FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Technical and Economic Analysis of Hybridisation of Renewable Energy Projects, including Energy Storage Systems

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October 14, 2025

Resumo

A integração de sistemas de armazenamento de energia por bateria (BESS) em centrais solares fotovoltaicas (PV) tem-se afirmado como uma solução relevante para responder aos desafios de flexibilidade e fiabilidade impostos pela crescente penetração de fontes renováveis variáveis na rede elétrica. Este trabalho incide sobre a análise técnica e financeira da implementação de um sistema BESS numa central PV de 40,23 MWp situada em Portugal, com o objetivo de maximizar o aproveitamento da geração de energia solar, reduzir o *curtailment* e permitir a injeção de energia em horários de maior procura e de menor produção de energia solar.

A abordagem metodológica parte da caracterização do sistema existente, das restrições técnicas impostas pela ligação à rede (31,9 MW) e da seleção de uma tecnologia comercial adequada: o PowerTitan 2.0 da *Sungrow*. É desenvolvido um modelo de degradação baseado em parâmetros reais de fabrico, que considera perdas de capacidade (SoH), eficiência energética (RTE) e ciclos diários médios. Em paralelo, constrói-se um modelo económico que inclui custos de investimento (CapEx), operação (OpEx), impostos e receitas por fornecimento de energia à Rede Elétrica de Serviço Público (RESP).

A análise compara diferentes configurações de autonomia (2 h vs 4 h), demonstrando que, devido à potência limitada de exportação, o sistema de 2 horas permite maior utilização efectiva e retorno sobre o investimento. O modelo calcula indicadores como Valor Atual Líquido (NPV), Taxa Interna de Rentabilidade (IRR), Payback, Custo Nivelado de Armazenamento (LCOS) e taxa de esforço do sistema. Realizam-se análises de sensibilidade e cenários otimista e conservador, identificando condições-limite de viabilidade.

Os resultados confirmam que, na ausência de incentivos específicos para armazenamento em Portugal, os projetos permanecem economicamente marginais. Contudo, pequenas melhorias no preço de venda da energia ou reduções no CapEx podem tornar a integração do BESS financeiramente viável. A dissertação conclui com propostas de políticas públicas e tarifárias que visam fomentar a adoção de BESS em sistemas PV, contribuindo assim para os objetivos nacionais de transição energética.

Palavras-chave: Armazenamento de Energia, Energia Fotovoltaica, Análise Financeira, BESS, *Curtailment*, LCOS, NPV, Degradação

Abstract

The integration of Battery Energy Storage Systems (BESS) into photovoltaic (PV) plants has emerged as a relevant solution to the flexibility and reliability challenges posed by the increasing penetration of variable renewable energy sources in the electricity grid. This work presents a technical and economic assessment of implementing a BESS in a 40.23 MWp PV plant located in Portugal, aiming to maximise solar energy utilisation, reduce curtailment, and enable energy injection during periods of higher demand and lower PV generation.

The methodological approach begins with the characterisation of the existing system, the technical constraints imposed by the grid connection (31.9 MW), and the selection of a commercially available technology, Sungrow's PowerTitan 2.0. A degradation model is developed based on real manufacturer parameters, accounting for capacity loss (State of Health), round-trip efficiency (RTE) degradation, and average daily cycling. In parallel, a financial model is constructed, incorporating capital expenditure (CapEx), operational expenditure (OpEx), taxation, and revenues from energy dispatch to the Public Service Electricity Grid (RESP).

The analysis compares different autonomy configurations (2 h vs 4 h), showing that, due to export power limitations, a 2-hour system enables more effective utilisation and higher return on investment. The model computes indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), payback period, Levelised Cost of Storage (LCOS), and system utilisation rate. Sensitivity analyses and scenario modelling (optimistic and conservative) are conducted to identify boundary conditions for financial viability.

The results confirm that, in the absence of specific incentives for energy storage in Portugal, such projects remain economically marginal. However, modest improvements in the energy selling price or reductions in CapEx can make BESS integration financially viable. The dissertation concludes with public policy and tariff recommendations aimed at promoting the adoption of BESS in PV systems, thereby supporting Portugal's national energy transition goals.

Keywords: Energy Storage, Photovoltaic, Financial Analysis, BESS, Curtailment, LCOS, NPV, Degradation

UN Sustainable Development Goals

The Sustainable Development Goals (SDGs), established by all United Nations Member States in 2015, represent a global call to action for building a more just, inclusive, and sustainable world. Comprising 17 interconnected goals (Figure 1), this initiative aims to eliminate poverty, reduce inequality, address climate change, and promote peace and prosperity for all by 2030.

Figure 1: The Sustainable Development Goals by United Nations [1]

In the context of energy systems, the long-standing trilemma of affordability, reliability, and sustainability continues to present significant challenges. While technical solutions are constantly evolving, their social acceptance and practical implementation add layers of complexity that must be considered by policymakers, engineers, and communities alike.

This thesis proposes a comprehensive approach to managing distribution systems more efficiently through the active involvement of end-users, ranging from individual citizens to large industrial players. By promoting a multi-energy systems perspective, the study highlights how integrating various energy sources and technologies can foster more resilient and cost-effective energy services.

The results of this work aim to empower stakeholders to make informed decisions that improve energy efficiency and accelerate the adoption of renewable sources. In doing so, this research directly contributes to climate mitigation efforts and supports a more sustainable energy transition.

Ultimately, this study aligns with several of the SDGs by addressing core issues such as renewable energy integration, system optimisation, and efficient resource management. Through the development and analysis of hybrid renewable energy systems combined with advanced control strategies, the research supports goals related to clean energy access, resilient infrastructure, climate action, and sustainable consumption.

The specific Sustainable Development Goals supported by this research include:

SGD	**Target**	**Contribution**	**Performance Indicators and Metrics**
7	7.1	Enhancing the efficiency of hybrid energy systems through advanced optimisation techniques, facilitating the increased use of renewable sources.	Increase in renewable energy share in the energy mix.
	7.2	Enhancing the efficiency of hybrid energy systems through advanced optimisation techniques, facilitating the increased use of renewable sources.	Increase in renewable energy share in the energy mix.
	7.3	Improving energy management and control strategies to enhance the reliability of distributed energy resources.	Percentage of energy efficiency improvements in microgrids.
8	8.1	Strengthening the resilience of energy infrastructure by integrating optimised hybrid configurations, reducing reliance on fossil fuels, and mitigating climate-related energy disruptions.	Increase in energy system resilience metrics and reduction in carbon footprint.
9	9.4	Implementing intelligent energy management solutions to improve system efficiency and reduce CO_2 emissions.	reduction in carbon footprint through optimised energy usage.

By leveraging cutting-edge optimisation strategies and innovative hybrid configurations, this study contributes to the practical role of sustainable energy goals. The findings offer a pathway toward more resilient, efficient, and economically viable renewable energy systems, reinforcing the broader vision of the SDGs.

Agradecimentos

Chegado ao fim deste percurso académico, é com gratidão que recordo todos os que, de forma direta ou indireta, contribuíram para que esta etapa fosse possível.

Ao Eng. Nuno Freitas, o meu sincero agradecimento pela oportunidade de integrar este projeto. Ao meu orientador, Eng. Márcio Sousa, deixo um especial reconhecimento pela dedicação, disponibilidade e boa disposição com que sempre me acompanhou. A sua experiência foi determinante para o sucesso do estágio e desta dissertação. Ao Prof. José Neves dos Santos, agradeço muito por ter aceite o convite mesmo já não exercendo funções. Agradeço claro também a orientação certeira e os contributos valiosos ao longo do processo.

Reconheço também o papel de todos os professores que, ao longo da licenciatura e do mestrado, me transmitiram conhecimento e sentido crítico.

Aos colegas de equipa e de departamento, agradeço o espírito de entreajuda e a boa disposição diária, que tornaram o ambiente de trabalho leve e motivador. Em particular, ao Gabriel Neneve e ao José Santos, o meu obrigado pelo apoio constante e pela ajuda técnica que foram dando, sempre procurando passar a motivação necessária.

À minha namorada, Beatriz, o meu mais profundo obrigado. Obrigado por estares sempre presente, mesmo nos dias mais difíceis, por cada palavra de incentivo e por acreditares sempre que ia conseguir. Esta conquista é também tua!

À minha família (pais, irmãs, avós e restantes) agradeço todo o carinho e confiança. Cada gesto e cada palavra de apoio fizeram parte deste caminho. Espero que se sintam representados neste trabalho, pois carrego comigo tudo o que me ensinaram.

Aos amigos de todas as horas, obrigado por partilharem comigo não só conquistas, mas também dúvidas, stress e alegrias. Em especial, aos Barcelenses e aos N2, por estarem sempre lá, por todas as gargalhadas e loucuras que tornaram os dias memoráveis.

A todos os que, de alguma forma, cruzaram este percurso — colegas, professores, familiares ou amigos — o meu sincero obrigado. Mais do que um trabalho académico, levo comigo memórias, amizades e aprendizagens que ficarão para além das páginas desta dissertação.

No momento da despedida, só me resta dizer: FEUP, foi uma honra.

João Vale

"Qualidade paga-se."

Beatriz Brandão

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List of Acronyms

AC	Alternating Current
AI	Artificial Intelligence
BESS	Battery Energy Storage System
BCP	Battery Connection Panel
BMS	Battery Management System
BSL	Battery Smart Lithium
CAPEX	Capital Expenditures
CPD	Cycles per Day
DC	Direct Current
DOD	Depth of Discharge
EDP	Energias de Portugal
EMS	Energy Management System
ESS	Energy Storage System
EU	European Union
EoL	End of Life
FEUP	Faculdade de Engenharia da Universidade do Porto
FIT	Feed-in Tariff
HRES	Hybrid Renewable Energy System
HV	High Voltage
HVAC	Heating Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal Rate of Return
LAB	Lead-Acid Battery
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
LFP	Lithium Iron Phosphate
LIB	Lithium-ion Battery
LID	Light Induced Degradation
LV	Low Voltage
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
MVA	Megavolt-Amperes
MVS	Medium Voltage System
MW	Megawatt
MWh	Megawatt-hour
MWp	Megawatt-peak
NPV	Net Present Value

OJIES	IEEE Open Journal of the Industrial Electronics Society
OPEX	Operating Expenditures
ORG	Onsite Renewable Generation
PCS	Power Conversion System
PHS	Pumped Hydro Storage
PNEC	Plano Nacional Energia e Clima
PR	Performance Ratio
PV	Photovoltaic
PVP	Photovoltaic Plant
PVSyst	Photovoltaic Software
REN	Redes Energéticas Nacionais
ROI	Return of Investment
RTE	Round-trip Efficiency
RTIEBT	Regulamento Técnico das Instalações Eléctricas de Baixa Tensão
SCADA	Supervisory Control and Data Acquisition
SOC	State of Charge
SOH	State-of-Health
TB	Terminal Box
TSO	Transmission System Operator
USA	United States of America
WT	Wind Turbine
Wp	Watt-peak
kVA	Kilo-Volt-Amperes
kWh	Kilowatt-hour

Chapter 1

Introduction

The global transition towards renewable energy is essential for reducing carbon emissions and ensuring a more sustainable energy future. However, the inherently variable and intermittent nature of solar and wind power poses substantial challenges in maintaining grid stability, balancing supply and demand, and ensuring efficient energy distribution.

Hybrid Renewable Energy Systems (HRES), which integrate multiple renewable sources with energy storage technologies, offer an effective strategy to address these limitations. By storing excess energy generated during periods of high availability and supplying it during peak demand or low-generation intervals, HRES improve grid reliability, maximises renewable resource utilisation, and reduces dependence on conventional backup systems such as diesel generators.

This dissertation explores the integration of a Battery Energy Storage System (BESS) into an existing renewable energy plant with the objective of enhancing both technical performance and economic viability. Several integration scenarios are evaluated, considering technical constraints, regulatory frameworks, and financial indicators. While the manufacturer often defines the detailed design of a BESS, this work focuses on optimising deployment and ensuring seamless integration within the hybrid system architecture.

Aligned with QUADRANTE's strategic vision, this research contributes to the optimisation of existing infrastructure, supports the sustainable energy transition, and strengthens the company's position in engineering-led innovation. By establishing structured methodologies for BESS integration in hybrid renewable energy projects, the study provides practical contributions towards the development of resilient, efficient, and future-oriented energy systems.

1.1 Research Environment

This dissertation was executed within QUADRANTE's Renewable Energy Division at its Porto office, an engineering consultancy at the forefront of sustainable infrastructure development. The research benefited from access to real-world project data, interdisciplinary collaboration with energy experts, and QUADRANTE's industry-leading technical frameworks, ensuring both academic rigour and practical applicability. Figure 1.1 shows the company's logo.

Figure 1.1: Quadrante logo.

1.2 Problem Statement and Objectives

One of the principal challenges associated with the broader adoption of renewable energy lies in its variability. Solar photovoltaic systems, for instance, only generate electricity during daylight hours, and even then, their output is strongly influenced by the angle of solar incidence and the presence of shading from nearby structures or vegetation. Similarly, wind turbines require specific wind speed ranges to operate efficiently. This intermittency often results in scenarios where either surplus energy is produced—exceeding immediate demand—or insufficient energy is available to meet consumption needs. Both situations can compromise grid stability and lead to wasted energy. To compensate for these imbalances, conventional energy sources are frequently used as a backup. However, this approach introduces drawbacks such as increased greenhouse gas emissions, environmental degradation, and long-term economic costs. In response to these limitations, hybrid renewable energy systems have been developed to incorporate energy storage and intelligent control strategies, thereby enhancing the reliability and effectiveness of renewable resource utilisation.

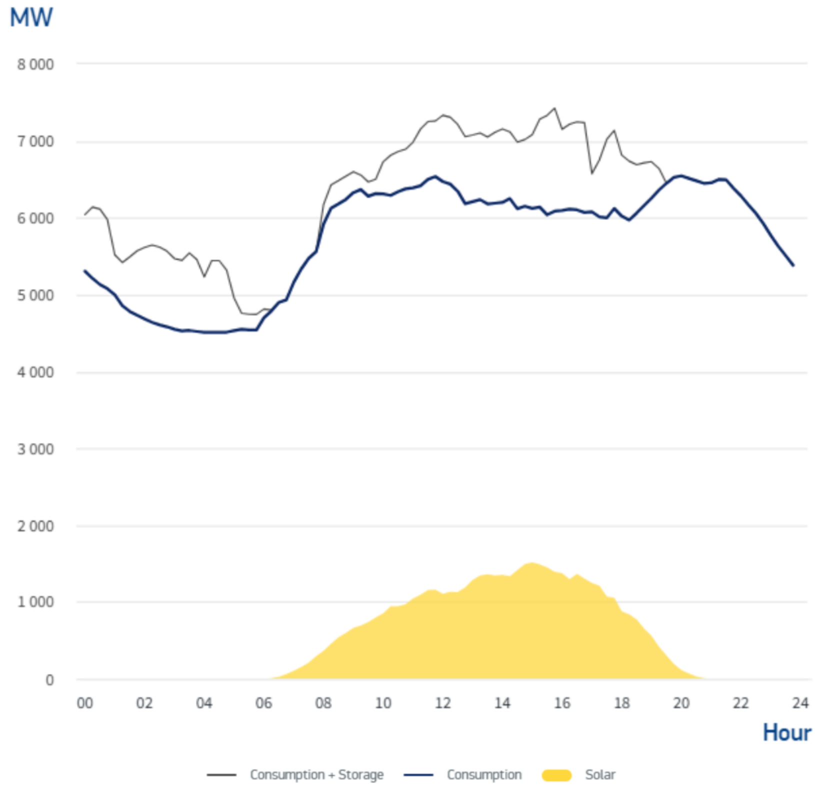

Figure 1.2: Solar Energy Production on the June 20th 2024, Portugal.

The graph in Figure 1.2 from [2] illustrates the variability in solar energy generation throughout the day, with peak production around midday and no generation during nighttime. The selected date corresponds to the summer solstice (the longest day of the year), emphasising the challenge of managing solar intermittency. The graph also presents consumption with and without energy storage. The visible difference between the lines shows how surplus energy produced during peak hours is stored and later used when energy generation is insufficient, highlighting the critical role of storage in hybrid renewable energy systems for ensuring grid stability and efficient energy utilisation.

This dissertation aims to explore both technical and economic solutions to optimise hybrid renewable energy systems by:

- Identifying and understanding various renewable energy sources and their production behaviours, along with the most suitable energy storage solutions for pairing.
- Creating hybrid systems that mix renewable energy technologies with storage solutions to solve specific problems.
- Analysing the technical feasibility and economic viability of hybrid combinations.
- Using current market data to show hybrid energy projects' financial benefits and feasibility.

- Developing a validation tool or software to assist in the planning and setting of future hybrid projects.
- Carrying out a detailed hybridisation study of a selected project to show how these findings can be applied in real-world scenarios.

The objective is to reduce dependence on conventional energy sources by creating a clean, efficient, and meaningful power generation framework that supports a higher share of renewable energy in the grid. These combined systems aim to make energy more available, reduce waste, improve the stability of the power grid, and help construct a more sustainable and reliable energy future.

1.3 Scope and Work Proposal

This research studies and tests renewable energy technologies with storage systems to find the best solutions for existing and future projects. The goal is to create models and simulations to understand how these systems work and improve their performance under different conditions. The study will also analyse the costs, including initial investments, expenses, and long-term advantages, to evaluate if these systems are cost-effective throughout the system's lifetime. Furthermore, the research will examine the compatibility and how these hybrid systems can be added to the current power grid, ensuring they function well together and maximise available resources.

The project will primarily focus on solar energy paired with battery energy storage systems while considering other well-established renewable sources such as wind. It will begin with a theoretical review and initial configuration of hybrid systems, emphasising those with the highest potential for efficient grid integration. Although various hybrid configurations exist, this study will prioritise PV+BESS setups, as they offer a compelling balance between reliability, flexibility, and economic feasibility. Moreover, PV+BESS is QUADRANTE's main scope in this area. These selected configurations will be further developed through computer simulations and cost evaluations to assess their technical and financial viability.

1.4 Motivation and Applications

The increasing demand for clean, reliable energy necessitates the development of solutions that overcome renewable energy's inherent limitations. Hybrid renewable energy systems are crucial in achieving energy security and sustainability. These systems are particularly significant for Portugal, with its abundant solar resources, as they can maximise renewable energy utilisation while ensuring grid stability. Commercial and Industrial consumers account for approximately 42% of global electricity consumption, making them significant contributors to carbon emissions [3]. Besides that, they are the primary targets of the projects developed by QUADRANTE. For this reason, these specific types of installations are also the focus of this work.

