more volatile, with frequent episodes of very low or even negative prices during hours of high renewable generation [4]. This creates opportunities for arbitrage, but also increases risks for investors, as the long-term stability of these patterns remains uncertain [5].

In addition to economic and regulatory challenges, financing and bankability also represent obstacles. The lack of consolidated business cases in Spain reduces investor confidence and increases the perceived risk of BESS projects. Recent European initiatives such as the Recovery and Resilience Plan (PRTR) and FEDER programs have tried to mitigate this barrier by providing subsidies and financial support [4]. Still, these mechanisms are temporary and cannot replace stable market revenues.

In summary, the state of the art reveals a paradox. From a technical point of view, BESS are mature, versatile, and capable of providing multiple services. From a regulatory and economic perspective, however, their large-scale deployment in Spain is still constrained by tariff structures, the absence of stable remuneration mechanisms, and limited commercial experience. The ambitious national targets contrast with the reality of a market where, for the moment, profitability depends on external support schemes. This situation highlights the importance of developing tools, such as the one presented in this work, to realistically evaluate the viability of storage projects and identify the conditions under which they can become competitive.

3. Objectives

The main objective of this Master's Thesis is to carry out a techno-economic analysis of the operation of Battery Energy Storage Systems (BESS) in the Spanish electricity market. To achieve this, a simulation tool has been developed in Excel-VBA, designed to evaluate both the technical performance and the economic feasibility of different battery configurations and operating strategies. The ultimate purpose is to provide a practical and transparent framework that supports decision-making in early stages of BESS project development.

In addition, the work defines the following specific objectives:

- Regulatory and market analysis: Review the Spanish regulatory framework and the functioning of the wholesale market, identifying the main opportunities, limitations, and barriers affecting the deployment of BESS, both as stand-alone assets and in hybrid configurations.

- Technological assessment: Compare the main battery technologies currently available, analysing their technical and economic characteristics (efficiency, lifetime, cost, scalability) and evaluating their suitability for different applications.

- Model development: Design and implement a simulation tool in Excel capable of integrating real market data (OMIE prices, regulated charges) and technical parameters of batteries. The tool allows the definition of operating thresholds and the evaluation of strategies such as arbitrage, time shifting, or participation in potential capacity markets.

- Scenario evaluation: Apply the tool to representative operating scenarios, analysing economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), as well as technical variables like equivalent cycles, degradation, and energy flows.

- Sensitivity analysis: Assess the impact of key parameters such as investment costs, efficiency, lifetime, and market prices on project profitability, in order to identify the most critical conditions for economic viability.

Through these objectives, the work seeks not only to quantify the current profitability of storage projects in Spain but also to highlight the role of BESS as an enabling technology for the energy transition.

4. Materials and Methods (Methodology)

The methodology of this work is based on the design and implementation of a techno-economic simulation tool in Excel-VBA, which allows the evaluation of BESS projects under realistic operating conditions in the Spanish electricity market. The tool integrates technical parameters of batteries, real and simulated wholesale prices (OMIE), regulated network charges, and economic variables in order to produce energy and financial indicators over a 20-year horizon.

4.1 Input parameters

The model begins with the definition of the technical and economic characteristics of the storage system. Users can specify the installed power, capacity, efficiency, depth of discharge, lifetime, and number of equivalent cycles, as well as the investment and operating costs. These inputs are structured in a parameter sheet that clearly distinguishes between user-defined values and automatically derived results, which can be seen in figures 1 and 2.

Parameter	Value
Charging/Discharging Power (MW)	5
Discharge Rate (C-rate)	0.5-C
Battery Technology	NMC/LMO
Charging threshold (low percentile)	0.15
Discharging threshold (high percentile)	0.85
Connection type	Behind the meter
Tariff type	6.4 TD
Year to Simulate	2034
Month to Simulate	12
Day to Simulate	15

Figure 1. Input parameters of the BESS simulation tool.

System Description	Value
Capacity (MWh)	10
Cycle Efficiency	0.92
Depth of Discharge (DoD)	0.9
Lifetime (cycles)	3500
Minimum Profit	25
Operating Cost (€/kWh)	7
Cost per Cycle (€/cycle)	20
Investment Cost (€/kWh)	311

Figure 2. System description parameters of the BESS simulation tool.

