MASTER’S DEGREE IN INDUSTRIAL TECHNOLOGIES ENGINEERING

MASTER EN INGENIERÍA DE LAS TECNOLOGÍAS INDUSTRIALES (MITI)

MASTER’S THESIS

Strategic Optimization of Hybrid Photovoltaic and Energy Storage Projects: Techno-Economic Analysis Oriented Toward Investment Decision-Making

AUTHOR: **MARIANO BLANCO LECAROZ-BADGER**

DIRECTOR: **MANDAR KHODEGAOKAR**

I hereby declare, under my own responsibility, that the Project presented under the title ***Strategic Optimization of Hybrid Photovoltaic and Energy Storage Projects: Techno-Economic Analysis Oriented Toward Investment Decision-Making*** at the ICAI School of Engineering – Comillas Pontifical University during the 2024/2025 academic year is my own work, original and unpublished, and has not been previously submitted for any other purpose. The Project is not a plagiarism, either in whole or in part, and all information taken from other documents has been duly referenced.

Signed: Mariano Blanco Lecaroz-Badger Date: 08/31/2025

Authorized for submission by
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To both the Business Analysis and Performance Engineering teams in Recurrent Energy USA for their consistent help.

To my family for their constant support.

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Universidad Pontificia Comillas

ABSTRACT:

This thesis provides an investment-oriented techno-economic evaluation of hybridizing utility-scale photovoltaic (PV) plants with battery energy storage systems (BESS). It compares AC- and DC-coupled configurations—including shared-inverter designs—using unlevered project metrics (IRR, LCOE, LCOS, and payback). It also proposes a practical adjustment to standard BESS merchant revenue curves that explicitly embeds two hybrid-specific effects: (i) free PV-based charging that recovers clipping and (ii) export constraints when PV and BESS share equipment such as inverters, transformers, or the interconnection. Incorporating these effects reduces bias across configurations and yields more realistic, decision-useful comparisons for investors and developers.

1. INTRODUCTION

PV+BESS hybridization is framed within decarbonization and market competition among configurations. The thesis addresses a practical modeling gap: merchant curves derived from standalone BESS miss both synergies and bottlenecks unique to hybrids, potentially biasing revenue estimates and investment valuation.

2. TECHNICAL AND FINANCIAL FUNDAMENTALS

PV and BESS operating principles and main integration families (AC-coupled and DC-coupled, including shared-inverter variants) are outlined. Cost structures (CAPEX/OPEX) and unlevered metrics (IRR, LCOE, LCOS, payback) are used to compare configurations without leverage-driven distortions.

3. CONFIGURATIONS AND REVENUE STREAMS

Physical configurations are mapped to feasible revenue schemes: PV (fixed PPA and merchant) and BESS (tolling, arbitrage, ancillary services, capacity, and clipping recapture). Co-location enables synergies (shared infrastructure and direct PV charging in DC) but introduces export limits (e.g., transformer or interconnection) and DC-side inverter bottlenecks.

4. BASELINE PROFITABILITY ASSESSMENT

Three representative cases—AC Standalone, AC Coupled co-located, and DC Classic—are defined with sector-typical assumptions for CAPEX/OPEX and revenues. Baseline results show moderate differences across configurations and contained sensitivity to degradation, solar yield, and market prices, suggesting that site-specific operational constraints largely drive the differential value.

5. FINANCIAL MODEL ENHANCEMENT

An adjustment module is proposed to (i) quantify the uplift from free PV-based charging (clipping recapture) and (ii) estimate the haircut from co-export limits. Both effects are converted to $/kW-month and applied to merchant curves prior to re-running the project model, offering a simple and transparent way to reflect hybrid-specific realities.

6. AQDJUSTED RESULTS AND DISCUSSIONS

After applying the adjustments, AC and DC IRRs converge toward the standalone case: in DC, the clipping uplift is partially offset by the inverter constraint; in AC, lacking direct PV charging, the transformer/interconnection haircut dominates. Implications for developers and investors include avoiding overstated hybrid advantages when physical limits are not modeled and prioritizing apples comparisons across sites.