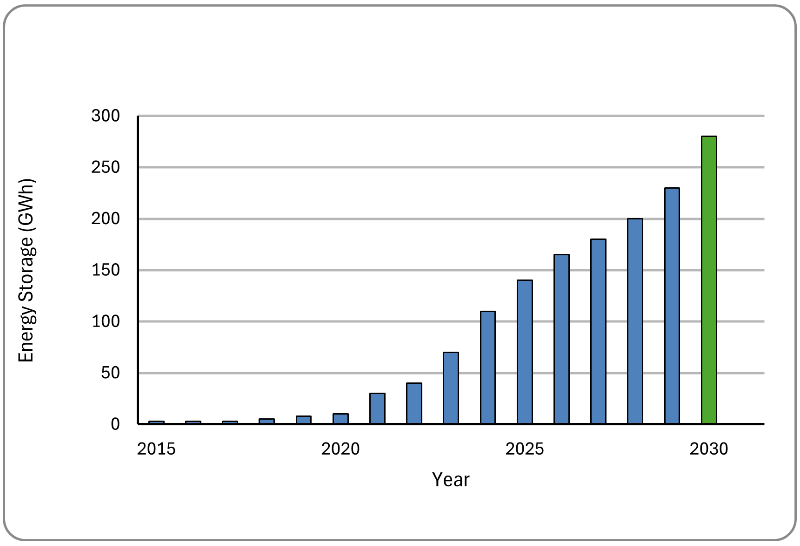

Figure 1.3: Global ESS trend, according to [4].

This rapid technological evolution is reflected in the global growth trend of ESS, as illustrated in Figure 1.3, highlighting the increasing worldwide deployment of these solutions to support the energy transition and enable greater integration of renewables, keeping the grid stable.

Applications include:

- Reducing carbon emissions and dependency on fossil fuels.
- Enhancing the reliability of rural and isolated power grids [5].
- Supporting national energy policies that encourage renewable energy and storage adoption.
- Providing insights and tools for industry stakeholders, including engineering firms and policymakers.

This work contributes to a more resilient energy sector, supporting future renewable energy growth by resolving intermittency and improving grid integration.

1.5 Structure of the Document

The document is structured to provide a logical and progressive exploration of HRES, with a particular focus on PV integration with BESS. The chapters are organised as follows:

Chapter 1 introduces the research context, objectives, scope, and motivation. It also outlines the structure of the dissertation and includes a summary of each chapter.

Chapter 2 presents a comprehensive literature review, covering hybrid system configurations, energy storage technologies, modelling approaches, control strategies, and economic assessment tools relevant to HRES.

Chapter 3 describes the Valen PV plant, including its technical specifications, simulation tools, and environmental compliance. This chapter establishes the foundation for the case study.

Chapter 4 details the integration of BESS into the Valen PV plant. It includes system architecture, operational logic, and component specifications, supported by manufacturer data.

Chapter 5 focuses on the dimensioning methodology and degradation modelling of the BESS. It compares different C-rate configurations and presents simulation results using Excel and PVsyst.

Chapter 6 provides a financial analysis of the BESS integration, including CAPEX, OPEX, revenue streams, and key financial metrics such as NPV, IRR, and LCOS. It also includes policy recommendations.

Chapter 7 concludes the dissertation by summarising the main findings, evaluating the achievement of objectives, and proposing future research directions.

Chapters 4, 5, 6 include summary sections at the end to consolidate key insights and facilitate the threader's understanding.

This structure ensures a coherent progression from theoretical foundations to practical application and economic feasibility, offering a comprehensive framework of the theme.

Chapter 2

Literature Review

2.1 Overview of Hybrid Renewable Energy Systems

Hybrid Renewable Energy Systems combine two or more renewable energy sources, like solar, wind, and hydropower, to overcome the weaknesses of using just one type. By using these sources together, HRES can reduce the need for backup systems and improve the stability of the power grid. For instance, solar energy works best during the day, while wind energy is often more substantial at night or in specific seasons. This teamwork ensures a steady energy supply, making HRES a good choice for connected and independent power systems [6].

HRES also support energy independence and reduces reliance on fossil fuels, aligning with global sustainability goals. Their modular nature allows scalable solutions tailored to specific geographic and resource conditions, offering a pathway to achieving energy equity in remote and underserved regions.

2.2 Common configurations in HRES

Hybrid systems typically combine solar PV and wind energy due to their complementary generation profiles. However, other sources, such as biomass and small-scale hydropower, can provide additional stability and flexibility. This section explores some of the most common configurations of HRES and how they contribute to overall system performance.

- **Hydroelectric + Solar PV:** The Alqueva floating solar installation in Portugal represents a pioneering step in the integration of solar and hydroelectric power. Installed on the Alqueva reservoir, this hybrid system combines a 5 MWp floating PV plant with the existing hydroelectric infrastructure. The project includes approximately 12,000 solar panels deployed over an area of 4 hectares, supported by floating structures designed to withstand variable water levels. The hybridisation allows for efficient energy balancing, as solar production is complemented by hydro generation when solar resources are insufficient. Furthermore, the system is equipped with battery storage of 2 MWh capacity, enhancing dispatchability and grid stability. One of the key advantages of this implementation is the ability of the PV system to leverage the existing grid connection point of the hydropower plant, significantly reducing infrastructure costs and simplifying integration. As the largest floating solar park on a hydro reservoir in Europe, the Alqueva project showcases the innovative potential of multi-technology renewable energy systems and their role in optimising resource utilisation while minimising environmental impact [7].

- **Solar PV + BESS:** This setup combines solar energy with battery storage, allowing excess energy to be stored and utilised during periods of low solar generation, enhancing system reliability. These systems are particularly beneficial for remote or isolated areas with unreliable grid connectivity [8, 9]. Additionally, modern BESS solutions incorporate advanced lithium-ion or other battery chemistries, ensuring high efficiency, longer cycle life, and improved energy density.

  BESS stabilises the grid through frequency and voltage regulation, peak shaving, and load shifting, optimising renewable energy use. Intelligent management systems ensure efficient charge cycles, extend battery life, and balance supply-demand fluctuations, improving power quality. These systems also reduce grid stress by balancing supply and demand fluctuations, improving overall power quality and resilience [10].

  Figure 2.1, from [11], illustrates a structured energy conversion path in a hybrid solar PV+BESS system. In this configuration, the PV unit generates DC electricity, which the PV converter transforms before feeding it into the AC grid. A dedicated BESS converter manages the BESS, connected in parallel to enable efficient energy storage and controlled discharge based on grid demand and generation conditions.

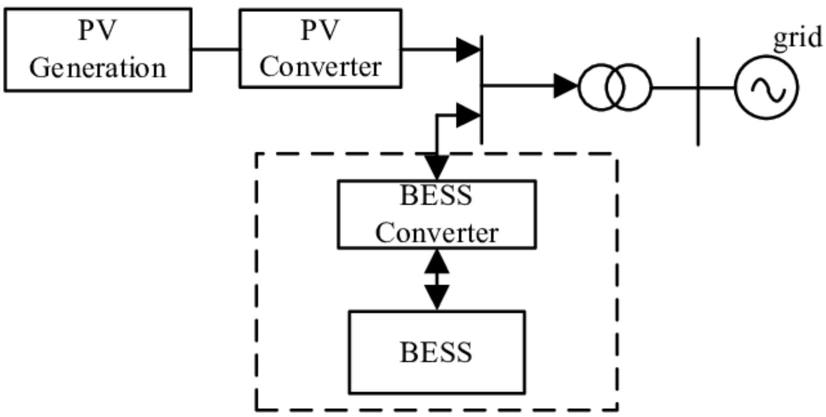

Figure 2.1: Structure of a PV+BESS system.

- **Solar PV + Wind + BESS:** This configuration leverages the complementary nature of solar and wind energy. Solar generation has its peaks during the day, while wind energy is sometimes more potent at night. Batteries are used as a buffer to store excess energy. This configuration reduces dependence on storage systems and is particularly efficient in areas with substantial seasonal or diurnal variations. These systems can reduce operational costs by up to 80% in some regions with more favourable conditions [8].

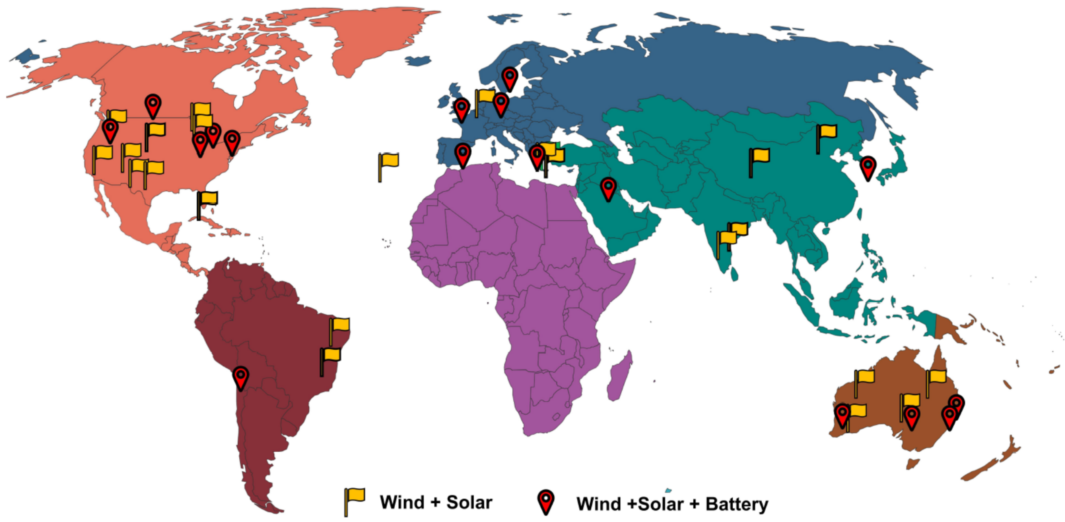

Figure 2.2: Worldwide wind+solar hybrid power plants.

Figure 2.2 from [12] presents the integration of wind turbines (WT) and solar panels within the same facility (both with and without energy storage) in the world in 2017. The visual representation underscores the synergy between these renewable energy sources, which are crucial for optimising land use and enhancing power generation efficiency in hybrid systems. The number of locations demonstrates this area's recent growth and how superficial and unstable its knowledge can still be. An idea or conception that is true today can be wrong tomorrow.

2.3 Variability

Seasonal and daily variations play a critical role in shaping the performance and design of systems that combine renewable resources like solar radiation and wind. Engineers must understand these fluctuations to optimise energy production and manage the system efficiently. In many HRES configurations, designers account for these variations to align the system with local resource patterns and demand profiles.

Hybrid systems need to adapt to pronounced seasonal shifts in resource availability. During winter and spring, reduced solar radiation increases reliance on WT and storage solutions to meet energy demand. Due to higher wind speeds, WT output is generally more consistent in these seasons. In contrast, summer typically sees high solar power output, reducing dependence on wind energy but requiring greater storage capacity to balance supply and demand effectively. Autumn provides an optimal balance of resources, enabling efficient system operation at minimal cost [13].

Daily resource variability further highlights the importance of hybrid configurations. Solar PV production peaks during daylight hours, while WT output often complements this by providing energy during the night. In certain conditions with high wind speeds and sunny weather, simultaneous production can occur, potentially leading to overproduction and system output fluctuations [14].

Figure 2.3 illustrates the typical daily wind generation pattern across all months. It shows clearly how wind production is distinct all over the year, yet mainly stronger in colder seasons. This visual evidence supports the need for seasonal adaptation in hybrid system planning and justifies the use of diversified resources and storage strategies to address temporal imbalances in energy availability.

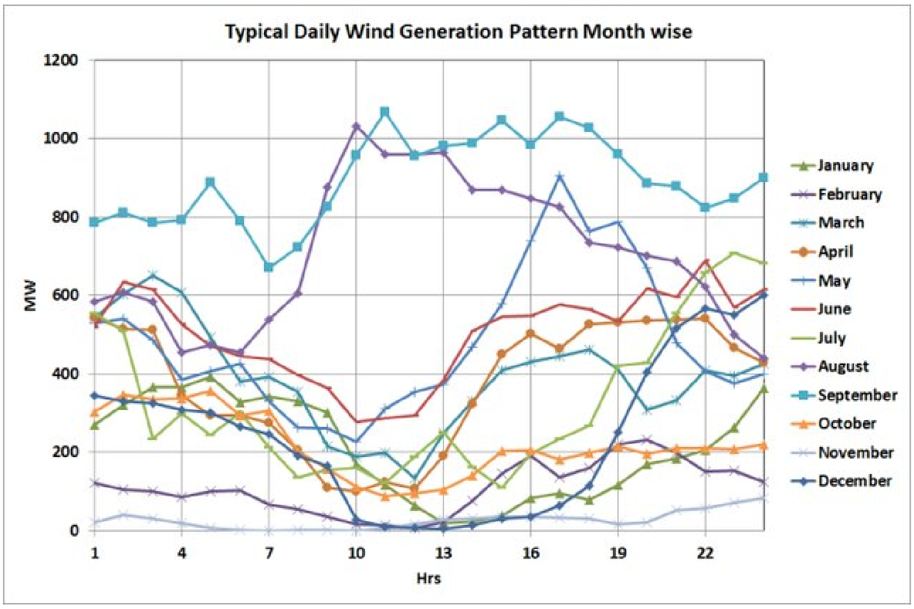

Figure 2.3: Typical day wind generation curve in each month of a year[15].

Advanced forecasting tools and intelligent energy management systems are essential to address these challenges. These tools allow for dynamic allocation of resources, ensuring high efficiency and cost-effectiveness by adjusting configurations to seasonal and daily resource fluctuations. A study by [13] emphasises the need for resource-specific configurations, such as the requirement for 100 PV panels, 40 wind turbines, and 3000 batteries in summer conditions, compared to just 50 PV panels, 10 wind turbines, and 600 batteries in winter. Such resource flexibility is key to ensuring the optimal operation of HRES throughout varying climate conditions.

2.4 Energy Storage Systems

Battery technologies have been used for many years, with rechargeable batteries being the preferred choice for power system applications. Their growing popularity in the energy sector is guided by their capacity to deliver working flexibility, rapid response times, declining costs per kWh, and continuous technological advancements. Batteries are now widely implemented across all voltage levels within power systems, offering technical and environmental benefits.

There are some types of storage systems with different natures, as mentioned in [16]:

- Lead-acid batteries (LABs) are valued for their affordability, versatility, and high recyclability. A typical LAB consists of a lead oxide positive electrode and a sponge lead negative electrode, separated by a microporous material. These batteries provide a nominal voltage of 2.1 V and operate with efficiencies ranging from 70–90%. Despite their moderate power output and cost-effectiveness, LABs face limitations including a relatively short cycle life (5–15 years), sulfation, and gas evolution during overcharging. The two main types (flooded and valve-regulated lead-acid batteries) are commonly applied in various grid and backup scenarios. Recent developments have improved performance, including incorporating carbon into the negative electrode and creating lead-carbon and ultra-battery systems. Ultra-batteries can achieve up to 17,000 cycles and deliver 50–60% more charge/discharge power, making them suitable for hybrid renewable applications requiring short-duration discharge support.

- Lithium-ion batteries (LIBs), including those with lithium iron phosphate ($LiFePO_4$, LFP) cathodes, are essential components in hybrid renewable energy systems, offering reliable energy storage for intermittent sources like solar and wind. LFP-based LIBs exhibit a nominal voltage of around 3.2–3.7 V and an energy density of 75–200 Wh/kg, combining high round-trip efficiency (>90%) with exceptional long-term durability, often exceeding 3000–5000 charge-discharge cycles due to their stable olivine crystal structure [17]. These batteries respond rapidly to fluctuations in generation and demand, contributing to grid stability.

  LIBs typically use lithiated graphite or lithium titanate as anodes and lithium metal oxides or LFP as cathodes, separated by lithium salt-based electrolytes. LFP cathodes provide superior thermal stability and safety compared to other LIB chemistries, attributed to strong P-O covalent bonds that resist thermal runaway. However, they have a moderately lower energy density than layered oxide cathodes. Degradation in LFP batteries is primarily driven by loss of lithium inventory and iron dissolution at high temperatures or states of charge, though their degradation rates remain slower than many alternatives under similar conditions [17].

  Despite higher upfront costs, LFP-based LIBs are increasingly favoured for their efficiency, compact design, and minimal memory effect, making them well-suited for renewable integration in hybrid systems. According to [18], LIB costs per cell have experienced a sharp decline, with a compound annual growth rate of –16% between 2013 ($502/kWh) and 2022

($120/kWh), and are expected to reach around $100/kWh by 2026, driven in part by the growing adoption of LFP chemistry and advances in extraction and refining.

- Pumped hydro storage (PHS) is the most widely used energy storage system, suitable for large-scale and long-term applications. It relies on geographic conditions with two elevations for water storage. Surplus energy pumps water mechanically to an upper waterhole when energy demand is low. During peak demand, the stored water is released to flow via turbines, generating electricity. With a conversion efficiency of 65 to 80%, PHS can deliver capacities ranging from a few megawatts to tens of gigawatts, depending on the elevation difference and the volume of water stored. This system is particularly effective for stabilising energy supply in regions with significant renewable energy deployment. However, it will not be in the spotlight in this research.

Although pumped hydro storage (PHS) remains the dominant technology in terms of total installed capacity worldwide, its use is geographically constrained. This solution typically requires significant altitude differences and large reservoirs, making it unsuitable for most locations and less flexible for decentralised or smaller-scale applications [19].

In contrast, battery-based energy storage systems have become increasingly relevant due to their modularity, scalability, and suitability for diverse applications, from grid support to behind-the-meter installations. Figure 2.4 shows the distribution of battery technologies currently deployed in storage projects.

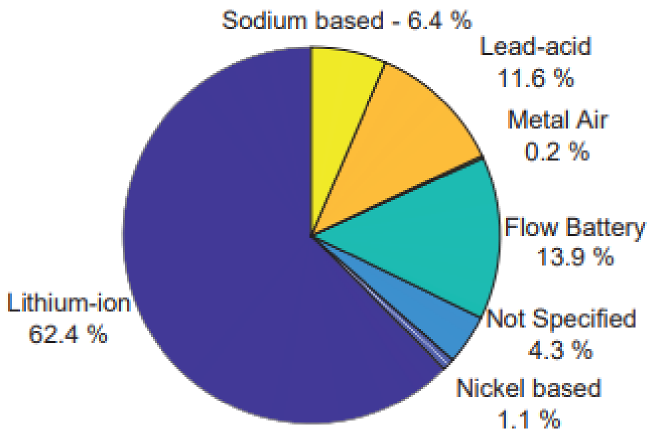

Figure 2.4: Global share of battery energy storage technologies [20]

The data highlights lithium-ion as the overwhelmingly dominant battery chemistry, representing 62.4% of installations. Flow batteries follow with 13.9%, while more mature chemistries such as lead-acid and nickel-based systems account for smaller shares (11.6% and 1.1%, respectively). Newer technologies like sodium-based batteries have begun to enter the market, but still represent a small portion. Other emerging or unspecified technologies complete the distribution.