In addition, the tool incorporates the regulated tariffs of the Spanish system. Depending on the contracted power and voltage level, different access periods and tolls are applied, which directly affect the cost of charging the battery. This is managed through a reference table that links each hour of the year with its corresponding tariff period (see *Figure 3)*

Tariff group	Voltage	Contracted power
6.4 TD	≥145 kV	No restriction
6.3 TD	≥ 72,5 kV y < 145 kV	No restriction
6.2 TD	≥ 30 kV y < 72,5 kV	No restriction
6.1 TD	≥ 1 kV y < 30 kV	No restriction
3.0 TD	<1kV	> 15 kW
2.0 TD	<1kV	≤ 15 kW

Figure 3. Tariff group by contracted power and voltage level

4.2 Simulation logic

The core of the tool is the simulation of battery operation on a daily, monthly, and annual basis. For each hour, the model compares the market price with two thresholds: a charging threshold (percentile of the cheapest hours) and a discharging threshold (percentile of the most expensive hours). If the price is below the first threshold, the battery charges; if it is above the second threshold, it discharges. The model updates the state of charge of the battery at each step, considering round-trip efficiency and capacity limits.

In addition, the model applies a minimum profit condition: if the arbitrage operations of a day do not exceed a predefined profitability margin, the battery remains idle. This feature prevents unrealistic operation in low-spread conditions.

4.3 Price data and projection

Historical hourly price data are taken from OMIE records and complemented with simulated future trajectories up to 2034, generated by a VBA macro. This projection considers average hourly profiles, long-term decreasing trends in prices, random variability, and extreme solar events with very low or even negative prices. To extend the analysis horizon to 2045, another macro replicates the behaviour of the last simulated years, applying degradation factors and battery replacement costs when lifetime limits are reached.

4.4 Output Indicators

The simulation produces a comprehensive set of technical and economic results. At the technical level, the tool reports the energy charged and discharged, average purchase and sale prices, captured spread, and equivalent cycles per year. At the economic level, it generates annual net cash flows and includes the possibility of considering battery replacement once the cycle limit is reached. These values feed into the calculation of Net Present Value (NPV) and Internal Rate of Return (IRR), which are used to assess project profitability (see *Figures 4 and 5*).

Indicator	Result
Total Energy Charged (MWh)	1820
Total Energy Discharged (MWh)	1825
Total Charging Cost (€)	117917.1
Total Revenue from Sales (€)	197672.8
Net Profit (€)	79755.69
Number of Equivalent Cycles	202.7778
Average Charging Price (€/MWh)	64.7896
Average Selling Price (€/MWh)	108.3138
Average Captured Spread (€/MWh)	43.5242

Figure 4. Annual technical and economic results of the BESS simulation

The tool is structured in four main blocks: **parameters, simulations, results, and economic analysis**; which makes it flexible and user-friendly, enabling its application to different technologies, system sizes, and operational strategies.

5. Results

5.1 Daily operation example

To illustrate the functioning of the simulation tool, Figure 5 presents an example of daily operation, showing the relationship between OMIE market prices and the battery state of charge. The model applies two operating thresholds: when the price falls below the charging threshold, the battery is charged, while discharge occurs if the price exceeds the discharging threshold.

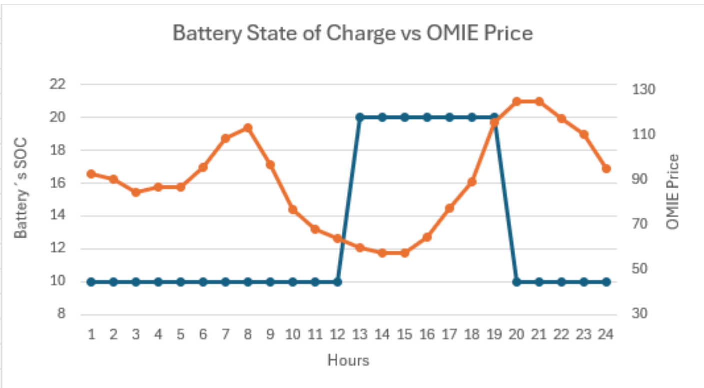

Figure 5. Battery state evolution vs OMIE Price

In the example, the battery remains idle during the first hours of the day as the price does not cross the defined thresholds. Between hours 7 and 10, the system identifies a period of high prices and starts discharging, reaching its maximum state of charge at hour 10. Later, during hours of low market prices (between 14 and 17), the battery charges again, taking advantage of cheap energy. Finally, in the evening peak, the battery discharges to capture the spread between low and high price periods.

This daily profile highlights the arbitrage potential of BESS in the Spanish market. It also shows how the tool enforces the operational constraints of the system: the battery never exceeds its maximum state of charge, efficiency losses reduce the net energy delivered, and idle periods are preserved when profitability thresholds are not met. This approach ensures that the simulated behaviour remains realistic and avoids overestimating revenues in scenarios with low spreads.

Month	Day	Hour	OMIE price	Period	Extra ATR (€/kWh)	Charge	Discharge	Charged Energy (MWh)	Discharged Energy (MWh)	SOC	Charge Cost (€)	Revenue from Sale (€)
12	15	1	92.97	6	0.000211	0	0	0	0	10.0	0	0
12	15	2	90.33	6	0.000211	0	0	0	0	10.0	0	0
12	15	3	84.82	6	0.000211	0	0	0	0	10.0	0	0
12	15	4	87.17	6	0.000211	0	0	0	0	10.0	0	0
12	15	5	86.93	6	0.000211	0	0	0	0	10.0	0	0
12	15	6	95.77	6	0.000211	0	0	0	0	10.0	0	0
12	15	7	108.81	6	0.000211	0	0	0	0	10.0	0	0
12	15	8	113.33	2	0.005482	0	0	0	0	10.0	0	0
12	15	9	97.02	1	0.010526	0	0	0	0	10.0	0	0
12	15	10	77.17	1	0.010526	0	0	0	0	10.0	0	0
12	15	11	68.23	1	0.010526	0	0	0	0	10.0	0	0
12	15	12	64.02	1	0.010526	1	0	10	0	10.0	745.46	0
12	15	13	59.68	1	0.010526	1	0	0	0	20.0	0	0
12	15	14	57.67	2	0.005482	1	0	0	0	20.0	0	0

Figure 6. Example of daily simulation: OMIE prices, charging/discharging decisions, energy flows, and associated costs.

5.2 Annual aggregated results

The annual results of the simulation are presented in Figure 7. The indicators provide an overview of the technical performance and the economic feasibility of the storage project under the baseline scenario. During the year simulated, the battery charged a total of 1,820 MWh and discharged 1,825 MWh, resulting in a net delivery of energy close to the expected round-trip balance. The small difference between charged and discharged energy reflects the efficiency losses of the system.

From the economic perspective, the total charging cost amounted to approximately 117,917 €, while revenues from selling the discharged energy reached 197,673 €. This generated a positive net profit of 79,756 € for the year. The average spread captured between purchase and selling prices was 43.5 €/MWh, which illustrates the ability of the battery to take advantage of daily price fluctuations in the Spanish wholesale market.

In terms of technical operation, the system completed around 203 equivalent cycles during the year. This value is consistent with the use of a storage asset designed for arbitrage purposes, as it corresponds to a relatively low cycling intensity compared to the lifetime capacity of modern lithium-ion batteries. The average charging price was 64.8 €/MWh, while the average selling price reached 108.3 €/MWh, confirming that arbitrage is only profitable when there is a significant price spread between valley and peak hours.

Overall, the annual results confirm that under current assumptions, BESS can generate positive yearly cash flows, although the magnitude of profits remains modest when compared with the high capital investment required. These findings align with national studies that underline the current limitations of arbitrage-only business models in Spain.

Indicator	Result
Total Energy Charged (MWh)	1820
Total Energy Discharged (MWh)	1825
Total Charging Cost (€)	117917.1
Total Revenue from Sales (€)	197672.8
Net Profit (€)	79755.69
Number of Equivalent Cycles	202.7778
Average Charging Price (€/MWh)	64.7896
Average Selling Price (€/MWh)	108.3138
Average Captured Spread (€/MWh)	43.52424

Figure 7. Annual technical and economic results of the BESS simulation.

5.3 Monthly Perfomance

To better understand the dynamics of BESS operation, Figure 8 shows the monthly distribution of energy charged and discharged, together with the corresponding profit. This representation highlights how both technical and economic results vary throughout the year depending on market conditions.

The energy charged and discharged remains relatively constant across months, reflecting the daily operation logic of the model. However, the associated revenues and profits show a clear variability. During certain months, higher wholesale prices in peak hours lead to larger spreads between charging and discharging, which translates into greater profitability. In contrast, months with lower volatility or compressed spreads generate lower margins, even if the total energy transacted remains similar.

This seasonal behaviour illustrates a key characteristic of the Spanish electricity market: while renewable generation patterns tend to reduce prices in spring and summer, demand peaks in winter and late summer increase spreads and make arbitrage operations more attractive. Consequently, profitability is not only a function of the total energy managed, but also of the timing of charging and discharging relative to price fluctuations.