This technological breakdown demonstrates the current reliance on lithium-ion solutions, primarily due to their energy density, cost reductions, and cross-sector demand (notably in electric vehicles). However, other chemistries may gain relevance depending on cost trends, safety profiles, environmental regulations, and application-specific requirements.

2.4.1 Key Parameters

The selection of an energy storage system (ESS) in HRES depends on key parameters such as energy and power capacity, energy density, cost, efficiency, and response time. Rechargeable batteries are especially valued for their fast response and adaptability, supporting both steady-state operation and dynamic grid stability.

In addition to these, several performance characteristics also influence technology selection, as [21] mentions:

- **DoD:** Indicates the proportion of the battery's total capacity that is used in each cycle.
- **Cycle Life:** The number of charge-discharge cycles a battery can endure, typically dependent on the DoD. Higher DoD levels generally reduce the lifespan.
- **SoC:** Represents the current available energy in the battery relative to its full capacity, expressed as a percentage.
- **Self-Discharge:** Refers to energy losses due to internal chemical reactions when the battery is idle; varies with battery chemistry.
- **Round-trip Efficiency (RTE):** The ratio between the energy output and input over a complete charge-discharge cycle, expressed as a percentage. It accounts for internal conversion and storage losses. Usually, in LIBs
- **C-rate:** Defines the rate at which a battery is charged or discharged, considering its maximum capacity. A 1C rate means a full charge or discharge in 1 hour, while a 0.25C rate corresponds to 4 hours. The C-rate influences thermal behaviour, cycle life, and the system's capacity to respond to power needs.

  In solar lithium batteries, a higher C-rate allows the system to quickly deliver power during periods of high demand or low solar production. Batteries with low C-rates may be unable to meet sudden power requirements, potentially causing voltage drops, performance issues, or system instability [22]. However, the lower the C-rate, the higher the number of cycles.
- **Temperature Sensitivity and Maintenance:** Environmental conditions and service needs affect the reliability, safety, and performance of ESS technologies. Extreme temperatures degrade the battery health and performance throughout the years [23].

The sizing of a BESS generally uses MW to indicate power and MWh for energy capacity. The ratio between these values defines the discharge duration, which is essential for identifying the intended application—such as frequency regulation, load shifting, backup, or, in this case, peak shaving.

Figure 2.5, adapted from [24], illustrates these parameters. The diagram uses coloured arrows to distinguish operating modes: green for charging, yellow for discharging, and orange for losses.

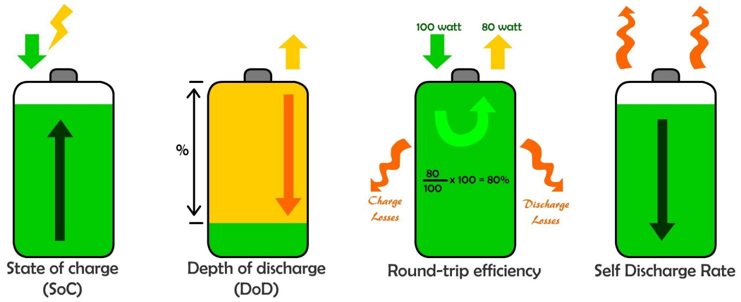

Figure 2.5: Some parameters of batteries according to [24].

2.5 BESS Technology

BESS play a central role in hybrid renewable energy systems by reserving excess energy during periods of extra production and supplying it during shortfalls. This capability mitigates the variability of sources like solar and wind, reduces consumption peaks, and improves supply reliability [14].

Despite their benefits, utility-scale battery deployment raises environmental concerns due to hazardous components. Proper recycling and disposal practices are necessary to reduce the ecological footprint and support long-term sustainability [9].

LIBs are the most prominent among available technologies due to their efficiency, durability, and compact design. They are particularly suited for integration with solar PV systems. Several leading manufacturers deliver LIB-based solutions with distinct output types, costs, and compatibility characteristics. This thesis takes these options into account to identify the most appropriate system for the proposed case study based on technical and economic criteria.

2.5.1 Electrical Architecture and Layout

The electrical architecture of a BESS defines the physical and functional arrangement of its main components, from individual battery cells to the grid connection infrastructure. A well-designed layout ensures optimal performance, safety, scalability, and integration with other energy assets. This section outlines the fundamental elements of a BESS, their roles within the system, and typical sizing considerations based on industry practices [25].

- **Cells**: These are the basic devices that make up a BESS. They convert electrical energy into chemical energy and vice versa, allowing energy storage.
- **Modules**: These are groups of cells assembled in a housing structure, electrically connected and equipped with a management and monitoring system.

- **Racks**: Structures composed of several modules connected in series and/or parallel. Racks facilitate the modular scaling of capacity and voltage levels.
- **Container**: A standardized enclosure (typically 6 m x 2.5 m x 3 m) suitable for outdoor deployment. Each container houses multiple racks along with safety, control, and thermal management systems. It is the primary unit used for logistics and site deployment.
- **Auxiliary Systems**: These systems are used for cooling, control, and safety of the system. The power supply comes from its energy generation.
- **Inverter / PCS**: Enables bidirectional AC/DC conversion between PV, BESS, and the grid. It ensures synchronisation with grid parameters, manages charge and discharge cycles, supports MPPT, provides reactive power and voltage/frequency regulation, and communicates with the BMS to maintain safe and efficient operation. Each PCS may connect to one or more containers, depending on system design [20].
- **LV/MV Transformer**: This transformer converts the BESS operating voltage into medium voltage, prior to switching to the substation.
- **Island**: A configuration consisting of one or more containers, a dedicated inverter, an LV/MV transformer, and auxiliary systems. Multiple islands can be deployed and aggregated within a single BESS project.
- **Substation**: A structure composed of various components whose objective is to step up the voltage from medium to high voltage for transmission grid connection. Mostly, there is only one substation for all the islands that form a BESS.
- **Battery Management System (BMS)**: Continuously monitors and controls cell voltages, temperatures, and SoC to ensure battery health, operational safety, and hazard prevention at both the module and rack levels. The BMS also manages charge and discharge processes to contain overcharging or deep discharging, thereby extending the battery's lifecycle [26].
- **Energy Management System (EMS)**: The high-level supervisory system that communicates with the other system elements and oversees power flows, schedules charging/discharging, and coordinates with external signals such as grid demands or market prices.

Figure 2.6 depicts a clean and simple layout of a typical BESS solution. Some details vary according to the manufacturer.

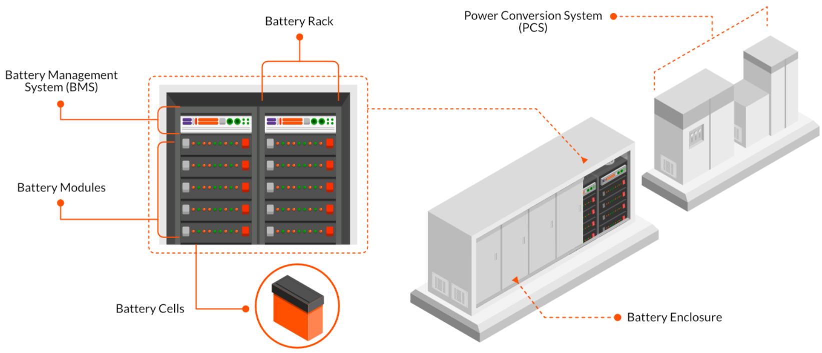

Figure 2.6: Scheme of BESS Components [27]

2.5.2 Operation of PV+BESS

PV generation systems typically inject electricity into the grid and generate revenue by selling that energy. However, solar output is inherently intermittent and peaks during midday, often exceeding the maximum power injection limits defined by grid codes or inverter specifications. To avoid grid congestion or instability, grid operators may enforce curtailment, i.e., the reduction of usable PV output when it surpasses allowable points such as the grid power limit for the given site [11]. As a result, valuable clean energy is wasted, and potential income is lost.

To mitigate this issue, BESS can be integrated with PV plants to absorb excess generation during peak solar hours and discharge the stored energy when production falls below grid capacity or when electricity prices rise. This time-shifting capability aligns directly with the concept of power arbitrage, one of the most straightforward and economically appealing services offered by BESS.

Power arbitrage causes charging of the battery when energy is abundant and cheaper, like when there is excess solar generation, and discharging it during periods of high demand or elevated market prices. This not only reduces energy losses due to curtailment but also allows for load curve shifting, where energy delivery is smoothed out over time, enhancing grid flexibility and enabling PV operators to benefit from higher tariffs or grid support incentives during peak hours.

Figure 2.7 from [11] illustrates a typical daily operation curve of a PV+BESS system, where the battery absorbs excess PV production that exceeds the injection limit and later discharges energy when PV output falls below the grid capacity.

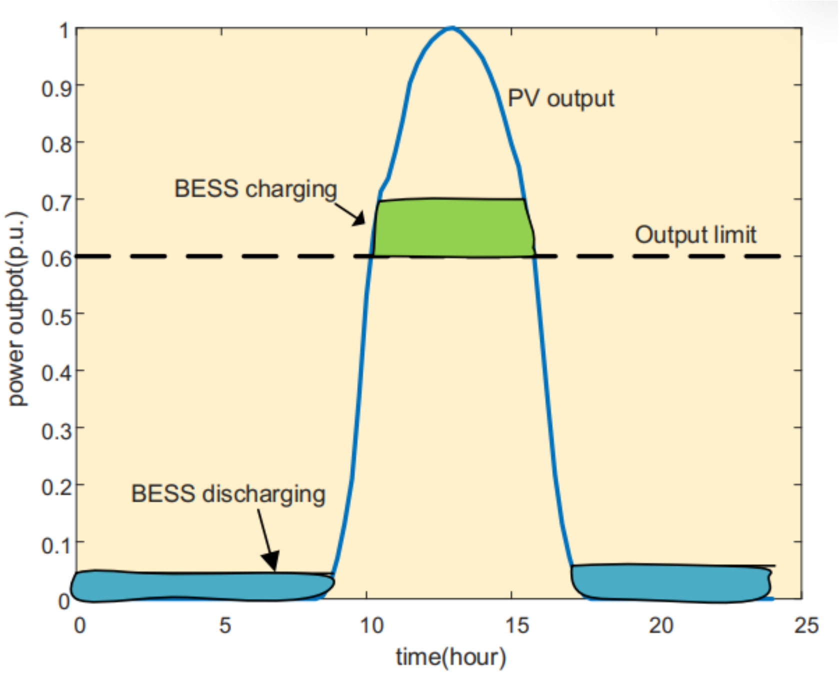

Figure 2.7: Operation of PV+BESS system

Moreover, this strategy may allow system designers to reduce the required grid connection size, since the battery handles fluctuations locally. However, these benefits must be balanced against the high capital cost of storage and the complexity of system integration. Proper sizing and operational strategies are essential to ensure that BESS investments are both technically effective and financially viable.

2.6 Modelling

Accurate modelling is essential for evaluating the feasibility and performance of HRES. Models must capture the behaviour of energy sources, storage systems, power electronics, and control strategies under varying environmental and load conditions. These simulations allow system designers to assess energy yield, optimise sizing, and ensure system reliability before deployment.

In addition to technical parameters, modelling must also consider market-specific factors such as supplier technologies and component compatibility. Several manufacturers offer tailored solutions with distinct system architectures. For instance, Huawei is known for its DC-coupled battery storage systems, which are commonly integrated with solar PV and optimised for efficiency through minimal conversion stages. In contrast, Tesla offers AC-coupled solutions, providing greater flexibility for retrofitting into existing AC infrastructures.

These architectural differences significantly influence the system design process. They affect inverter sizing, energy management algorithms, and the choice of coupling configuration (AC, DC, or hybrid). Consequently, selecting an appropriate supplier and system architecture must be reflected accurately in the modelling phase to ensure technical and economic alignment with project goals.

2.6.1 DC Coupled Hybrid Systems

DC-coupled systems are widely employed in small HRES due to their simple architecture and efficient energy flow. As shown in Figure 2.8, all energy sources (solar PV, WT, and DGs) are connected to a common DC bus through rectifiers. The stored energy is fed into batteries and converted to AC via inverters when needed by AC loads [28].

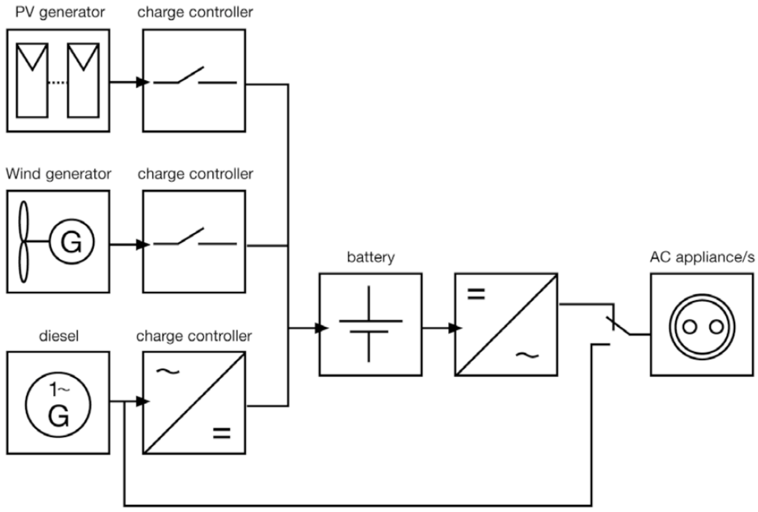

Figure 2.8: System layout of a DC-coupled hybrid system.

This configuration is standard in off-grid scenarios and enables scalable integration of additional energy sources. However, efficient energy management becomes critical for system stability.

Advantages of DC-Coupled Systems:

- Higher system efficiency due to fewer power conversion steps.
- Lower initial costs and simpler overall system architecture.
- Easier to manage and optimise storage charging and discharging cycles.
- Flexibility in expanding the system with other DC-based technologies.

Disadvantages of DC-Coupled Systems:

- Requires additional converters when interfacing with AC components.
- Less suitable for integrating AC-based sources like WTs or DGs.
- Complex control strategies are needed for managing DC voltage stability.

2.6.2 AC Coupled Hybrid Systems

AC-coupled configurations are suitable for medium to large-scale HRES due to their modular nature and ability to interface with conventional grid-tied technologies easily. As shown in Figure 2.9 from [28], each source (PV, WT, diesel) typically operates through its inverter and synchronises to a standard AC bus. Energy storage systems are connected via separate inverters.

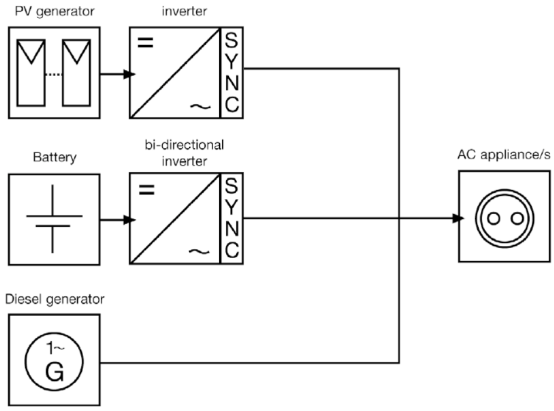

Figure 2.9: AC-coupled system with modular technology.

This approach allows independent control of each power source and simplified system maintenance.

Advantages of AC-Coupled Systems:

- Highly modular, allowing easy integration of legacy and new AC components.
- Well-suited for retrofitting existing AC generators and loads.
- Facilitates long-distance power transmission and distribution.
- Mature inverter technologies available with advanced grid-support features.

Disadvantages of AC-Coupled Systems:

- Lower efficiency due to multiple conversion stages (DC to AC and back).
- Higher cost owing to the need for multiple inverters and transformers.
- Synchronisation and frequency stability become more challenging in standalone systems.

2.6.3 Combined AC-DC Coupled Systems

Combined AC-DC hybrid architectures increasingly leverage the strengths of both configurations. Figure 2.10, adapted from [28], shows a typical setup where PV and battery systems connect on the DC side, while generators operate on the AC side. A central hybrid inverter or bidirectional converter manages the interaction between the AC and DC buses.

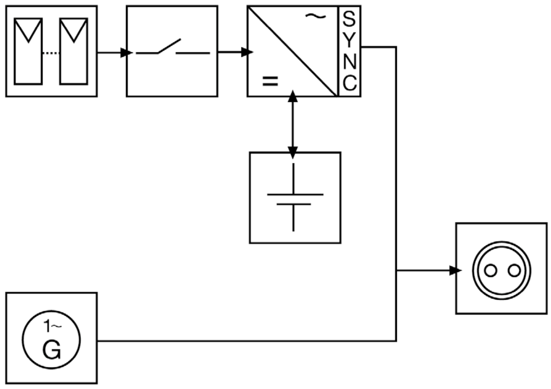

Figure 2.10: AC-DC coupled hybrid system with shared inverter control.

This hybrid architecture is suitable for microgrids and complex power systems requiring both grid-forming and grid-following capabilities [28].

Advantages of Combined AC-DC Systems:

- Maximises efficiency by minimising unnecessary conversions.
- Facilitates integration of a wider range of energy sources and loads.
- Offers flexible control strategies for balancing AC and DC demands.
- Enhances system reliability and resilience in islanded or weak-grid scenarios.

Disadvantages of Combined AC-DC Systems:

- Increased system complexity in design, control, and protection schemes.
- Higher initial investment due to advanced power electronics and control systems.
- Requires sophisticated energy management systems for coordination.

2.7 Control Strategies

Hybrid photovoltaic and battery energy storage systems (PV+BESS) require advanced control and optimisation strategies to ensure high efficiency, reliability, and cost-effectiveness. These strategies must coordinate generation, storage, and grid interaction to manage variable generation, system constraints, and load demands.

The integration of BESS in hybrid systems allows for greater operational flexibility, but it also increases the complexity of system control. Key goals of control strategies include maintaining power balance, managing the SoC of batteries, supporting voltage and frequency stability, and ensuring optimal economic performance through energy arbitrage or peak shaving.