The monthly analysis therefore provides valuable insight for investors. It shows that annual profitability is driven by a limited number of favourable months, while other periods contribute much less to overall revenues. This underlines the importance of flexible operating strategies and, in the future, potential participation in complementary markets such as balancing or capacity mechanisms to stabilize income.

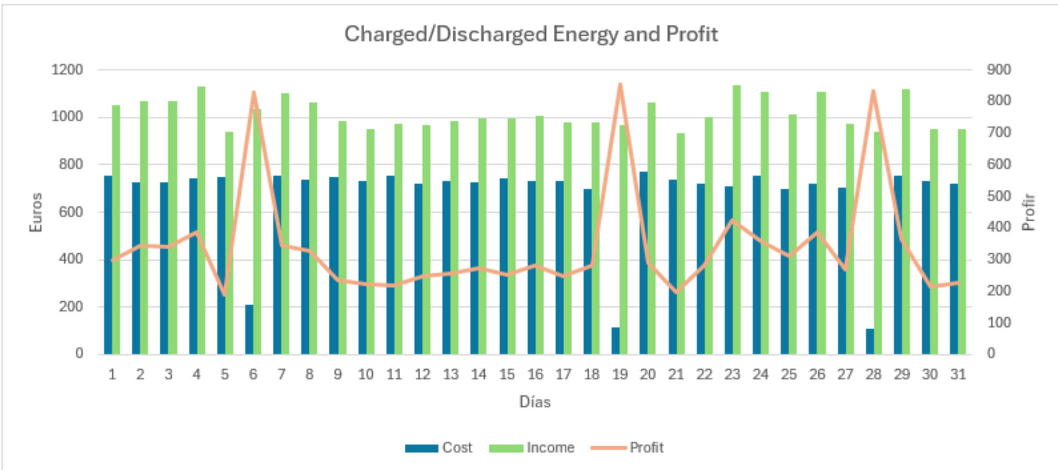

Figure 8. Monthly charged/discharged energy and profit.

5.4 Cycles and Degradation

Figure 9 presents the distribution of equivalent cycles per month, which provides insight into the intensity of battery usage across the year. The number of equivalent cycles varies depending on market conditions, with higher cycling occurring in months where daily spreads are more pronounced. Conversely, in months with compressed spreads or reduced volatility, the battery performs fewer charging and discharging operations. Over the entire year, the system completed approximately 203 equivalent cycles, which corresponds to a moderate level of utilization compared to the technical lifetime of lithium-ion batteries (typically above 3,500 cycles). This result confirms that under an arbitrage strategy, the asset does not experience excessive degradation in the short term, as it is not cycling every day to its full capacity.

The analysis also shows that degradation is not uniform across months: periods with higher profitability coincide with a greater number of cycles, which accelerates wear on the system. This trade-off between revenue maximization and lifetime consumption is a key factor in project design, since excessive cycling can reduce the economic life of the asset and force earlier reinvestment. Therefore, understanding the monthly distribution of equivalent cycles is essential for evaluating the long-term sustainability of the business model. Investors must balance short-term profitability with the need to preserve the technical lifespan of the battery, ensuring that financial returns are not eroded by premature replacement costs.

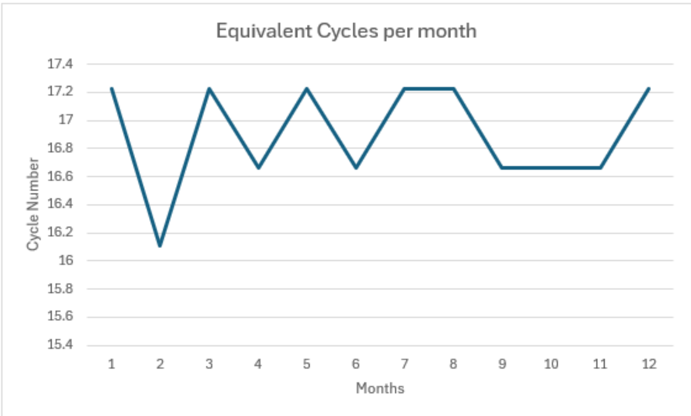

Figure 9. Equivalent cycles per month.

5.5 Sensitivity Analysis

A sensitivity analysis was carried out to assess the impact of key parameters on the profitability of BESS projects. The purpose is to identify which variables have the greatest influence on financial performance and to understand the conditions under which storage becomes a viable investment.

Three main aspects were evaluated:

1. Charging and discharging thresholds
   By varying the percentile thresholds that define charging and discharging hours, the model shows how arbitrage results are highly sensitive to this parameter. Conservative thresholds (e.g., 0.15 for charging and 0.85 for discharging) result in fewer cycles but higher average spreads, leading to more profitable operations with reduced degradation. On the contrary, looser thresholds increase the number of cycles but reduce the spread, often lowering overall profitability.

Configuration 1 – Thresholds 0.15 / 0.85 (Full Results)

Indicator	Result
Total Energy Charged (MWh)	1,820
Total Energy Discharged (MWh)	1,825
Total Charging Cost (€)	117,917
Total Revenue from Sales (€)	197,673
Net Profit (€)	79,756
Number of Equivalent Cycles	202.78
Average Charging Price (€/MWh)	64.79
Average Selling Price (€/MWh)	108.31
Average Captured Spread (€/MWh)	43.52
Net Present Value (NPV)	-1,151,293 €
Internal Rate of Return (IRR)	5.51%

Figure 10. Configuration 1 –Results

Configuration 2 – Thresholds 0.30 / 0.70 (Full Results)

Indicator	Result
Total Energy Charged (MWh)	1,920
Total Energy Discharged (MWh)	2,110
Total Charging Cost (€)	136,379
Total Revenue from Sales (€)	214,251
Net Profit (€)	77,872
Number of Equivalent Cycles	234.44
Average Charging Price (€/MWh)	71.03
Average Selling Price (€/MWh)	101.54
Average Captured Spread (€/MWh)	30.51
Net Present Value (NPV)	-1,539,322 €
Internal Rate of Return (IRR)	11.31%

Figure 11. Configuration 2 –Results

When comparing the two configurations, the results confirm the expected trade-off between the number of cycles and the profitability per cycle. Configuration 1 (0.15 / 0.85) performed fewer equivalent cycles (203 per year) but achieved a higher average spread (43.5 €/MWh), leading to more selective but efficient arbitrage. In contrast, Configuration 2 (0.30 / 0.70) resulted in more frequent cycling (234 cycles) and higher total energy throughput, but the average spread was significantly reduced (30.5 €/MWh).

From an economic perspective, both cases show a negative Net Present Value (NPV), but with notable differences in Internal Rate of Return (IRR). Configuration 1 achieved a modest IRR of 5.5%, while Configuration 2 reached 11.3%. Although the second configuration improved financial performance in relative terms, the lower spreads reduced overall profitability, and the accelerated cycling implies greater long-term degradation.

These findings suggest that conservative thresholds provide higher margins and help preserve battery life, while looser thresholds increase short-term revenues but at the cost of higher degradation and a less favourable balance between NPV and IRR. In practice, the optimal operating point would likely fall between these two extremes, depending on market volatility and the investor's tolerance for risk and degradation.

2. <u>Battery size and Technology</u>
   Increasing storage capacity while keeping power constant (longer-duration systems) leads to

higher absolute revenues, as more energy can be shifted between low- and high-price periods. However, the marginal profitability per unit of energy decreases beyond a certain point, since not all additional capacity can be used efficiently every day. This result suggests that optimal battery sizing is a trade-off between investment cost and utilization rate.

As shown in Figure 12, the 30 MWh LFP system achieved significantly higher annual revenues and net profit compared to smaller systems, thanks to its ability to manage larger energy volumes. It charged 5,460 MWh and discharged 5,475 MWh, with total revenues of 554,433 € and a net profit of 200,592 €. However, despite these strong operational results, the large investment cost of such a system resulted in a highly negative NPV (–3,993,531 €) and an IRR of only 7.78%. This indicates that, under current cost assumptions, large-scale projects struggle to recover capital, even if they perform well technically.

By contrast, Figure 13 shows the results for the 10 MWh NMC/LMO system, which delivered much lower absolute revenues (197,673 €) and net profit (79,756 €), consistent with its smaller size and throughput (1,820 MWh charged, 1,825 MWh discharged). Nevertheless, its reduced capital requirements allowed it to achieve a less negative NPV (–1,151,293 €), although the IRR was also lower at 5.51%.

Taken together, these results confirm the trade-off highlighted at the beginning of this section: larger systems maximize revenues but face a heavier investment burden, while smaller systems reduce financial risk but generate modest profits. In practice, optimal battery sizing must balance these two forces. At current technology costs, intermediate storage sizes may offer a more favourable compromise between utilization rate and investment recovery, making them more attractive for investors in the Spanish market.