A fundamental distinction among control strategies lies in the degree of centralisation and the amount of information available to the controller. As illustrated in Figure 2.11, hybrid systems may adopt one of the following main control approaches, as classified by Stecca et al. [20]:

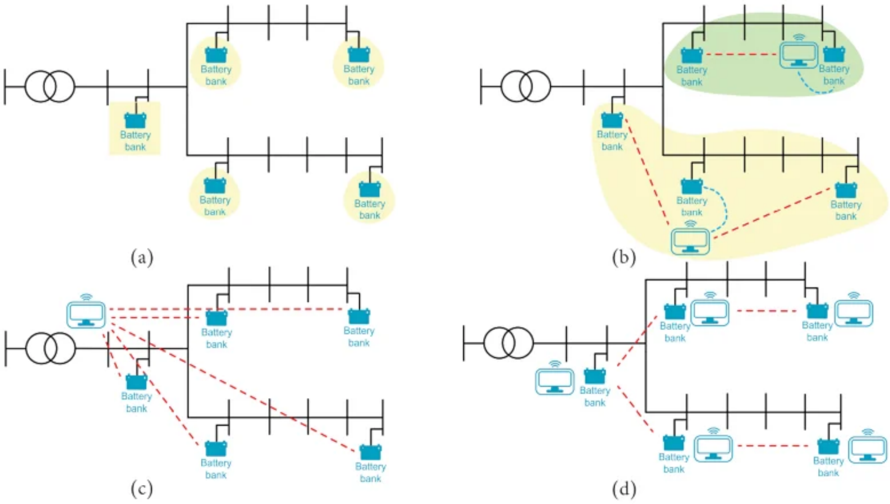

Figure 2.11: Example BESS management strategies: (a) Local control, (b) Decentralised control, (c) Centralised control, (d) Distributed control [20].

- **Local Control (a)**: Each BESS operates independently based on locally measured variables such as voltage, current, or SoC. While this approach is simple and scalable, it may result in suboptimal global behaviour due to the lack of coordination.
- **Decentralised Control (b)**: BESS units communicate with each other but still make control decisions individually. This allows for limited coordination and improved overall performance without relying on a central entity.
- **Centralised Control (c)**: A single central controller collects system-wide information and sends control signals to each BESS. This architecture achieves optimal global performance but introduces communication overhead and vulnerability to central point failures.
- **Distributed Control (d)**: Combines local decision-making with system-wide coordination via distributed algorithms. Agents communicate and collaborate through multi-agent frameworks or consensus protocols, striking a balance between scalability and performance.

The choice of control architecture depends on the system size, communication infrastructure, cybersecurity constraints, and performance requirements. In the context of hybrid PV + BESS systems, distributed or decentralised strategies are increasingly favoured due to their scalability, resilience, and capacity to integrate with smart grid paradigms [8].

2.8 Software Tools

Due to the involvement of multiple generations of systems, analysing hybrid systems is highly complex and demands detailed evaluation. This requires the use of software tools for system design, analysis, optimisation, and assessment of economic feasibility. The instruments provide capabilities to design, analyse, and optimise hybrid renewable energy systems [29].

- HOMER: This is a user-friendly tool developed by NREL, USA, that allows simulation, optimisation, and sensitivity analysis for off-grid and on-grid systems. It provides an hourly resolution of resource inputs while offering such economic outputs as NPC and LCOE. The limitation of the software is in the functionalities for multi-objective optimisation and modelling of depth-of-discharge for batteries.
- RETScreen: A financial feasibility tool with a robust meteorological database. It estimates environmental and economic aspects, including CO_2 reductions. Unlike HOMER, it is not capable of handling time-series data inputs; thus, it is better suited for pre-feasibility studies.
- iHOGA: Known for its use of genetic algorithms, this tool excels in optimising system components, including battery degradation and emissions. It boasts an educational (free) and professional (paid) version, with the latter offering advanced sensitivity analysis.
- TRNSYS: A FORTRAN-based software that is ideal for thermal and electrical energy systems; it permits the user to model dynamic system behaviour. It lacks built-in optimisation features but allows for precise modelling of system components like PV-thermal hybrids.
- Hybrid2: Good for detailed statistical modelling, supporting long-term simulation for PV, wind, and diesel hybrid setups. It has a very user-friendly GUI but runs on outdated platforms with limited configurability.
- PVsyst: Developed by the University of Geneva, this software is widely used for designing large photovoltaic systems and performance assessment. It enables detailed modelling of PV generation profiles and system losses, making it suitable for evaluating solar energy performances in large hybrid systems with BESS [30].

Some studies like [5] and [12] highlight the use of advanced energy management strategies using tools like HOMER Pro. These setups incorporate components such as PV panels, WT and batteries into unified systems.

In this dissertation, Microsoft Excel supports the analysis process. This choice aligns with the company's standard practices, ensuring compatibility with current workflows and data management systems. Excel's comprehensive functions for data analysis, financial modelling, and scenario evaluation make it suitable for assessing economic feasibility. Its flexibility, advanced formula capabilities, and ability to integrate with external data sources enable the development of customised models tailored to the complexity of this study.

Additionally, this work uses PVsyst to perform the technical design and sizing of the photovoltaic system and BESS. The company commonly applies this software in its projects, as it enables detailed modelling of PV systems, including BESS integration.

2.9 Future of Batteries

BESS are expected to play a critical role in the decarbonisation of the power sector. Among the various technologies, lithium-ion batteries continue to dominate due to their superior energy density, cost trajectory, and manufacturing maturity. The declining cost of lithium-ion technology, coupled with performance improvements, is driving its widespread adoption in utility-scale applications. According to BloombergNEF, the average price of lithium-ion batteries could fall by nearly 50% by 2030, mainly due to economies of scale and innovations in production and materials [31]. The study considers that energy storage will become a practical solution to replace the construction of new power plants or the reinforcement of networks.

From a technical perspective, research and commercial deployments are focused on extending cycle life, enhancing thermal stability, and improving charge/discharge efficiency. These developments are vital for applications such as peak shaving, load shifting, and frequency regulation. Emerging technologies like solid-state batteries and redox flow batteries present alternatives with potential advantages in safety and scalability [32].

In addition to technological advancements, the evolution of regulatory frameworks is also pivotal. At the European level, the Clean Energy Package and subsequent directives encourage the integration of storage into electricity markets [33]. In Portugal, the national energy and climate plan (PNEC 2030) highlights energy storage as a priority for grid flexibility and renewable integration. Specific auction mechanisms for storage capacity, though still under development, are anticipated to stimulate investment [34].

Overall, while lithium-ion remains the primary choice for now, the landscape is diversifying. Advances in flow batteries, compressed air storage, and hydrogen-based systems may offer complementary solutions, especially in long-duration storage and sector coupling.

Chapter 3

Valen PVP Characterisation

The Valen Photovoltaic Plant is a utility-scale solar installation located in the south of Portugal. It is projected to generate approximately 69,653.638 MWh annually over 30 years [35]. Specific technical and locational details have been deliberately omitted due to strategic and privacy considerations.

3.1 Simulation Tools

The simulation of the Valen PV Plant was carried out using the commercial software PVSyst v8.0.9, which enabled detailed analysis of meteorological conditions, shading effects, and system losses. The software also supported dimensioning optimisation and economic assessment, providing quantitative outputs, such as performance ratios and loss breakdowns that facilitated both technical validation and cost-effectiveness evaluation.

Microsoft Excel was another relevant engine used to perform technical, economic, and system performance calculations.

3.2 Plant Characterization

The plant is composed of two main zones, connected to a common grid interconnection point at 60 kV.

3.2.1 Climatic Characterization

The performance analysis was backed by site-specific climatic data sourced from the SolarGIS platform to reflect long-term expectations better. The study will be conducted using this generic data. Across this document, the simulation timestamps will not relate to a specific year, but they will follow the region's patterns and forecasts.

Table 3.1: Average Climatic Characterisation of the Project Site

Parameter	**Value**
Average Temperature (°C)	17.4
Maximum Temperature (°C)	41.8
Minimum Temperature (°C)	0.2
Annual Precipitation (mm)	765.8
Average Wind Speed (km/h)	13
Maximum Wind Pressure (Pa)	9.8
Average Relative Humidity (%)	74
Average Solar Radiation (W/m²)	163
Altitude (m)	77

Table 3.1 summarises the average climatic conditions at the project site, providing essential environmental context for the PV plant's operation. A selection of the generation profile is displayed in Figure 3.1; the data is collected at the PV inverter output. The image presents clearly the typical solar power plant curve in the Northern Hemisphere, with the highest production in the summer months.

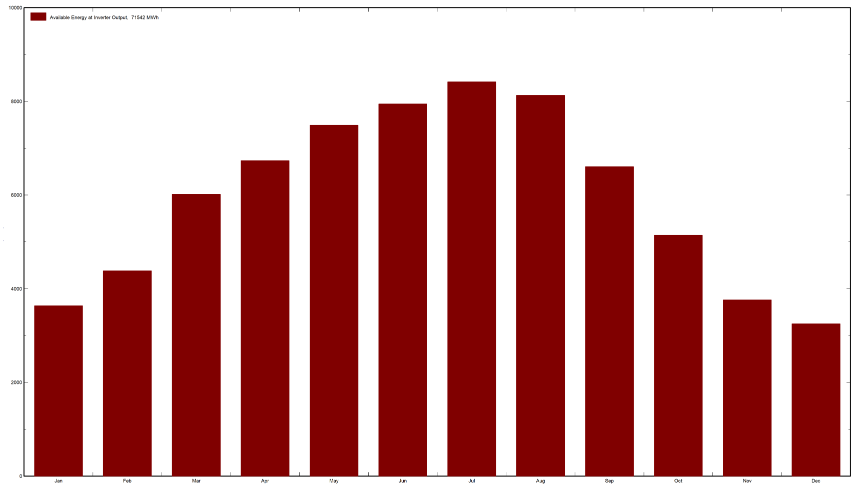

Figure 3.1: Monthly totals of PV Generation in Valen PVP

3.3 Technical Specifications

Table 3.2: Characterisation of the system in PVSyst

Parameter	**Value**
Location	Portugal
Area	52.66 ha
PV Capacity	40.23 MWp (DC) / 34.24 MVA (AC)
Ratio DC/AC	1.068
Modules	65,716 Trina Solar TSM-DEG19MC.20
Module Power Rating	610 and 615 Wp
Inverters	104 Sungrow SG350HX (Decentralised)
Inverter Rating	352 kVA each
Grid Connection	60 kV
Medium Voltage Level	30 kV

Table 3.2 outlines the key technical specifications of the Valen PV Project, detailing its components and grid integration characteristics. Note that the PV modules are placed using 2V14 and 2V28 fixed structures that are driven 2 to 3 metres into the ground, designed for wind and snow loads.

Figure 3.3 shows a glimpse of the PV module used in the system. These modules have 610 and 615 Wp. Both subtypes present: *Voc* = 49.0 V / 49.3 V and *Isc* = 15.86 A / 15.89 A.

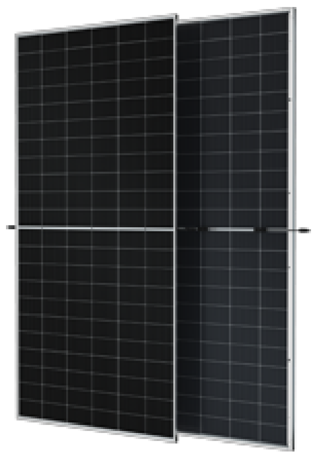

Figure 3.2: Trina Solar Monocrystalline PV Module TSM-NEG19RC.20 (max. 620W)

Figure 3.3 represents the look of the PV inverters placed in the plant. This equipment is an important piece when connecting the BESS subsystem. There are several control strategies, as Section 2.7 in Chapter 2 enumerates. However, in this case, the inverters are decentralised.

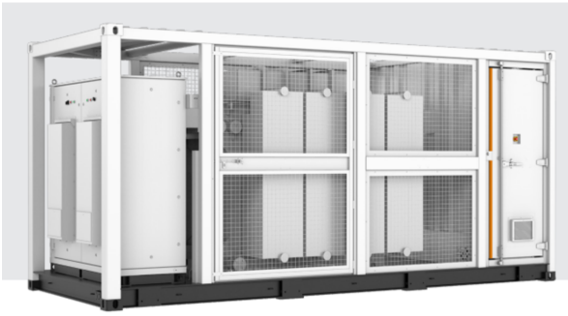

Figure 3.4: Sungrow MVS6400-LV

Figure 3.3: String Inverter Sungrow SG350HX

The system also includes:

- Power Stations:
  - 3 units: Sungrow MVS6400-LV (Figure 3.4): Nominal power of 6 400 kVA;
  - 2 units Sungrow MVS 8960-LV: Nominal power of 8 960 kVA;
  - Both models with LV/MV Transformer: 0,8/30 kV.
- SCADA, protection, and communication systems:
  - SCADA system;
  - DC auxiliary supply system;
  - Communication cabling.

3.3.1 Cabling Overview

The underground cable network includes low-voltage DC/AC, medium-voltage, and auxiliary circuits. DC cables are buried at a minimum depth of 60 cm, while MV cables are laid at 80 cm. Type H1Z2Z2-K conductors are used on the DC side, and LXAV/LX1AV (400 mm^2) and LX-HIOZ1 17.5/30(36) kV are used on the AC and MV sides. Losses were constrained below 0.5% for DC and 1% for both LV and MV AC paths, in compliance with RTIEBT and IEC norms.

3.4 Simulation Results

Figure 3.5 was obtained through PVSyst's report of PV performance. The variable Performance Ratio (PR) is a key indicator of a PV system's overall performance, representing the ratio (or percentage) of actual energy output to the theoretical maximum output under ideal conditions. Basically, it shows the proportion of energy produced after accounting for losses. The basic formula (Equation 3.1) for calculating PR is:

$$PR = \frac{\text{Actual Energy Output}}{\text{Theoretical Energy Output}} = 0.8907 \tag{3.1}$$

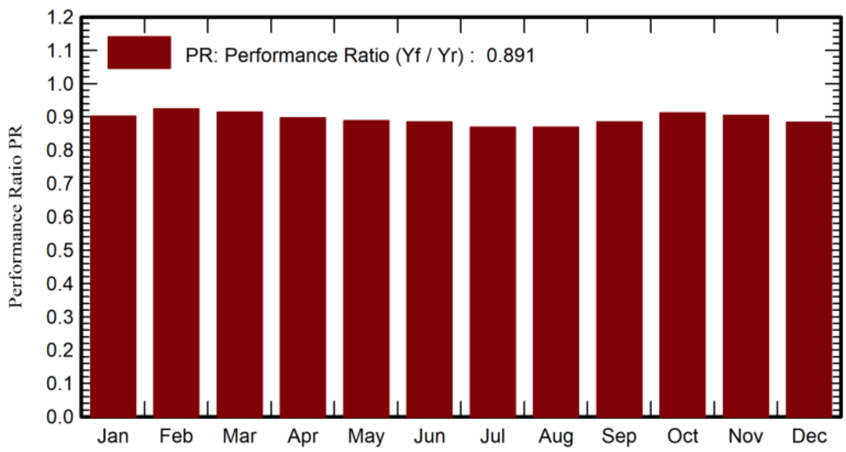

Figure 3.5: PR values from PVSyst output

The software enabled the calculation of the specific yield of 1,713 kWh/kWp/year.

The system also underwent a P50–P90 evaluation, as shown in Figure 3.6. This probabilistic assessment accounts for the inherent uncertainty in energy yield forecasts due to interannual variability in solar irradiance, system losses, and modelling assumptions. The P50 value represents the median expected yield, indicating a 50% probability that the actual generation will be higher. In contrast, the P90 value corresponds to a more conservative estimate, where there is a 90% probability that the actual generation will exceed this figure.

In this case, the P50 value was approximately 68.91 GWh/year, while the P90 yield was around 64.72 GWh/year. This difference is particularly relevant for financial modelling, as lenders and investors typically rely on the P90 forecast to evaluate project profitability and revenue stability under conservative scenarios.

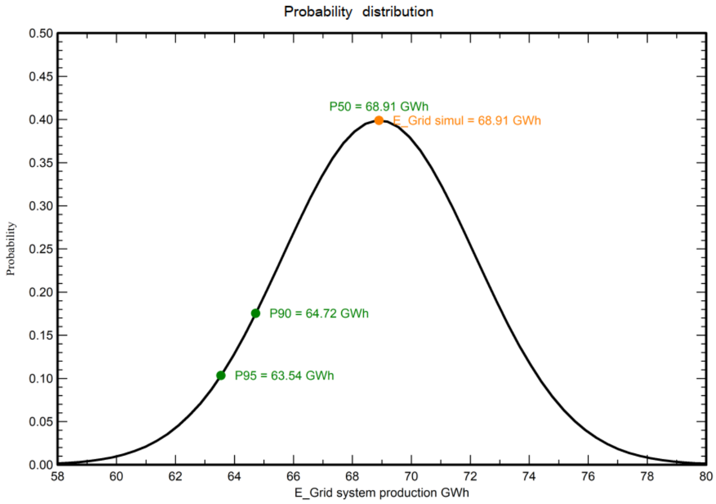

Figure 3.6: P50–P90 Evaluation

A detailed breakdown of electrical and environmental losses was included in the reproduction. These accounted for effects such as:

- Thermal behaviour of modules, based on air-circulated mounting conditions;
- DC and AC ohmic losses (0.5% and 1.0% respectively);
- Medium-voltage cable losses (0.5%) and transformer efficiency factors;
- Soiling (2.0%), module mismatch (1.0%) and LID - LigH Induced Degradation (0.3%);
- Auxiliary consumption set at 3 W/kW of installed capacity.

These losses were defined directly in PVSyst using equipment-specific performance curves and layout parameters.

According to PVSyst's CO_2 emission analysis, the carbon savings over the lifetime of the plant reinforce its environmental contribution: 544,773.4 tons.

3.4.1 Loss Summary

The total system losses are summarised in Table 3.3 and characterised using PVSyst's detailed loss diagram. These include both system-internal effects (e.g., wiring and inverters) and environmental constraints (such as shading, radiation angle and dirt accumulation).

Table 3.3: Summary of Energy Losses Considered in PVSyst

Loss Type	**Value (%)**
Soiling Losses	2.0
Wiring (DC/AC/MV)	0.5 / 1.0 / 0.5
Transformer Losses	1.1 (LV/MV), 0.45 (HV)
LID / Mismatch	0.3 / 1.0

3.5 Regulatory and Environmental Compliance

The plant complies with national [34] and international [33] standards applicable to photovoltaic installations. Relevant legislation includes:

- Decree-Law no. 15/2022 and amendment DL 99/2024;
- Portuguese standards for low-voltage systems (regulation RTIEBT);
- Portaria 596/2010 – Reactive energy regulations.

Additional standards from the International Electrotechnical Commission (IEC) taken into consideration during the design include:

- IEC 62305-1-2-3 – Protection against lightning;
- IEC 61215 – Crystalline silicon terrestrial PV modules;
- IEC 61730 – PV module safety qualification (Parts 1 and 2);
- IEC 61643-11 – Surge protective devices;
- IEC 61000-3-2 – Limits for harmonic current emissions.
- IEC 61936-1:2010 – Electrical installations exceeding 1 kV AC;

This section completes the technical overview of the Valen PV Plant, which was elaborated in the company's previous studies. In the next chapter 4, the BESS component is approached in detail.

Chapter 4

BESS Integration in Valen PVP

4.1 Scope

This chapter analyses the technical and economic feasibility of integrating a BESS into the existing 40.23 MWp Valen PVP in Portugal. The main goal is to optimise the BESS operation to maximise revenue through peak shaving and curtailment mitigation strategies.