Scenario 1 – 30 MWh LFP (Full Results)

Indicator	Result
Total Energy Charged (MWh)	5,460
Total Energy Discharged (MWh)	5,475
Total Charging Cost (€)	353,751
Total Revenue from Sales (€)	554,433
Net Profit (€)	200,592
Number of Equivalent Cycles	202.78
Average Charging Price (€/MWh)	64.79
Average Selling Price (€/MWh)	101.25
Average Captured Spread (€/MWh)	36.46
Net Present Value (NPV)	-3,993,531 €
Internal Rate of Return (IRR)	7.78%

Figure 12. Scenario 1 –Results

Scenario 2 – 10 MWh NMC/LMO (Full Results)

Indicator	Result
Total Energy Charged (MWh)	1,820
Total Energy Discharged (MWh)	1,825
Total Charging Cost (€)	117,917
Total Revenue from Sales (€)	197,673
Net Profit (€)	79,756
Number of Equivalent Cycles	202.78
Average Charging Price (€/MWh)	64.79
Average Selling Price (€/MWh)	108.31
Average Captured Spread (€/MWh)	43.52
Net Present Value (NPV)	-1,151,293 €
Internal Rate of Return (IRR)	5.51%

Figure 13. Scenario 2 –Results

3. Technology choice

Different chemistries show distinct economic profiles. NMC-based batteries provide higher energy density but shorter lifetime and higher costs, while LFP technology offers longer durability and lower investment per cycle, making it more attractive for stationary applications. The model confirms that profitability indicators such as NPV and IRR are strongly dependent on the chosen technology, with LFP typically outperforming NMC in long-term scenarios.

The sensitivity analysis demonstrates that the economic viability of storage is not only determined by market prices but also by technical decisions and operating strategies. Optimal parameter selection can significantly improve profitability and extend the useful life of the system. For investors and project developers, this highlights the importance of flexible models capable of adapting to different market conditions and technological pathways.

The comparison between NCA and LFP chemistries highlights the impact of technology choice on both technical and economic outcomes.
From a technical perspective, the NCA-based system (Scenario 3) achieved slightly higher annual energy throughput, with 3,650 MWh discharged compared to 3,550 MWh for LFP (Scenario 4). This translated into higher gross revenues (€402,589 vs. €364,058). However, these gains came at the cost of higher charging expenses (€226,344 for NCA vs. €213,783 for LFP), which reduced the advantage in net profit. As a result, the difference in profitability narrowed, with NCA reaching €176,246 of net profit and LFP €150,275.
When considering economic indicators, the outcomes shift in favor of LFP. Despite slightly lower revenues, the Net Present Value (NPV) for LFP was less negative (-€2.95M vs. -€3.00M for NCA), and the Internal Rate of Return (IRR) was higher (8.00% vs. 7.24%). This suggests that LFP technology, with its lower investment per cycle and better cost-efficiency, offers a more sustainable profile for long-term stationary storage projects.
The spread captured per MWh reinforces this conclusion: 44.5 €/MWh for NCA vs. 38.2 €/MWh for LFP. While NCA can exploit higher market differentials due to its energy density, its shorter lifetime and higher capital cost penalize overall returns. LFP, conversely, demonstrates more balanced results with lower spreads but superior economic indicators.
In summary, the results confirm that LFP outperforms NCA from a long-term investment perspective, as its lower costs and longer durability outweigh the revenue advantage of NCA. This reflects the general industry trend favouring LFP for stationary applications, where resilience and cost-effectiveness are prioritized over high energy density.

Scenario 3 – NCA Technology (Full Results)

Indicator	Result
Total Energy Charged (MWh)	3,440
Total Energy Discharged (MWh)	3,650
Total Charging Cost (€)	226,344
Total Revenue from Sales (€)	402,589
Net Profit (€)	176,246
Number of Equivalent Cycles	202.78
Average Charging Price (€/MWh)	65.80
Average Selling Price (€/MWh)	110.30
Average Captured Spread (€/MWh)	44.50
Net Present Value (NPV)	-3,003,414 €
Internal Rate of Return (IRR)	7.24%

Figure 14. Scenario 3 –Results

Scenario 4 – LFP Technology (Full Results)

Indicator	Result
Total Energy Charged (MWh)	3,320
Total Energy Discharged (MWh)	3,550
Total Charging Cost (€)	213,783
Total Revenue from Sales (€)	364,058
Net Profit (€)	150,275
Number of Equivalent Cycles	197.22
Average Charging Price (€/MWh)	64.40
Average Selling Price (€/MWh)	102.55
Average Captured Spread (€/MWh)	38.16
Net Present Value (NPV)	-2,947,982 €
Internal Rate of Return (IRR)	8.00%

Figure 15. Scenario 4 –Results

6. Discussion

The results obtained in this study provide valuable insights into the technical and economic performance of battery energy storage systems (BESS) within the Spanish electricity market. The analysis shows that operational strategies, system size, and technology selection strongly influence profitability, confirming that storage is not only a matter of energy arbitrage but also of optimizing design parameters and investment decisions.

First, the sensitivity analysis on charging and discharging thresholds demonstrated that market participation strategies are highly dependent on the percentile selection. Conservative thresholds reduced the number of cycles but achieved higher spreads, improving operational margins, while looser thresholds increased utilization but eroded profitability. This aligns with the findings of international studies, which highlight the importance of balancing cycle frequency and degradation costs in order to maximize net value over the project lifetime [1,2].

Second, battery size was shown to be a critical driver of profitability. Larger systems (30 MWh LFP) generated higher absolute revenues but suffered from diminishing marginal returns per unit of capacity, since not all stored energy could be effectively monetized. Smaller systems (10 MWh NMC/LMO), in contrast, exhibited lower revenues but more efficient capacity utilization. These results confirm the existence of an optimal trade-off between system size, investment costs, and market opportunities, which is consistent with previous techno-economic analyses of storage deployment in European markets [3].

Finally, the comparison between technologies revealed significant differences in economic performance. While NCA and NMC chemistries benefited from higher energy density and spreads, their shorter lifetimes and higher costs translated into worse NPVs and IRRs. LFP technology, with lower investment per cycle and longer durability, achieved better long-term performance despite lower spreads. This reinforces current industry trends that position LFP as the preferred technology for stationary storage applications [4,5].

Overall, the discussion highlights that the economic viability of BESS projects cannot be assessed solely on market prices. Instead, it requires a comprehensive evaluation of technical parameters, degradation, and capital costs. For policymakers, these results underline the need for regulatory frameworks that properly value the flexibility and grid services provided by storage. For investors, they emphasize the importance of carefully tailoring system design and technology choice to market conditions. Future research could expand on this work by incorporating additional revenue streams (e.g., ancillary services or capacity markets), stochastic modelling of price uncertainty, and hybrid configurations that combine different storage technologies. Such extensions would provide a more complete picture of the role BESS can play in accelerating the energy transition in Spain and beyond.

7. Conclusions

This study has carried out a comprehensive technical and economic assessment of battery energy storage systems (BESS) in the Spanish electricity market. Using an Excel-based simulation tool, different operational strategies, system sizes, and battery technologies were evaluated to determine their impact on project profitability. The results provide several key conclusions that contribute to a better understanding of the challenges and opportunities of energy storage in Spain.

1. Impact of operational thresholds

The first set of simulations revealed that battery profitability is highly sensitive to the definition of charging and discharging thresholds. Conservative thresholds (e.g., 0.15 for charging and 0.85 for discharging) limited the number of annual cycles but achieved higher spreads between purchase and sale prices. This strategy improved operational margins and reduced degradation, extending the system's useful life. On the contrary, looser thresholds increased the frequency of cycles and total discharged energy but captured smaller spreads, which ultimately reduced economic results.

This finding shows that the optimal operation of a BESS cannot rely exclusively on maximizing the number of cycles, but must instead strike a balance between utilization, degradation, and arbitrage opportunities. Operators should therefore carefully adjust thresholds according to market price volatility and project lifetime expectations.

2. Influence of system size

The analysis of two different capacities (30 MWh and 10 MWh) confirmed the existence of economies of scale but also of diminishing returns. Larger systems generated higher absolute revenues, since more energy could be shifted between low- and high-price periods. However, the additional capacity was not always fully utilized, which penalized marginal profitability. Smaller systems achieved lower revenues in absolute terms but presented better efficiency in the use of their capacity and lower investment needs.

This result highlights that optimal battery sizing is a fundamental decision in project development. Oversizing leads to underutilized assets, while under sizing limits income opportunities. Therefore, dimensioning should not be based only on technical potential but must also consider the volatility of market prices, the expected frequency of arbitrage opportunities, and financing constraints.

3. Technology choice and performance

A comparison between chemistries (NMC/LMO, NCA, and LFP) revealed clear differences in both technical and economic performance. NMC and NCA technologies benefited from higher energy density and higher spreads captured per MWh, but their shorter lifetimes and higher investment costs resulted in more negative NPVs and lower IRRs. By contrast, LFP technology, with lower energy density but greater durability and lower cost per cycle, delivered superior long-term indicators.

These findings align with current industry practice, where LFP is increasingly adopted for stationary applications due to its resilience, safety, and favourable cost profile. For investors and developers, this confirms that technology choice is not a neutral factor but a decisive variable in ensuring the long-term success of BESS projects.