The system is designed to store excess PV generation during midday, when curtailment risk is higher, and release that energy during periods of high demand or limited generation. Achieving these results involves careful BESS dimensioning based on grid constraints, as well as defining operating parameters that ensure economic viability.

In this particular situation, the chosen discharge patterns were defined for simulation purposes as “After sunset”. This way, the goal of discharging energy into the grid when production is lower and demand is higher can be reached.

Other variants, such as “in specific hours”, would limit the discharge in summer months, for example. In these periods, PV production can happen later in the day, as Table C.1 from appendix C demonstrates. From the table, it is visible that in the summer months, the average PV production can last until 7 p.m. In contrast, in winter, the latest hour is 5 p.m.

By imposition of the Decree-Law [36], storage facilities are obliged to provide the full capacity of their system whenever the public service energy grid (“RESP” in Portugal) needs it.

4.2 Market Contact and Data Collection

To support this analysis, several BESS manufacturers were contacted to gather technical specifications and indicative pricing, particularly for lithium-ion battery systems suitable for AC-coupled hybrid PV integration. Sungrow responded with detailed documentation for its ST5015UX and PowerTitan 2.0 platforms, which are used as the case basis for this study.

Other suppliers either lacked systems compatible with the project configuration or did not provide commercial quotations. Figure 4.1 shows the manufacturer’s logo used in this assessment.

Figure 4.1: Sungrow company logo

4.3 Design Constraints

The maximum export capacity at the point of interconnection (POI) is 31.9 MW, as defined by the Portuguese TSO (REN). This limit plays a central role in determining curtailment exposure and, by extension, the required BESS capacity.

- If the grid export limit increases, energy losses due to curtailment decrease, reducing the required storage capacity.
- If the grid export limit decreases, more storage capacity may be needed to absorb excess midday generation. However, even then, the BESS can saturate, and some energy may still be curtailed.

According to [37], when BESS dispatch is controlled correctly, curtailment can be significantly reduced, leading to improved utilisation of PV resources.

4.4 Comparison of AC-Coupled and DC-Coupled Architectures

Figure 4.2 and Figure 4.3 illustrate two distinct coupling strategies for integrating BESS into photovoltaic plants: AC-coupled and DC-coupled architectures, respectively. Both schemes are according to the supplier's design and documentation, like [38].

AC-Coupled System (Figure 4.2): In this configuration, the BESS is electrically independent of the PV inverter. Each battery rack is interfaced with a dedicated PCS, which converts DC to AC and vice versa. The AC output is synchronised with the grid via medium-voltage (MV) switchgear (particularly 30 kV). This modular structure allows:

- Independent operation of the BESS, even when PV generation is offline;
- Full grid service capabilities such as black start, voltage support, and frequency regulation;
- Ease of retrofitting into existing PV plants.

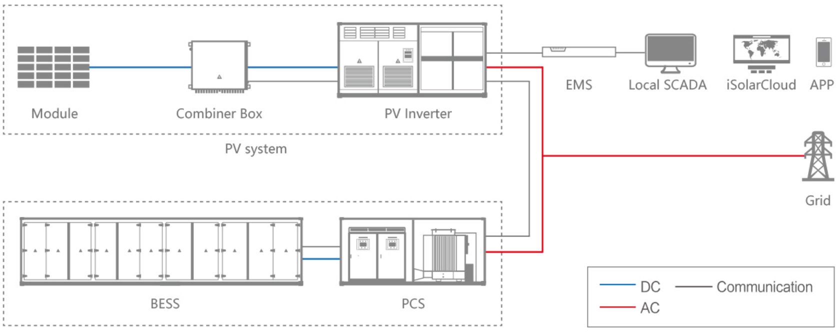

Figure 4.2: AC-coupled ESS scheme with multiple containers and grid integration

DC-Coupled System (Figure 4.3): Here, the batteries are directly connected to the DC bus of the PV inverter. This setup simplifies infrastructure and can achieve higher round-trip efficiencies due to reduced conversion stages. However, its limitations include:

- Reduced flexibility for providing standalone grid services;
- Less suitable for hybrid systems where independent battery dispatch is needed.

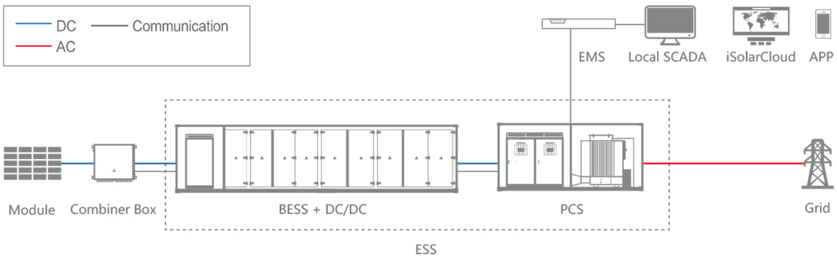

Figure 4.3: Reference diagram for a DC-coupled ESS scheme

While DC coupling offers advantages in efficiency and cost, it is typically more constrained in terms of operational flexibility. AC coupling, as used in the Sungrow PowerTitan 2.0 system, supports multi-functional grid applications and is preferred in utility-scale hybrid systems where modularity and independent dispatchability are priorities.

4.5 BESS Architecture and Power Flow

The flowchart in Figure 4.4 from [39] outlines the operational logic of a PV+BESS system. It shows how the system prioritises energy dispatch based on conditions like PV availability, BESS charge and discharge status, and grid permissions. The main goal is to reduce curtailment as much as possible.

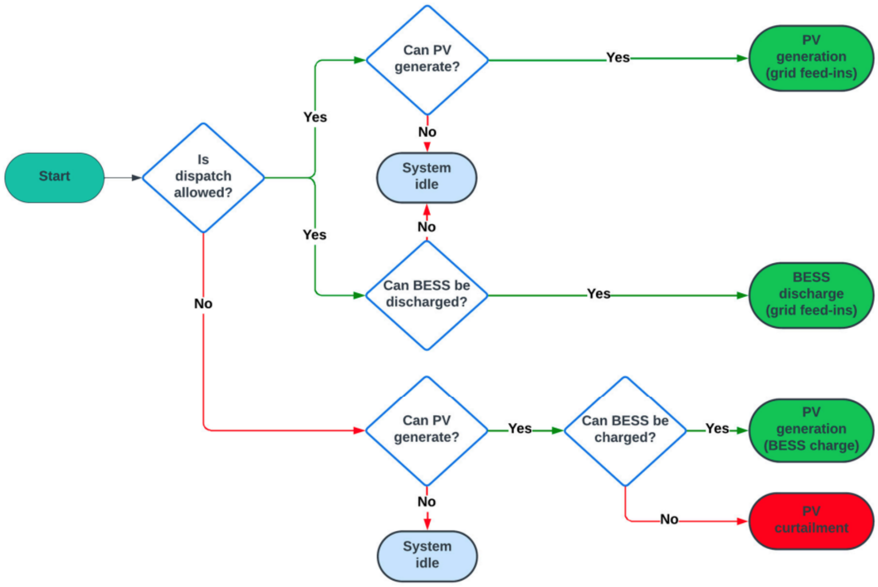

Figure 4.4: PV+BESS operation status flowchart

The PowerTitan 2.0 system operates in an AC-coupled layout, meaning the battery system includes its own dedicated Power Conversion System (PCS), which handles AC-DC-AC power conversion. Energy from the PV array is converted by the inverter for grid compliance, while the battery can both absorb and dispatch energy via its PCS. The AC outputs from the PCS are routed through MV switchgear, operating at 30 kV, for export to the grid.

4.6 Power Conversion System and Operating Modes

The PCS enables bi-directional power flow, grid services, and seamless integration with the energy management system (EMS). It supports various control strategies such as constant power factor mode, volt-watt response, and reactive power compensation, as illustrated in Figure 4.5 from [40].

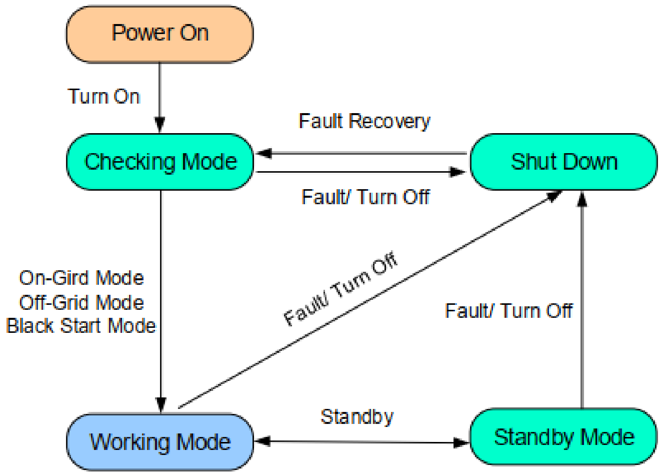

Figure 4.5: PCS operational modes and transitions

Figure 4.5 presents the operational flowchart of the PCS, illustrating its transition between key modes: Power On, Checking, Working, Standby, and Shut Down. Within the Working Mode, the PCS can operate in On-Grid, Off-Grid, or Black Start configurations.

These modes correspond to the BESS operational states as follows:

- Charging: Occurs during On-Grid Mode when surplus PV energy is available.
- Discharging: Takes place in On-Grid or Off-Grid Mode when energy is supplied to the grid or local loads.
- Idle: Represented by Standby Mode, where the PCS remains energised but is not actively charging or discharging.

This logic ensures safe and efficient transitions between operational states, supporting grid stability and optimal energy management.

4.7 Sungrow System Layout and Configuration

Each PowerTitan 2.0 container houses 12 vertical battery racks, 6 PCS units, a Battery Connection Panel (BCP), and switches (labelled “QS”).

The internal single-line diagram (SLD) detailing connections among packs, racks, PCS units, and BCP is depicted in Figure 4.6.

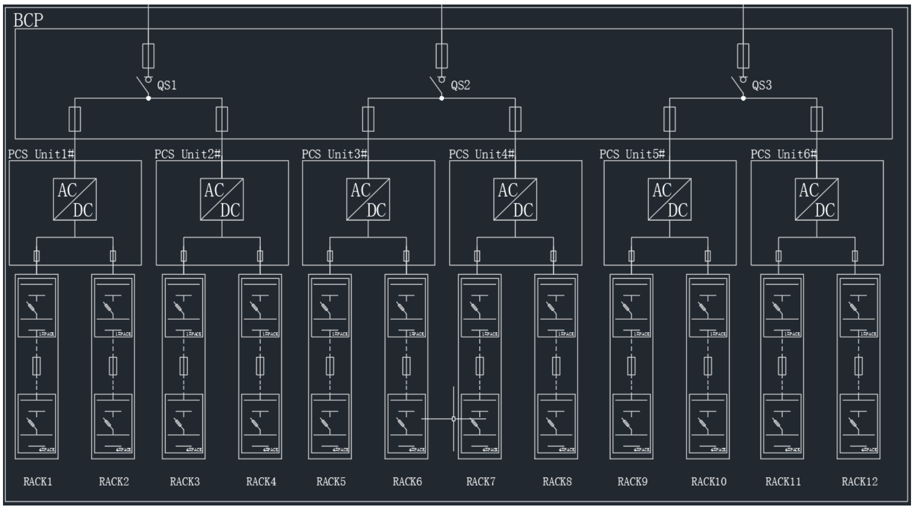

Figure 4.6: SLD of 1 Battery Container

4.8 Battery System Design: ST5015UX

The ST5015UX is Sungrow's latest utility-scale BESS model, offering greater energy capacity, enhanced cooling, and tighter integration than its predecessors.

Figure 4.7 displays the external view of one containerised PowerTitan unit. Each container is equipped with built-in PCSs, allowing for bidirectional energy conversion and flexible dispatch.

Figure 4.7: PowerTitan 2.0 Visual [4]

Internally, the container comprises 12 vertical racks connected in parallel. Each rack contains 4 PACKs. There is 1 PCS unit for 2 racks, but it can vary according to the C-rate value. PACKs follow a 416S12P topology (416 cells in series and 12 strings in parallel), resulting in a nominal voltage of 1331.2 V [38].

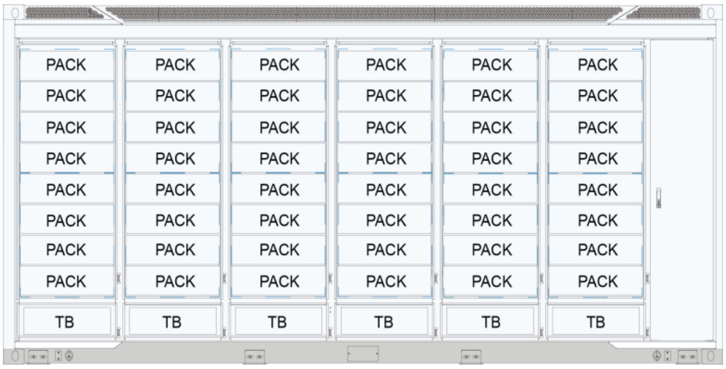

Figure 4.8: Sungrow ST5015UX cluster layout [41]

Figure 4.8 illustrates the stacking configuration of a battery cluster where TB stands for Terminal Box.

To ensure long-term performance and safety, the system employs an advanced liquid cooling circuit, shown in Figure 4.9. This system maintains cell temperature uniformity within 2.5°C [38], significantly reducing thermal gradients and slowing down degradation.

Figure 4.9: Internal liquid cooling circuit of a ST5015UX container [41]

Battery technical specifications include:

- Charge cut-off voltage: 1497.6 V
- Discharge cut-off voltage: 1123.2 V
- Maximum current: 942 A
- Coulombic efficiency: 96.0%
- Operating temperature: –30°C to 55°C
- Round-trip efficiency: 89.5%

The enclosure is rated IP55 and C5, making it suitable for harsh outdoor environments. Its containerised format ensures fast deployment, modular expansion, and simplified maintenance.

4.9 Chapter Summary

This chapter presented the technical feasibility of integrating a BESS into the 40.23 MWp Valen PV plant, with a focus on Sungrow's PowerTitan 2.0 system. The system uses an AC-coupled architecture, enabling independent battery operation, grid service provision, and modular deployment.

The ST5015UX units were selected for their compatibility, integrated PCS, high efficiency, and robust thermal management.

This configuration supports curtailment mitigation, peak shaving, and improved grid compliance, forming the technical foundation for the dimensioning and degradation analysis in Chapter 5.

Chapter 5

Dimensioning and Degradation Methodology

This Chapter presents the technical and methodological framework for sizing the BESS, with particular focus on the key design parameters and their impact on system configuration and performance. These parameters include the definition of C-rate (2-hour vs 4-hour storage), cycle depth and frequency, RTE, SoC limits, degradation modelling, and auxiliary power requirements. These considerations are subsequently applied to the dimensioning of the BESS for the associated PV plant. Two operational scenarios (0.25 C and 0.5 C) are compared, and intermediate simulation results from Excel and *PVSyst* are discussed.

5.1 Key BESS Technical Parameters

Several critical technical parameters govern the performance and longevity of a BESS. Each parameter is defined, and its implications on battery sizing, operation, and lifetime are explained. Furthermore, the influence of these choices on overall system efficiency and long-term degradation is discussed. These technical considerations form the foundation of the BESS dimensioning methodology.

5.1.1 Cycles Per Day and Usage Profile

One of the fundamental parameters is the number of charge/discharge cycles the BESS performs per day. A "cycle" typically denotes a full charge and discharge, though partial cycles contribute proportionally. For PV energy shifting applications, approximately 1 cycle per day is standard (charging during solar surplus hours and discharging during peak demand periods like the end of the day). In some configurations, the battery may perform more than 1 cycle per day (for instance, when also providing ancillary services), resulting in an equivalent cycle count greater than 1 CPD.

The cycling regime directly impacts battery wear: increased cycling accelerates capacity fade. Consequently, the battery must be sized according to the intended operational profile. For example, daily cycling over a 20-year lifespan equates to approximately 7000 cycles. Given the finite cycle life of lithium-ion batteries, higher cycle counts necessitate either oversizing to meet throughput requirements or acceptance of a reduced usable life.

Manufacturers often provide cycle life ratings at specific DoD values. Sungrow considers end-of-life (EoL) at 65% of the original capacity for these systems. Limiting cycles or employing partial cycles can extend life, while aggressive cycling necessitates greater initial capacity or more frequent replacement. For this study, an average of 1 full CPD is assumed for the primary energy shifting application. This is consistent with typical PV+BESS use cases and is reflected in degradation modelling and total energy throughput estimations.

Table 5.1: SoH Evolution over Time for Different CPD Scenarios

	SoH (%)		
Year	**0.5 CPD**	**1.0 CPD**	**1.5 CPD**
0	100.00	100.00	100.00
1	98.91	98.31	97.72
10	89.07	83.15	77.22
20	79.24	67.98	56.72

Table 5.1 presents SoH evolution using the model created over 20 years according to the frequency of cycling variation. There are other parameters influencing this degradation, but it is clear that by performing 1.5 CPD, the battery EoL would occur before the 20th year.

5.1.2 Depth of Discharge

DoD refers to the proportion of the battery's capacity that is discharged during each cycle, expressed as a percentage. A 75% DoD implies that the battery is cycled between 95% and 20% SoC. This parameter is a key determinant of battery lifespan: deeper discharges impose greater stress and accelerate degradation. Empirical data indicate that lithium-ion batteries endure significantly more cycles at reduced DoD [42].

Operational DoD is usually limited to mitigating degradation. A common approach involves maintaining the SoC within bounds such as 20–95%, yielding an effective DoD of 75%. This buffer reduces electrode stress and enhances longevity. Equation 5.1 defines the usable energy per battery unit(ST5015UX):

$$E_{\text{usable}} = \text{DoD} \times E_{\text{nominal}}, \tag{5.1}$$

where $E_{\text{nominal}} = 5.015$ MWh and DoD = 75%, then $E_{\text{usable}} = 3.761$ MWh.

For this analysis, 75% DoD is assumed, balancing usable energy and longevity. This assumption directly feeds into the degradation model, as the cycle degradation rate is a function of DoD.

5.1.3 Round-Trip Efficiency

The RTE quantifies energy losses in a complete charge-discharge cycle and is defined as:

$$\text{RTE} = \frac{E_{\text{discharged, net}}}{E_{\text{charged, net}}} \times 100\%, \tag{5.2}$$

Where $E_{\text{charged, net}}$ is the net input energy (including charging inefficiencies and auxiliary loads), and $E_{\text{discharged, net}}$ is the net energy delivered to the grid (after discharge losses and auxiliaries).

The C-rate influences RTE. At lower C-rates (e.g. 0.25 C), the system experiences reduced I^2R losses due to lower currents, yielding marginally higher RTE. Conversely, higher C-rates (e.g. 0.5 C) generate more resistive heat, reducing efficiency.

Using a baseline RTE of 89.5% [4], 100 MWh input yields approximately 89.5 MWh output, with 10.5 MWh lost to internal inefficiencies and auxiliary consumption. Its degradation is addressed in the section 5.5.1.

5.1.4 State-of-Charge Limits

SoC represents the instantaneous energy stored in the battery as a percentage of its usable capacity. SoC limits define the minimum and maximum SoC at which the battery is operated. These limits are closely related to the DoD and charge reserve discussed previously. For instance, operating the BESS between 20% and 95% SoC corresponds to a DoD of 75%.

Enforcing SoC limits is essential for safety and longevity. Cells should not routinely reach 0% (fully depleted) or 100% (fully charged) SoC, as these extremes accelerate degradation and may lead to unsafe conditions—such as lithium plating during full charge or cell undervoltage at deep discharge [42]. Manufacturers typically recommend operating within a conservative SoC window (like Huawei announced 5–95%, [43]), even though BMS prevent actual extremes.

Figure 5.1 shows the voltage variation with SoC. AS it is observable, the voltage suffers accentuated deviations when SoC reaches extreme values (when lower than 20% or higher than 80%). This behaviour explains why the selected DoD is more conservative than the default maximum recommended value [44].

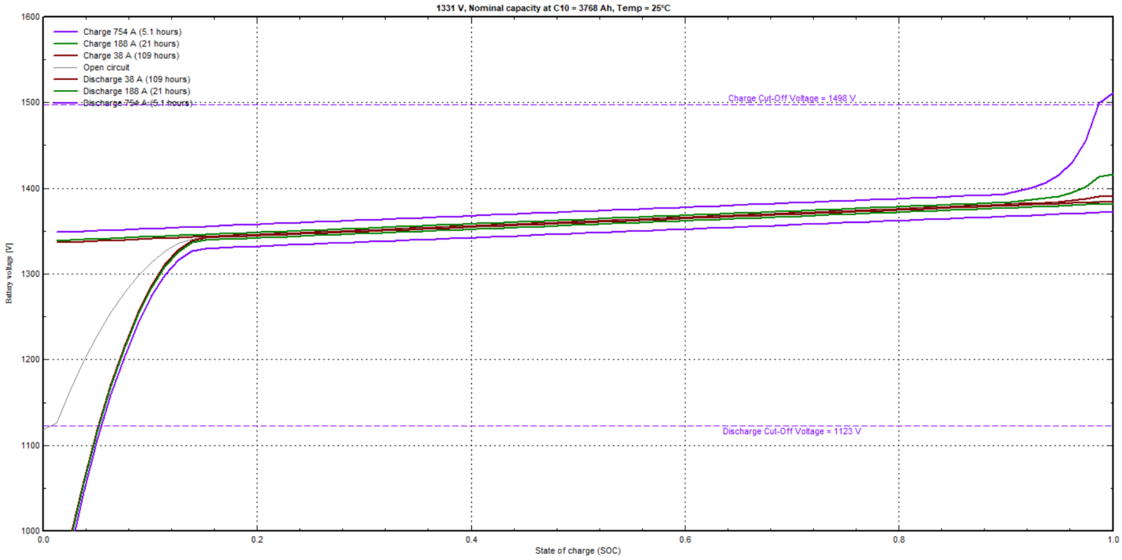

Figure 5.1: Graph of battery voltage directly from the supplier [38]

Holding high SoC for extended periods accelerates calendar ageing. To mitigate this, charging is often scheduled to reach maximum SoC shortly before discharge, and thermal systems may actively cool the battery at high SoC. Thus, SoC management integrates closely with thermal and operational strategies.

These limits are enforced in simulations such that energy dispatched always remains within the allowable SoC range, as it is visible in the graph from Figure 5.2.

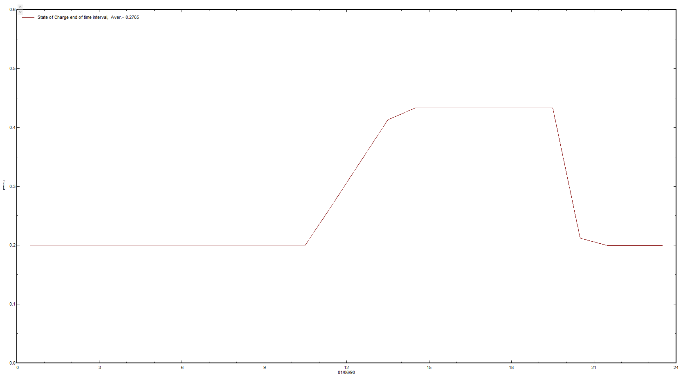

Figure 5.2: SoC during June 1st, according to PVSyst simulation

The battery's maximum potential is never fully enabled. However, the risk-benefit of this change would be dangerous as the battery performance would be severely damaged.

As [23] demonstrates, the higher the resting SoC, the more protected the system stays and the healthier it is for the batteries. Although it became clear during the work that a higher resting SoC was important for a minor degradation, a higher resting percentage was not possible to simulate. The software did not include that level of detail. In case there is the possibility to include this specification, it can be advantageous for the system since there might be consecutive days where the BESS is in the "Idle" state (Section 4.5 in Chapter 4).

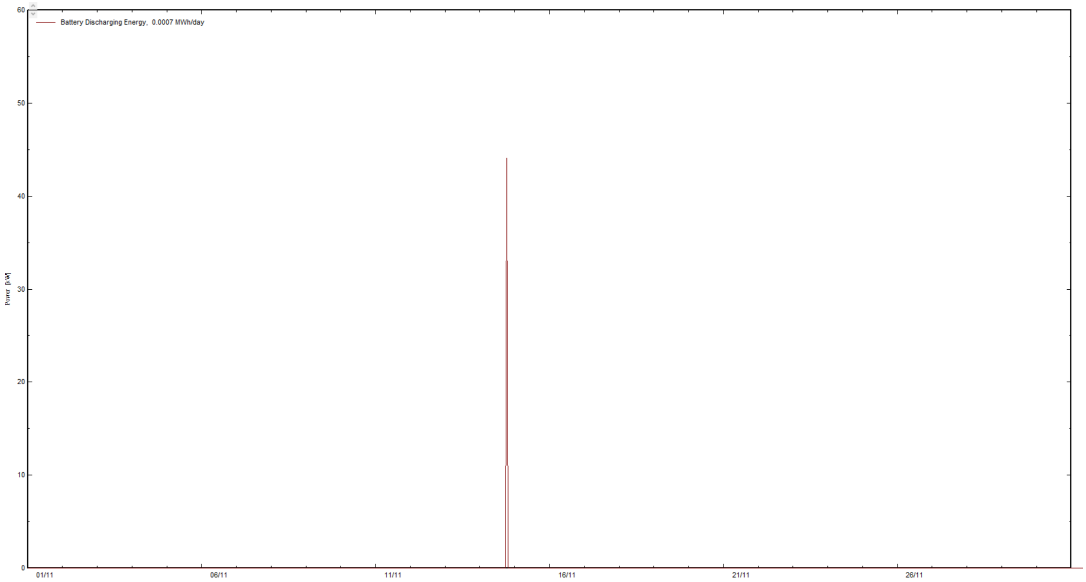

Figure 5.3: Discharged energy in November and December

Figure 5.3 demonstrates those consecutive "Idle" periods in two low PV production months, and that is why it would be relevant to have a higher minimum SoC for the battery to hold while not being used. The red spike in the Figure represents the charge and discharge of the battery on that day, which means that the battery was not used on the rest of the days of that month.

5.2 Sizing of the BESS

The dimensioning of the BESS is based on operational constraints derived from PV generation patterns and grid injection limits. Key design values were extracted from the Excel-based simulation tool developed for this project, aligning with inputs provided in Chapter 4 and Section 4.5.

The required storage capacity, expressed as usable energy, was calculated as the difference between available PV production and the 31.9 MWac grid limit. The BESS must therefore deliver a continuous power of up to 8.33 MW, corresponding to the peak excess generation expected during midday curtailment windows.

Given a DoD constraint of 75%, the nominal energy required per day becomes:

$$E_{\text{nom}} = \frac{E_{\text{usable}}}{\text{DoD}} = \frac{8,334.74 \text{ kWh}}{0.75} = 11,112.99 \text{ kWh} \tag{5.3}$$

Each ST5015UX unit has a nominal capacity of 5.015 MWh. Thus, the total number of containerised units required for energy purposes is:

$$n_{\text{energy}} = \frac{11,112.99}{5,015} = 3 \text{ units} \tag{5.4}$$

The total number of containers required for this configuration is governed by the power requirement, calculated in the following Section 5.3.

5.3 Definition of C-Rate

The C-rate is a dimensionless ratio that expresses the charging or discharging speed of a battery relative to its nominal energy capacity, expressed by Equation 5.5:

$$\text{C-rate} = \frac{P_{\text{discharge}}}{E_{\text{nominal}}} \tag{5.5}$$

In these project conditions, each c-rate value will demand a different number of batteries, depending on discharge power.

Sufficient parallel units must support the required discharge rate of 8.33MW. The following maths describes both possibilities.

- 0.5 C:

$$P = 0.5 \times 5.015 = 2.5075 \text{ MW}, \quad t = 2 \text{ h} \tag{5.6}$$

$$n_{\text{power}} = \frac{8,334.74}{2,5075} = 4 \text{ units} \tag{5.7}$$

- 0.25 C

$$P = 0.25 \times 5.015 = 1.25375 \text{ MW}, \quad t = 4 \text{ h} \tag{5.8}$$

$$n_{\text{power}} = \frac{8,334.74}{1,253.75} = 7 \text{ units} \tag{5.9}$$

The total number of containers required for this situation needs to be an integer and rounded up. It is controlled by the power requirement provided by Equations 5.7 and 5.9.

5.4 Auxiliary Power Consumption

Battery systems require a variety of auxiliary subsystems to operate safely and effectively. These include thermal management (cooling), power electronics cooling, control and monitoring systems, safety and fire suppression equipment, lighting, HVAC (Heating Ventilation Air Conditioning System) in battery enclosures, and an uninterruptible power supply (UPS) for critical backup. Although these components do not contribute directly to energy storage, they consume electrical energy continuously or intermittently, thereby reducing net energy output.

Auxiliaries operate in two modes:

- **Standby:** Battery is idle; control systems and minimal HVAC maintain system readiness.
- **Operation:** Battery is charging or discharging; thermal and electronic systems operate at higher intensity.

The executed calculations considered that these two modes could not operate simultaneously (i.e. if the system was operating, standby mode was not consuming any power).

5.4.1 Auxiliary Impact on Net Energy and Efficiency

Auxiliary losses scale with system size. A 4-hour BESS with more containers has higher absolute auxiliary loads but also higher output, making the per-unit energy impact comparable or slightly lower due to economies of scale. For instance:

- 2-hour system: 64.72 MWh/unit/year auxiliaries for total output of 5,491 MWh/year (1.17%) visible in Figure D.1;
- 4-hour system: 64.15 MWh/unit/year auxiliaries for total output of 9,609 MWh/year (0.67%) visible in Figure D.2.

Even when idle, auxiliaries consume 1.64 MWh/unit/year. Thus, auxiliary consumption must be included in efficiency and lifecycle cost models.

The Auxiliary Consumptions calculations are displayed in Figures D.1 and D.2 from Appendix D. These results were calculated per container according to the supplier's primary information regarding the equipment that integrates an ST5015UX unit in the PowerTitan 2.0 context (including PCS and even the power station connected). The operating hours according to each C-rate value were considered, and 1 CPD was assumed. Sungrow indicated 35ºC as the working temperature.

To conclude, auxiliaries consume less than 1.5% of BESS's annual energy throughput, depending on climate and operation mode. The temperature control system is the dominant component (>50% of auxiliary load).

5.4.2 Comparison of C-rates

At this point, it is reasonable to present Table 5.2 where both options are overviewed.

	C-Rate	
Parameter	**0.5 C (2H)**	**0.25 C (4H)**
Discharge duration	2 hours	4 hours
Power per battery	2.51 MW	1.25 MW
Nominal energy per battery	5.015 MWh	5.015 MWh
Battery count	4	7
Auxiliary Consumptions per battery	64,721.8 kWh	64,152.4 kWh
Degradation trajectory	Steeper	Softer
Dimensioning Margin	20.4%	5.0%

Table 5.2: comparison between 0.5 C and 0.25 C BESS configurations

Briefly, the 0.5 C system is more compact and power-oriented, while the 0.25 C system is more energy-oriented and durable but requires more hardware.

As shown in Figure C.1, battery discharge occurs predominantly between 18:00 and 20:00, especially during summer months. While a 4-hour system is typically recommended for PV+BESS applications targeting curtailment mitigation and evening peak support, this particular project exhibits constraints that alter that recommendation.

Due to the grid connection limit of 31.9 MW, the BESS system was dimensioned at a reduced scale. Consequently, it frequently discharges in less than two hours, as the energy stored during midday is fully exported over a shorter window. This is evident from the table, where no sustained 4-hour discharge pattern is observed throughout the year.

Under these conditions, a 4-hour system would not be utilised to its full potential, making the additional capacity economically unjustified. A 2-hour system, although less versatile in meeting extended grid support needs, aligns better with the current energy throughput profile and grid export constraints. It also incurs lower capital expenditure. However, the trade-off includes reduced flexibility, lower income potential, and a higher system utilisation rate—implying faster degradation compared to a lower-C-rate 4-hour configuration.

The resulting setup—4 ST5015UX units providing 20.060 MWh of total capacity and 10.030 MW discharge power—is fully compliant with the grid export constraints and PV oversupply conditions. The layout represents an oversizing of approximately 20.4%.

5.4.2.1 Transformer Implications

To enable full power export of the BESS system under the selected 0.5 C discharge strategy, two medium-voltage transformers are required. Given the 5.14 MVA rating of the standard Sungrow MVS5140-LS transformer, a minimum of two such units is necessary to sustain both the power and auxiliary loads safely and efficiently. Technical specifications for the MVS5140-LS can be found in Figure A.2.

5.5 Battery Degradation Modelling

Battery degradation over time is primarily driven by two mechanisms: calendar ageing and cycling degradation. For utility-scale systems such as the ST5015UX, an accurate representation of both is necessary to predict long-term performance and replacement timelines. The model adopted here follows a simplified, literature-backed approach, separating the effects of each degradation pathway.

The model represents a semi-empirical environment. Degradation is calculated annually by applying each year's calendar fade and cumulative cycling impact.

Effective Cycle Degradation

The degradation per cycle is not constant but increases non-linearly with the DoD. Based on empirical studies, this relationship can be modelled as:

$$D_{\text{eff}} = D_{\text{base}} \cdot \left(\frac{\text{DoD}}{100} \right)^{\alpha} \tag{5.10}$$

where:

- $D_{\text{base}} = 0.005\ \%/\text{cycle}$ is the base degradation rate at 100% DoD, based on literature for LFP under moderate temperature and SoC conditions [42, 45]
- $\alpha = 1.5$ is the empirical DoD adjustment exponent according to [46, 47]
- $\text{DoD} = 75\%$ as defined by the project's operational envelope

Substituting:

$$D_{\text{eff}} = 0.005 \cdot \left(\frac{75}{100} \right)^{1.5} \approx 0.00325\ \%/\text{cycle}$$

With an operational profile of 1 complete cycle per day, the annual number of cycles is:

$$N_{\text{cyc}} = 1 \cdot 365 = 365 \text{ cycles/year}$$

Hence, the total annual degradation attributed to cycling is:

$$D_{\text{cycle,year}} = D_{\text{eff}} \cdot N_{\text{cyc}} = 0.00325 \cdot 365 \approx 1.1854\ \%/\text{year}$$

As the graph from Figure 5.4 illustrates, 1.5 CPD may be perverse to the system's performance, according to the developed model.

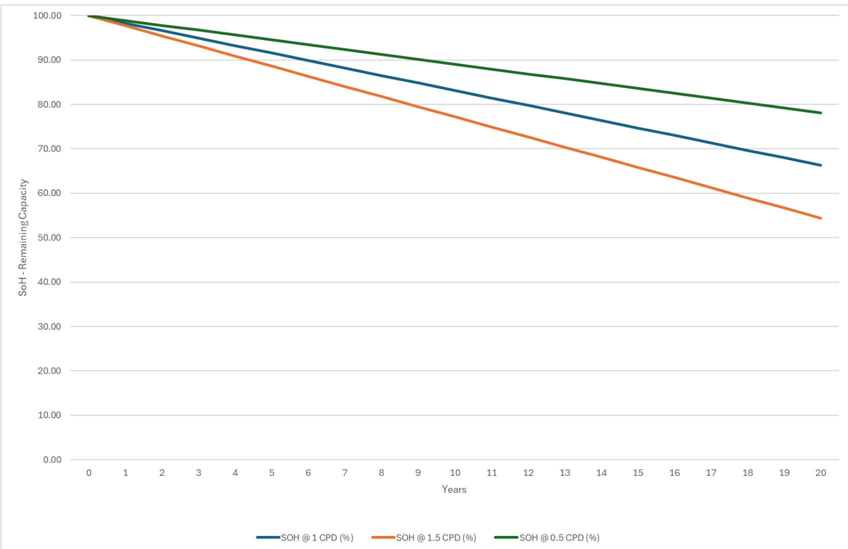

Figure 5.4: SoH evolution with varying cycling patterns

Calendar Degradation

Independent of usage, battery materials degrade over time due to chemical reactions and temperature exposure. For LFP systems, the annual calendar degradation is conservatively estimated at:

$$D_{\text{calendar}} = 0.5\ \%/\text{year}$$

This value aligns with recent studies, for instance [48, 49], benchmark for utility-scale storage systems under nominal conditions.

Total Capacity Loss

Combining both mechanisms, the annual degradation rate becomes:

$$D_{\text{total}} = D_{\text{cycle,year}} + D_{\text{calendar}} = 1.1854 + 0.5 = 1.6854\ \%/\text{year}$$

The SoH at year t is calculated recursively as following Equation 5.5 describes:

$$\text{SoH}(t) = \text{SoH}(t-1) - D_{\text{total}} \tag{5.11}$$

with $\text{SoH}(0) = 100$.

The following Figure 5.5 reflects discharged energy variations under defined circumstances.