4. Policy and regulatory implications

The results also highlight the importance of the regulatory environment in enabling the economic viability of storage. In the Spanish market, the absence of a stable remuneration mechanism for capacity or flexibility services limits the profitability of storage projects that rely solely on price arbitrage. As shown in the simulations, even under favourable price spreads, NPVs remained negative, reflecting the challenge of recovering investment exclusively through energy markets.

For policymakers, this underlines the need to design market frameworks that value the multiple services provided by BESS, including grid stability, renewable integration, and peak shaving. The implementation of capacity markets or ancillary service remuneration schemes would significantly improve the bankability of projects and accelerate deployment.

5. Methodological contributions

Beyond the numerical results, this work also contributes methodologically by developing a transparent, flexible, and user-friendly simulation tool in Excel. The model allows the adjustment of parameters such as thresholds, system size, technology, tariff type, and investment costs, providing a versatile platform for sensitivity analysis. This tool can be applied to evaluate specific projects, test different regulatory scenarios, or support investment decision-making, representing an added value beyond the scope of the study itself.

6. Limitations and future research

It should be noted that the analysis focused primarily on the energy arbitrage strategy and did not account for other potential revenue streams such as ancillary services, capacity markets, or bilateral contracts. Moreover, price forecasts were treated deterministically, without considering stochastic approaches that could capture the uncertainty of future market conditions. These limitations open up avenues for further research. Future extensions of the model could integrate:

- Probabilistic simulations of market prices.
- Inclusion of multiple revenue streams.
- Hybrid systems combining batteries with renewable generation or hydrogen storage.
- Analysis of degradation models with higher technical granularity.

Final reflection

Overall, the conclusions of this study confirm that BESS projects in Spain face significant challenges if based solely on arbitrage, but they also present a wide range of opportunities if technical, economic, and regulatory factors are carefully aligned. Profitability depends not only on market signals but also on the ability to optimize operational strategies, choose the right technology, and size the system appropriately. In addition, the role of public policies will be decisive in determining whether energy storage can become a fully integrated and profitable pillar of the Spanish power system.

In summary, this work demonstrates that battery storage is a key element in achieving the energy transition objectives. With adequate regulation, optimal design, and complementary revenue sources, BESS can play a central role in providing flexibility, improving renewable integration, and ensuring the stability of the electricity system in Spain.

Appendix A

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

References

1. IEA. International Energy Agency. Batteries and Secure Energy Transitions. https://www.iea.org/reports/batteries-and-secure-energy-transitions.
2. MITECO**.** Ministerio para la Transición Ecológica y el Reto Demográfico. *Estategia de Almacenamiento.* [En línea] febrero de 2021. https://www.miteco.gob.es/content/dam/miteco/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf.
3. BOE. Gobierno de España. Real Decreto 1183/2020, de 29 de diciembre, de acceso y conexión a las redes de transporte y distribución de energía eléctrica. [En línea] https://www.boe.es/eli/es/rd/2020/12/29/1183/con.
4. IDAE**.** Instituto para la Diversificación y Ahorro de la Energía. *Ánalisis del estado actual del almacenamiento detrás del contador en España.* [En línea] Junio de 2021. https://www.idae.es/publicaciones/analisis-del-estado-actual-del-almacenamiento-detras-del-contador-en-espana.
5. BID. Banco Interamericano de Desarrollo. *Incorporación de almacenamiento de energía en los sistemas eléctricos*. [En línea] Noviembre de 2023. https://publications.iadb.org/es/incorporacion-de-almacenamiento-de-energia-en-los-sistemas-electricos-experiencias-internacionales
6. Rodríguez, Diego Rodríguez. Fedea. *Comentarios sobre la reforma del mercado eléctrico.* [En línea] Marzo de 2023. https://documentos.fedea.net/pubs/ap/2023/ap2023-07.pdf.
7. FENIE. Federación Nacional de Empresarios de Instalaciones de España. Principales puntos del RD 1183/2020. [En línea] https://apeme.es/wp-content/uploads/2021/02/resumen_fenie_rd_acceso_y_conexion_v2.pdf.

8. EMBER. *European Wholesale Electricity Price Data.* [En línea] https://ember-energy.org/.
9. IDAE. Instituto para la Diversificación y Ahorro de la Energía. *Proyectos Innovadores de Almacenamiento Energético FEDER.* [En línea] https://www.idae.es/ayudas-y-financiacion/proyectos-innovadores-de-almacenamiento-energetico-feder-21-27.