Year	Cumulative Cycles	Cycle Degradation (%)	Calendar Degradation (%)	Total Degradation (%)	SOH @ 1 CPD (%)
0	0	0	0.0	0	**100.00**
1	365	1.185372271	0.5	1.685372271	**98.31**
2	730	1.185372271	0.5	1.685372271	96.63
3	1095	1.185372271	0.5	1.685372271	94.94
4	1460	1.185372271	0.5	1.685372271	93.26
5	1825	1.185372271	0.5	1.685372271	91.57
6	2190	1.185372271	0.5	1.685372271	89.89
7	2555	1.185372271	0.5	1.685372271	88.20
8	2920	1.185372271	0.5	1.685372271	86.52
9	3285	1.185372271	0.5	1.685372271	84.83
10	3650	1.185372271	0.5	1.685372271	**83.15**
11	4015	1.185372271	0.5	1.685372271	81.46
12	4380	1.185372271	0.5	1.685372271	79.78
13	4745	1.185372271	0.5	1.685372271	78.09
14	5110	1.185372271	0.5	1.685372271	76.40
15	5475	1.185372271	0.5	1.685372271	74.72
16	5840	1.185372271	0.5	1.685372271	73.03
17	6205	1.185372271	0.5	1.685372271	71.35
18	6570	1.185372271	0.5	1.685372271	69.66
19	**6935**	**1.185372271**	**0.5**	**1.685372271**	**67.98**
20	7300	1.185372271	0.5	1.685372271	66.29

Figure 5.5: Capacity Degradation Over Project Lifetime

This simplified approach reflects a conservative degradation envelope with adequate daily cycling.

5.5.1 Round-Trip Efficiency Degradation

In addition to capacity fade, RTE diminishes over time due to increased internal resistance and degradation in power electronics. The RTE decay is modelled exponentially, assuming a constant annual decay rate:

$$RTE(t) = RTE_0 \cdot (1-r)^t \tag{5.12}$$

With:

- $RTE_0 = 89.5\%$ (initial RTE)
- $r = 0.002$ (i.e. 0.2% per year, literature standard [50])

Examples of degraded RTE over project lifetime:

$$RTE(10) \approx 87.7\%, \quad RTE(15) \approx 86.9\%, \quad RTE(20) \approx 86.2\%$$

Although the decline is modest, the cumulative energy lost due to RTE degradation affects the actual net discharge delivered to the grid. Over 20 years, this accounts for a few percentage points of lost revenue.

5.6 Annual Energy Output with Degradation Considerations

To estimate the actual net energy output of the BESS throughout its lifetime, both capacity fade (SoH) and RTE degradation must be considered. These parameters affect the amount of usable energy discharged to the grid, and hence the system's economic viability. The calculations below integrate these effects, including auxiliary power losses.

5.6.1 Baseline Energy Output Before Degradation

The initial annual energy output of the BESS (before accounting for degradation) is derived from the usable energy per container and the daily cycling pattern. Assuming a 4-unit configuration, where each ST5015UX unit provides 3.761 MWh of usable energy (corresponding to 75 % DoD), and one full cycle per day for 365 days:

$$E_{\text{usable,unit}} = 5.015 \text{ MWh} \times 0.75 = 3.761 \text{ MWh} \tag{5.13}$$

$$E_{\text{annual,total}} = 3.761 \text{ MWh} \times 365 \times 4 = 5,491.65 \text{ MWh} \tag{5.14}$$

This value is then corrected by the system's initial round-trip efficiency, $RTE_0 = 89.5\,\%$, to obtain the net annual discharged energy at commissioning:

$$E_{\text{discharged}} = 5,491.65 \text{ MWh} \times 0.895 = 4,914,825.38 \text{ kWh} \tag{5.15}$$

This result corresponds to cell `B19` of the financial Excel model and serves as the baseline discharge energy for economic assessment before degradation or auxiliary loads are applied.

5.6.2 Net Output Over Lifetime with Degradation and Auxiliaries

Both SoH and RTE deterioration are included in calculating the net energy delivered each year. The annual discharged energy in year t, excluding auxiliary consumption, is given by:

$$E_{\text{w/o AUX},t} = E_0 \cdot RTE_t \cdot \text{SoH}_t \tag{5.16}$$

where $E_0 = 15,045$ kWh represents the initial nominal usable energy from 4 containers, RTE_t is the RTE in year t, and SoH_t is the remaining capacity expressed as a percentage.

Auxiliary systems consume a small but constant portion of energy. To incorporate these losses, a derating factor $f_{\text{aux}} \approx 0.985$ is used:

$$E_{\text{w/ AUX},t} = E_{\text{w/o AUX},t} \cdot f_{\text{aux}} \tag{5.17}$$

Table 5.3 summarises the evolution of annual discharge across 20 years, adjusted for both degradation and auxiliary consumption.

Table 5.3: Annual Discharged Energy over 20 Years with Degradation and Auxiliaries

Year	RTE w/ AUX (%)	SoH (%)	Energy w/o AUX (kWh)	Energy w/ AUX (kWh)
0	88.32	100.00	4,914,825.38	4,850,103.58
5	87.32	91.57	4,455,832.92	4,391,111.12
10	86.10	81.54	3,916,456.22	3,851,734.42
15	85.40	76.40	3,563,373.39	3,586,651.59
20	84.43	67.98	3,219,268.08	3,154,546.28
Total	–	–	**81,116,480.97**	**79,822,044.97**

5.7 Chapter Summary

This Chapter provided a detailed technical analysis of BESS performance under two C-rate scenarios (0.5 C and 0.25 C), using Excel and PVSyst simulation tools. The key findings include:

- Defined C-rate to 0.5 C, based on the discharging and PV profiles;
- Developed a degradation model predicting capacity at year 20;
- Quantified auxiliary consumption as of energy throughput, noting its differences depending on C-Rate.

As shown in this Chapter, energy output projections considering both SoH and RTE degradation yield significantly lower cumulative discharge than static models, underlining the importance of degradation-aware sizing.

The next Chapter will focus on evaluating the financial viability of the configuration, making use of various economic indicators and applying the results obtained from the developed model.

Chapter 6

Financial Analysis of BESS Integration

This chapter presents an Excel-made structured financial analysis of integrating a Battery BESS into the existing PV infrastructure. The objective is to assess economic viability through standard metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, Levelised Cost of Energy (LCOE), and Levelised Cost of Storage (LCOS). These indicators are derived using a discounted cash flow model that includes battery degradation, operational costs, and varying remuneration levels.

6.1 Methodology and Assumptions

The financial model is based on a deterministic yearly cash flow structure over a 20-year project lifetime. Cash inflows are generated from revenue obtained by delivering energy to the grid, while outflows account for investment and operating expenses. Battery degradation (SoH and RTE) is included, affecting the usable energy delivered annually.

Table 6.1 presents the initial conditions composing the analysis.

Table 6.1: Main economic and operational inputs.

Parameter	**Value**	**Notes**
Project lifetime (n)	20 years	Fixed across scenarios
Capital Expenditure (CapEx)	130–150€/kWh	Quoted by manufacturer
Operational Expenditure (OpEx)	1.5% of CapEx/year	Fixed over project life [51]
Daily cycles	1	One full cycle per day
Remuneration	8.86€/MWh	Base case A (Appendix B)
Alternative Remuneration	11.14€/MWh	Minimal value in Portugal [48]
Discount rate (r)	6%	Time value + risk
Inflation rate	2.5%/year	Average EU Value from [52]
Support	none	No incentives or subsidies
Degradation	Calendar + Cycling	As in Section 5.5

Due to confidential information or unanswered contacts, 130–150€/kWh was the only quote possible to obtain from the conducted market research.

6.2 Definition of Financial Metrics and Variables

All financial outputs are derived from time-indexed expressions of revenue and cost, using methodologies established in recent energy finance literature and modelling tools.

Net Present Value

$$\text{NPV} = \sum_{t=1}^{n} \frac{CashFlow_t}{(1+r)^t} - \text{CapEx} \tag{6.1}$$

Where $CashFlow_t$ is the annual net cash flow at year t. A positive NPV indicates that the project's discounted revenue exceeds the initial investment. This is a standard metric used to evaluate the profitability of renewable and storage projects [53].

Internal Rate of Return

$$0 = \sum_{t=1}^{n} \frac{CashFlow_t}{(1+\text{IRR})^t} - \text{CapEx} \tag{6.2}$$

The IRR is the interest rate at which the NPV equals zero. A project is considered financially viable when the IRR exceeds the investor's required rate of return or discount rate (assumed here as $r = 6\%$) [54].

Payback Period

$$\text{Payback Period} = \min\left\{ n \in \mathbb{N} : \sum_{t=0}^{n} \frac{CashFlow_t}{(1+r)^t} \geq 0 \right\} \tag{6.3}$$

It represents the earliest year t in which the cumulative discounted cash flow becomes non-negative. In this expression:

- $CashFlow_t$ is the net cash flow in year t, with $CashFlow_0 = -\text{CapEx}$
- r is the discount rate
- n is the year when cumulative inflows first offset the initial investment

This discounted payback period accounts for both the time value of money and yearly cash flow variations, and is commonly used together with NPV for risk evaluation [55].

Levelised Cost Metrics

$$\text{LCOE} = \frac{\sum \frac{\text{CapEx}_t + \text{OpEx}_t}{(1+r)^t}}{\sum \frac{\text{Energy Output}_t}{(1+r)^t}} \tag{6.4}$$

The LCOE represents the average cost of electricity generated over the system's lifetime. It is used primarily for standalone generation assets like PV and wind [56].

$$\mathrm{LCOS} = \frac{\sum \frac{\mathrm{CapEx}_{\mathrm{BESS}}+\mathrm{OpEx}_{\mathrm{BESS}}}{(1+r)^t}}{\sum \frac{\text{Discharged Energy}_t}{(1+r)^t}} \tag{6.5}$$

Here, r is the discount rate. LCOS reflects the cost per unit of usable electricity discharged from a battery system, accounting for degradation and round-trip efficiency losses. The LCOS formulation used follows the discounted cost-of-ownership approach recommended by [51].

6.2.0.1 Standalone Project Assumptions

The PV system is considered a completed investment since it was previously installed. Therefore, the base financial analysis in this chapter focuses exclusively on the integration of the BESS. All capital and operational costs considered relate to the BESS only. Likewise, only the energy discharged by the BESS and injected into the grid contributes to project revenue.

The PV plant is assumed to provide zero-cost energy for charging the BESS. No direct PV revenue is included, nor is its capital expenditure factored into the financial metrics. As such, all economic indicators (including NPV, IRR, payback period, and LCOS) reflect the economic viability of the storage investment in isolation.

6.2.1 Economic Calculations

The total system cost over 20 years consists of CapEx based on the installed battery capacity and OpEx calculated as a fixed percentage of CapEx. In this case, 4 ST5015UX containers are assumed, each with a nominal energy capacity of 5,015 kWh, totalling 20,060 kWh. Accounting for a DoD of 75%, the usable capacity becomes:

$$\mathrm{Capacity}_{\mathrm{usable}} = 4 \times 5,015 \times 0.75 = 15,045 \text{ kWh} \tag{6.6}$$

Two different capital cost assumptions were analysed—150€/kWh and 130€/kWh. In both cases, the annual OpEx is fixed at 1.5% of CapEx and remains constant throughout the project lifetime. The 20-year cumulative cost is then calculated as:

$$\text{Total Cost}_{20\,\mathrm{yr}} = \mathrm{CapEx}_{\mathrm{total}} + 20 \times \mathrm{OpEx}_{\mathrm{annual}} \tag{6.7}$$

Annual OpEx represents the recurring operational expenses on a yearly basis. The model indicates an annual OpEx of 1.5% of the initial CapEx.

Unforeseen Costs are a percentage applied to the annual OpEx to account for unexpected expenses. The model uses a factor of 0.15 (15%).

The total annual OpEx, including unforeseen costs, can be calculated as:

$$\text{Total Annual OpEx} = \text{Annual OpEx} \times 115\% \tag{6.8}$$

Table 6.2: CapEx and OpEx comparison for 4 ST5015UX units

Parameter	**150€/kWh**	**130€/kWh**
Number of Containers	4	
Nominal Capacity	20,060 kWh	
Usable Capacity (75 % DoD)	15,045 kWh	
Total CapEx	€3,009,000	€2,607,800
Annual OpEx (1.5 %)	€45,135	€39,117
Total Annual OpEx (+15%)	€47,391	€41,072
Cumulative 20-Year OpEx	€902,700	€782,340
Total 20-Year Cost	€3,911,700	€3,390,140

As shown in Table 6.2, reducing the CapEx from 150€/kWh to 130€/kWh lowers the total project cost over 20 years by €521,560. This represents a reduction of approximately:

$$\frac{3,911,700 - 3,390,140}{3,911,700} \approx 13.33\,\% \tag{6.9}$$

This 13.3% decrease in total expenditure impacts financial performance metrics such as NPV and IRR, particularly in low-revenue scenarios. It highlights the importance of capital cost control.

6.3 Energy Output Profile

The annual discharged energy is calculated using the expression:

$$\text{Annual Discharge Energy}_t = \text{Nominal Capacity} \times \text{SoH}_t \times \text{RTE}_t \times \text{Annual Cycles} \tag{6.10}$$

Where t represents the year of operation, and SoH_t and RTE_t are the degraded state of health and round-trip efficiency, respectively.

Over 20 years, SoH declines from 100% to approximately 68%, and RTE also decreases from 89.5% to 86.16%. These degradations reduce the annual discharged energy, significantly impacting the revenue generated in later years.

The following Table 6.3 demonstrates the impact of degradation in some of the affected metrics, considering a remuneration of 0.00886€/kWh.

Table 6.3: Economic Impact of Battery Degradation

Metric	**No Degradation**	**With Degradation**	**Difference**
LCOS (€/MWh)	0.002805	0.003363	+29.41%
Effective Capacity (Year 10)	100%	83.15%	-16.85%
Total Income (€)	661,767.53	544,561.96	-17.71%

Battery degradation has a substantial negative impact on both the technical and financial performance of BESS. Over time, declining SoH and RTE reduce usable energy and increase system losses. As highlighted in Table 6.3, LCOS rises by over 29%, while total income drops by nearly 18%, directly affecting project profitability.

Ignoring degradation leads to overestimated returns and underestimated costs, resulting in unrealistic investment assessments.

6.4 Revenue and Cash Flow Dynamics

Revenue is generated from injecting BESS-discharged energy into the grid. The key revenue calculation formulas are:

$$\text{Annual Revenue} = \text{Annual Discharge Energy} \times \text{Fixed remuneration} \tag{6.11}$$

$$\text{Annual Revenue (after tax)} = \text{Annual Revenue} \times (1 - \text{Tax Rate}) \tag{6.12}$$

With a base remuneration of 0.00886€/kWh and a tax rate of 23%, the initial annual revenue is approximately 33,088€, decreasing over time due to degradation. Operational costs are assumed at 41,072€/year, including a 15% unforeseen cost margin. The annual cash flow is:

$$\text{Annual Cash Flow} = \text{Annual Revenue (after tax)} - \text{Total Annual OpEx} \tag{6.13}$$

Initial investment (CapEx) is treated as a Year 0 negative cash flow.

6.5 Scenario Comparison and Results

This section compares the financial outcomes of four different scenarios for BESS integration, varying in CapEx and remuneration levels. The results, summarised in Table 6.4, show that all standalone BESS cases suffer from negative IRRs and extended payback periods, indicating poor financial performance under the current assumptions.

Table 6.4: Financial performance under different scenarios.

Scenario	**CapEx** (€/kWh)	**Remuneration** (€/kWh)	**NPV** (€)	**IRR** (%)
Case A (Base)	130	0.00886	–818.27	–14.38
Case B	150	0.00886	–50,959.76	–13.50
Case C	130	0.01114	82,842.13	–16.39
Case D	150	0.01114	32,700.65	–15.02

In the base case, the initial investment is relatively low, but the returns remain insufficient to make the project viable.

Raising the CapEx to €150/kWh in Case B significantly worsens the financials, highlighting the sensitivity of the project to capital costs when revenue is fixed.

Improved revenue via a higher remuneration (€0.01114/kWh) in Cases C and D leads to positive NPVs. However, both still exhibit negative IRRs, suggesting that while revenue helps, it does not overcome the investment burden, even when degradation is not considered.

Although none of the scenarios are economically viable, Case C can be considered the “best” option, achieving a modestly positive NPV among the two configurations with a higher remuneration. Nonetheless, its IRR remains significantly negative. Even under the most optimistic assumptions (low CapEx and high remuneration), the project fails to recover its investment within its 20-year lifetime.

Figure 6.1 contains a graph showing the projected annual revenue over the project lifetime, demonstrating the impact of battery degradation. This simulation compares Case A with C (remuneration scenarios for the same CapEx).

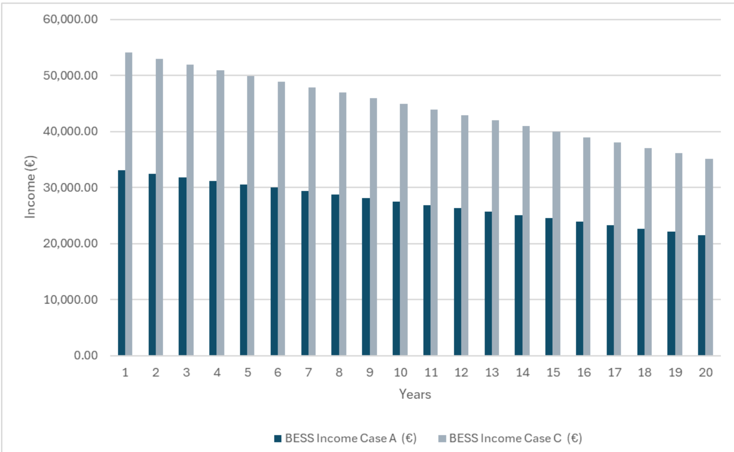

Figure 6.1: Project income with degradation over the years

Throughout this analysis, it becomes evident that profitability in a PV+BESS system is not solely driven by financial levers such as feed-in tariffs or reduced capital expenditure. Instead, the single most decisive factor influencing project viability is the total discharged energy delivered to the grid over the system’s lifetime.

This parameter, directly tied to battery size, degradation rate, and operational strategy, dictates the cumulative revenue stream. In the current model, despite stable operational expenditure and a low remuneration level, the total discharged energy remains insufficient to amortise the upfront investment within 20 years. The outcome is further aggravated by the compounding effects of calendar and cycling degradation, which reduce both SoH and RTE over time.

It is therefore safe to conclude that, under the current technical configuration, the battery system would need to deliver significantly more energy than currently simulated to reach profitability.

This could be achieved through:

- Increasing the number of daily cycles (e.g., 1.5 per day);
- Reducing idle periods via load shifting or grid service participation;
- Combining BESS with dynamic pricing strategies (e.g., arbitrage).

The implication is that energy throughput must be carefully optimised when dimensioning a BESS. A technically oversized battery that fails to discharge regularly offers limited economic return, whereas a well-utilised, right-sized system may outperform even with modest tariffs.

6.6 Conclusions

Key Financial Findings

- All standalone BESS scenarios analysed show negative IRRs and payback periods exceeding the system lifetime.
- Battery degradation substantially reduces discharged energy and long-term revenue.
- Lower CapEx and higher remuneration improve outcomes, but not enough to ensure bankability under current assumptions.

Deployment Strategy

- Integrating BESS with an existing (already amortised) PV plant is more realistic and improves asset utilisation, but may still fall short of profitability.
- Hybrid systems benefit from time-shifting and curtailment mitigation, increasing energy injection without new generation costs. the applied remuneration model strongly influences item Project viability. Fixed Remunerations offer predictability but low income; market prices and PPAs offer potential upside but introduce volatility.

Policy Recommendations

- Introduce dedicated BESS remuneration through capacity markets, flexibility services, or environmental incentives.
- Enable participation in carbon credit schemes to monetise avoided emissions.
- Provide CapEx subsidies, tax incentives, or remuneration premiums for dispatchable renewable energy.

Portugal currently lacks dedicated support mechanisms for standalone storage. The prevailing fixed remuneration levels are too low to sustain long-term investment in BESS infrastructure. Without new policies that reflect the system-level value of flexibility and reliability services, storage deployment will remain limited.

Although BESS is not viable under today's market and regulatory conditions, it still provides operational and environmental value by reducing renewable energy curtailment and supporting grid integration. Unlocking this value requires a shift in how storage is rewarded not only as a commodity, but as a critical enabler of the energy transition.

Chapter 7

Conclusions

This dissertation provided a comprehensive technical and economic assessment of integrating BESS into an existing installation (case study of a PVP). The objective was to evaluate whether such hybridisation could increase system efficiency and grid value while remaining economically viable under current and predictable conditions.

Accomplishment of the Objectives

The objectives defined at the beginning of this dissertation were comprehensively addressed. A summary of how each goal was approached is presented below:

The work began by examining the production characteristics of solar PV systems and identifying lithium-ion batteries as the most appropriate storage solution to pair with intermittent generation, based on their commercial maturity and technical performance.

A hybrid PV+BESS system was then designed to respond to a fundamental operational constraint (a grid export limitation), demonstrating how storage can be used to mitigate curtailment by shifting energy injection to more favourable periods.

Technical and economic feasibility were both analysed in depth. From a technical perspective, the system was dimensioned using realistic assumptions for depth of discharge, charge/discharge rates, and long-term degradation. From a financial standpoint, various scenarios were evaluated using a discounted cash flow model that incorporated degradation impacts, fixed remuneration levels, and operational expenditure over a 20-year horizon.

Current market data were used throughout the study. CapEx, OpEx, and tariff values were obtained from recent quotations, public databases, and regulatory references, ensuring that the analysis reflected actual Portuguese conditions. This allowed for a grounded discussion on the financial limits of storage systems under static tariff regimes.

A validation software was developed based on a structured Excel simulation model. This tool supported energy flow calculations and financial sensitivity analysis and may serve as a foundation for future hybrid project planning and evaluation.

The proposed methodology was applied to a real case study of a PV installation with injection limits, illustrating the practical relevance of the work and how the proposed approach can be adapted to real-world conditions.

Although the hybrid system analysed did not prove financially viable under current assumptions, the study delivered a complete assessment workflow and identified key points for technical and economic success. The findings confirm that the viability of such systems is highly context-dependent and may evolve rapidly with changes in battery pricing, regulatory support, or electricity market conditions.

Technical Assessment

The hybrid system was dimensioned using a 2-hour BESS configuration, selected based on grid export limitations and production profiles. A 0.25 C rate and 75 % DoD were adopted to manage degradation while enabling one complete cycle per day. The degradation model, introduced in Chapter 5, combined calendar and cycling degradation and revealed a capacity loss of approximately 17 % after 10 years, as well as an RTE drop from 89.5 % to 86.2 % over 20 years.

Although technically sound, the modelling process encountered limitations stemming from the simulation software used. PVSyst, though effective for PV yield assessment, offered limited flexibility for detailed BESS analysis. Variable access was inconsistent across time resolutions, degradation was not dynamically integrated, and output formatting lacked customisability. These shortcomings required additional spreadsheet-based processing and reduced the accuracy of hybrid system projections. Software such as HOMER Pro, more suited to hybrid simulations, could offer improved modelling capabilities, but licensing constraints prevented its application in this work.

Economic Performance

Chapter 6 presented a financial analysis based on four scenarios combining different CapEx values (130€/kWh and 150€/kWh) with two remuneration levels (8.86€/MWh and 11.14€/MWh). Results demonstrated that none of the configurations achieved financial viability.

In all cases:

- NPV remained negative;
- IRR fell below zero;

Even the most optimistic scenario (low CapEx and high remuneration) produced a negative IRR and a delayed breakeven point beyond the system's operational life. These results align with previous findings in the literature, such as [57], which highlight that energy arbitrage alone is insufficient to justify BESS investment in most European markets under current cost structures.

Limitations and Modelling Assumptions

Some structural limitations must be acknowledged. The financial model applied a deterministic structure, assuming one daily cycle, static OpEx, and no inverter or battery replacement. Input parameters such as degradation profiles were extracted from literature and manufacturer data sheets, not from monitored system operation.

In addition, PVSyst's limitations reduced the modelling fidelity for BESS dispatch and degradation tracking. The time invested in this software was considerably more than the benefits (performance results or study contributions) that it delivered. Alternative platforms could improve both the temporal resolution and energy flow logic required for accurate hybrid system simulation.

Policy and Strategic Outlook

While the financial results are currently unfavourable, the strategic value of BESS remains compelling. Storage systems support PV integration by increasing self-consumption, reducing curtailment, and improving grid reliability. These benefits extend beyond pure economic return and align with national decarbonisation goals.

However, Portugal's regulatory framework still imposes significant barriers. Fixed remunerations are static and do not reward flexibility, and the market for ancillary services remains underdeveloped. Unlocking the value of BESS will require:

- Revising tariffs to enable dynamic, market-linked remuneration;
- Reducing VAT or grid levies on renewable-sourced storage;
- Allowing grid charging at discounted rates during off-peak periods;
- Enabling BESS participation in frequency regulation and capacity markets.

In parallel, technical pathways can help reduce dependence on external support. Improving round-trip efficiency, extending cycle life, and reducing wear costs can lower the levelised cost of storage. Likewise, advanced control strategies, hybridisation with EVs or industry, and modular, application-specific design offer new ways to adapt BESS to market constraints and increase profitability. Without policy reform, these internal innovations may represent the only feasible route to commercial viability.

Technological Pathways in the Absence of Policy Support

In a scenario where financial incentives and regulatory reforms remain unavailable, the economic viability of BESS must rely more assertively on technological progress and operational innovation. This dissertation has shown that several internal pathways could enhance their performance and reduce reliance on external support mechanisms.

Technological improvements in round-trip efficiency and degradation rates are essential. Batteries capable of sustaining more cycles with minimal wear can distribute capital expenditure more effectively across their lifespan. Modular architectures tailored to specific applications—such as curtailment mitigation or peak shaving—can also improve cost-effectiveness by avoiding oversizing.

Advanced control strategies using Artificial Intelligence, including predictive dispatch based on weather forecasts and market signals, may increase revenue without changing external conditions. Additionally, flexible operating profiles that prioritise energy injection during periods of higher tariff differentials can optimise returns.

In this context, BESS will need to evolve not only in cost and efficiency, but also in adaptability, integration potential, and operational intelligence.

Future Research Directions

This study offers a solid foundation for further investigation. A recommended line of work is to adopt hybrid simulation tools such as HOMER Pro that would allow for integrated modelling of PV production, storage degradation, and market participation.

Another proposal is that system-level benefits such as avoided emissions, curtailment mitigation, and grid services should be included in multi-criteria evaluations.

Finally, policy-oriented studies comparing the Portuguese context with leading markets could inform local reform strategies.

Final Remarks

In summary, this work demonstrates that under current CapEx and remuneration structures, standalone BESS investments in Portugal are not financially attractive. Nonetheless, the operational, environmental, and strategic value of hybrid PV–storage systems remains strong.

- BESS enables more flexible and dispatchable renewable energy;
- Financial viability depends heavily on market design, remuneration levels, and energy output profile;
- Technological improvements—such as higher efficiency, longer lifetime, and market-responsive operation—are key enablers in the absence of policy support;
- Current modelling tools for PV projects are insufficient for advanced BESS/hybrid analysis;
- This dissertation contributes to methods and degradation logic that can support future simulation and policy assessment;
- A realistic, future-oriented perspective is needed to assess the potential of storage as costs fall and compensations evolve.

Although the project studied was not viable today, its architecture, modelling and assumptions provide a valuable base for future techno-economic studies. With falling prices and increasing regulatory maturity, BESS may soon transition from a marginal asset to a cornerstone of distributed energy systems.

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Appendix A

Equipment Datasheets

A.1 ST5015UX

Product name	ST5015UX-2H	ST5015UX-3H	ST5015UX-4H
DC side			
Cell type	LFP 3.2 V / 314 Ah		
Battery configuration	416S12P		
Nominal capacity	5015 kWh		
Nominal voltage range	1123.2 V ~ 1497.6 V		
AC side			
Nominal AC power	210 kVA * 12	127 kVA * 12	210 kVA * 6
AC current distortion rate	< 3 % (Nominal Power)		
DC component	< 0.5 %		
Nominal AC voltage	690 V		
AC voltage range	621 V ~ 759 V		
Termination (LV)	352 A * 3 Phase * 6	212 A * 3 Phase * 6	352 A * 3 Phase * 3
Power factor	> 0.99 (Nominal Power)		
Adjustable range of reactive power	-100 % ~ 100 %		
Nominal frequency	50 Hz / 60 Hz		
Isolation method	Transformerless		
System parameter			
Dimension (W * H * D)	6058 mm * 2896 mm * 2438 mm		
Weight	42500 kg	42500 kg	42000 kg
Degree of protection	IP55		
Anti-corrosion degree	C4		
Operation temperature range	-30 ℃ ~ 50 ℃ (> 45 ℃ Derating)		
Operation humidity range	0 % ~ 100 %		
Max. operation altitude	4500 m		
Temperature control method	Intelligent Liquid Cooling		
Fire suppression system	Default: FACP, FK5112, Flammable gas detector, Smoke detector, Heat detector, Sounder beacon, Alarm bell, Warning sign, Extinguishant abort button, Ventilation system, Pressure relief port, Manual automatic switching and emergency starting device Optional: Sprinkler, Explosion vent panel, Aerosol		
Communication	Ethernet		
Standard	IEC 61000, IEC 62619, IEC 62933, G99, UN 38.3 / UN 3536, CE, IEC 62477		

Figure A.1: ST5015UX-2H

A.2 MVS5140-LS

Product Name	MVS5140-LS
MV transformer	
Rated power	5140 kVA
MV / LV voltage	11 kV ~ 33 kV / 0.69 kV
Transformer vector	Dy11
Insulation level	A
Rated frequency	50 Hz / 60 Hz
Impedance	8 % (Tolerance ± 10 %)
Material of winding (MV / LV)	Aluminum / Aluminum
Cooling method	ONAN
Degree of protection	Transformer body: IP68 Other parts: IP55
RMU	
Rated voltage	24 kV / 36 kV
Rated current	630 A (50 Hz) / 600 A (60 Hz)
Units	DCV / CCV / CV / DV
Relay protection	ANSI 50 , 50N , 51 , 51N
Rated short-time withstand current	20 kA / 3 s or 25 kA / 1 s
Smart control cabinet	
Protection	AC Breaker
Surge protection	Type II
Meter for main circuit	Optional
AC insulation detection	Support
Temperature control method	Air cooling and HVAC
Degree of protection	IP55
UPS	15 min (Default) 2 / 3 / 4 h (Optional)
General data	
Dimensions (W * H * D)	6058 mm * 2896 mm * 2438 mm
Weight	17400 kg
Cable entry	Bottom Entry
Degree of protection	IP55
Anti-corrosion Degree	C4
Operation temperature range	-40 °C ~ 60 °C > 40 °C derating (Default) > 45 °C derating (Optional)
Operation humidity range	0 % - 100 %
Max. operating altitude	4500 m
Communication	Ethernet , Optical fiber , RS485
Standard	IEC 62271-202, IEC 61439

* 15min UPS only supplies power for the control and communication devices in the MVS
** 2 / 3 / 4 h UPS supplies power for the control and communication devices in the the MVS, and the ventilation system in the battery container

Figure A.2: MVS5140-LS Datasheet

Appendix B

"Licença Produção" Valen PVP

Presents the fixed remuneration of this project mentioned in Chapter 6

REPÚBLICA PORTUGUESA
AMBIENTE E
AÇÃO CLIMÁTICA

Direção-Geral
de Energia e Geologia

A energia elétrica produzida será remunerada nos termos Cláusula 13ª do Caderno de Encargos do Procedimento Concorrencial de 2019, ficando sujeita a um contributo para o SEN de 8,86 €/MWh.
Cumprir os pareceres das Entidades que se pronunciaram no âmbito do procedimento de licenciamento;
Cumprir os requisitos e os procedimentos de demonstração de conformidade decorrentes do Regulamento (UE) 2016/631 da Comissão, de 14 de abril de 2016, que estabelece um código de rede relativo a requisitos da ligação de geradores de eletricidade à rede, bem como da Portaria n.º 73/2020, de 16 de março.

Figure B.1: Production License of Valen PVP

Appendix C

Valen PVP Simulation Results

Month / Hour	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure C.1: Hourly Average Energy Discharge by Batteries in 1 Year

Table C.1: Hourly Distribution of PV Production by Month (MWh)

Month / Hour	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0	0	0	0	0	0	0	0	2	9	15	18	19	20	17	13	6	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	5	12	18	21	24	25	23	17	11	3	0	0	0	0	0	0
March	0	0	0	0	0	0	0	2	10	17	22	26	28	27	24	20	14	7	0	0	0	0	0	0
April	0	0	0	0	0	0	1	7	15	22	26	27	28	28	26	22	16	8	1	0	0	0	0	0
May	0	0	0	0	0	0	2	10	17	24	28	28	29	29	27	23	17	10	3	0	0	0	0	0
June	0	0	0	0	0	0	3	10	18	24	29	31	32	31	30	25	19	12	4	1	0	0	0	0
July	0	0	0	0	0	0	2	9	17	24	30	32	33	33	30	27	20	12	5	1	0	0	0	0
August	0	0	0	0	0	0	1	8	16	23	29	32	32	33	31	26	20	11	3	0	0	0	0	0
September	0	0	0	0	0	0	0	6	14	21	26	29	29	29	26	21	14	7	0	0	0	0	0	0
October	0	0	0	0	0	0	0	3	10	17	21	25	25	24	20	15	8	1	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	6	11	15	17	20	21	18	13	5	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	3	8	13	16	17	18	16	11	4	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	1	5	11	18	23	25	26	27	24	19	13	6	1	0	0	0	0	0

Month / Hour	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21h	22H	23H
January	0	0	0	0	0	0	0	0	2	9	15	18	18	19	17	12	6	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	5	11	17	21	23	24	22	16	10	3	0	0	0	0	0	0
March	0	0	0	0	0	0	0	2	9	16	22	25	26	25	23	19	13	7	0	1	0	0	0	0
April	0	0	0	0	0	0	1	6	15	21	25	26	27	26	25	21	15	8	1	1	1	0	0	0
May	0	0	0	0	0	0	2	9	17	23	26	26	27	27	25	22	16	10	3	0	2	0	0	0
June	0	0	0	0	0	0	3	10	17	23	28	29	30	29	28	24	18	11	4	1	2	0	0	0
July	0	0	0	0	0	0	2	9	17	24	28	30	31	30	28	26	19	12	5	0	2	0	0	0
August	0	0	0	0	0	0	1	7	16	23	28	30	30	30	30	25	19	11	3	0	3	0	0	0
September	0	0	0	0	0	0	0	6	14	20	25	27	27	27	25	20	14	6	0	1	0	0	0	0
October	0	0	0	0	0	0	0	2	10	16	20	24	24	23	19	14	8	1	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	5	11	15	17	19	20	18	13	5	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	3	8	13	15	17	18	16	11	4	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	1	4	11	17	22	24	25	25	23	19	12	6	1	0	1	0	0	0

Figure C.2: Hourly Average of Energy Injected into the Grid in 1 Year (MW)

Appendix D

Auxiliary Services Power Consumption

2H System	Temperature (ºC)	35

	Device	STANDBY (kW)	OPERATION (kW)	Max. Distribution Cap(kVA)	STANDBY Per day(kWh)	OPERATION Per day(kWh)	STANDBY Annual(kWh)	OPERATION Annual(kWh)
ST5015UX	Temperature control system	0.00	76.72	168.00	0.00	153.44	0.00	56005.60
	FAN	0.00	1.32	2.00	0.00	2.64	0.00	963.60
	FSS	0.00	0.32	0.32	0.00	0.64	0.00	233.60
	PSBoard (w/CMU)	0.00	0.62	1.40	0.00	1.24	0.00	452.60
Sungrow MVS5140-LS	HVAC	0.10	0.90	0.98	1.60	3.60	584.00	1314.00
	UPS	0.10	2.20	3.00	1.60	8.80	584.00	3212.00
	FAN	0.00	0.54	0.54	0.00	2.16	0.00	788.40
	Others	0.08	0.08	0.09	1.28	0.32	467.20	116.80
						Subtotal (kWh)	1635.20	63086.60
						Total per battery (kWh)	64721.8	
						Fraction	1.178598%	
						Total (kWh)	237688	

CPD	1.00
C-rate	0.50
Operation time (hours per day)	4.00
Duration (hours, from C-rate)	2.00
Number of batteries	4
Total Output (kWh)	5491425

Figure D.1: Auxiliary Services Power Consumption 2H system (0.5 C)

4H System	Temperature (^{o}C)	35

	Device	STANDBY (kW)	OPERATION (kW)	Max. Distribution Cap(kVA)	STANDBY Per day(kWh)	OPERATION Per day(kWh)	STANDBY Annual(kWh)	OPERATION Annual(kWh)
ST5015UX	Temperature control system	0.00	66.24	73.60	0.00	132.48	0.00	48355.20
	FAN	0.00	2.64	4.00	0.00	5.28	0.00	1927.20
	FSS	0.00	0.64	0.64	0.00	1.28	0.00	467.20
	PSBoard (w/CMU)	0.00	1.24	2.84	0.00	2.48	0.00	905.20
Sungrow MVS5140-LS	HVAC	0.10	0.90	0.98	1.60	7.20	584.00	2628.00
	UPS	0.10	2.20	3.00	1.60	17.60	584.00	6424.00
	FAN	0.00	0.54	0.54	0.00	4.32	0.00	1576.80
	Others	0.08	0.08	0.09	1.28	0.64	467.20	233.60
						Subtotal (kWh)	**1635.20**	**62517.20**
						Total per battery (kWh)	**64152.4**	
						Fraction	**0.66756%**	
						Total (kWh)	**374081.2**	

CPD	1.00
C-rate	0.25
Operation time (hours per day)	8.00
Duration (hours, from C-rate)	4.00
Number of batteries	7
Total Output (kWh)	9609994

Figure D.2: Auxiliary Services Power Consumption 4H system (0.25 C)