7. CONCLUSIONS

Explicitly representing operational synergies and constraints improves the credibility of hybrid PV+BESS financial assessments. The proposed methodology is transferable and scalable, supporting more rigorous investment decisions. Future work includes integrating hourly hybrid dispatch models and deepening market-specific regulatory nuances.

Optimización estratégica de proyectos híbridos fotovoltaicos y de almacenamiento de energía: análisis técnico-económico orientado a la toma de decisiones de inversión

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RESUMEN:

Este Trabajo Fin de Máster evalúa, con un enfoque técnico-económico orientado a la decisión de inversión, la hibridación de plantas fotovoltaicas (PV) con sistemas de almacenamiento con baterías (BESS). Se comparan configuraciones AC y DC (incluida la variante de inversor compartido), cuantificando rentabilidades a nivel de proyecto mediante métricas unlevered (IRR, LCOE, LCOS y payback). Se propone, además, una metodología para ajustar las curvas merchant estándar de BESS a la realidad de los sistemas híbridos, incorporando dos efectos clave: (i) la recarga 'gratuita' desde PV que permite recapturar clipping/cortas y (ii) las limitaciones de exportación cuando PV y BESS comparten equipos como inversores, transformadores o la interconexión. La inclusión de estos efectos reduce el sesgo a favor de ciertas configuraciones, ofrece comparaciones más realistas y refuerza la robustez del análisis de inversión.

1. INTRODUCCIÓN

Se contextualiza la hibridación PV+BESS en la transición energética y la competencia tecnológica entre configuraciones. El trabajo parte de una necesidad práctica: los modelos financieros suelen apoyarse en curvas merchant de BESS 'standalone', que no capturan sinergias ni cuellos de botella propios de los híbridos, pudiendo sesgar la estimación de ingresos y la valoración de inversiones.

2. FUNDAMENTOS TECNICOS Y FINANCIEROS

Se resumen los principios de operación de PV y BESS, y las principales familias de integración (AC-coupled y DC-coupled, incluyendo diseños de inversor compartido). Se define la estructura de costes (CAPEX/OPEX) y las métricas unlevered (IRR, LCOE, LCOS, payback) empleadas para comparar configuraciones sin introducir efectos de apalancamiento ni de estructuras de financiación.

3. CONFIGURACIONES Y STREAMS DE INGRESOS

Se mapean configuraciones físicas con esquemas de ingresos: PV (PPA fijo y merchant) y BESS (tolling, arbitrage, ancillary, capacidad y recaptura de clipping). La co-ubicación aporta sinergias (uso compartido de infraestructura y, en DC, carga directa desde PV), pero introduce límites de exportación (p.ej., transformador o punto de interconexión) y cuellos de botella (p.ej., inversor del lado DC).

4. EVALUACION BASE DE RENTABILIDAD

Se definen tres casos representativos —AC Standalone, AC Coupled co-located y Classic DC Coupled— con supuestos sectoriales para CAPEX/OPEX e ingresos. Los resultados base muestran diferencias moderadas entre configuraciones y sensibilidad contenida a variaciones de degradación, rendimiento solar y precios de mercado, lo que sugiere que el valor diferencial depende en gran medida de restricciones operativas específicas de cada sitio.

5. MEJORA METODOLOGICA DEL MODELO FINANCIERO

Se propone un módulo de ajuste que (i) cuantifica el 'uplift' por energía PV capturada sin coste (clipping recapture) y (ii) estima el 'haircut' por límites de co-exportación. Ambos se traducen a $/kW-mes y se aplican a las curvas merchant antes de recalcular resultados financieros, permitiendo reflejar de forma simple y transparente las particularidades híbridas.

6. RESULTADOS AJUSTADOS Y DISCUSION

Tras aplicar los ajustes, las IRR de las configuraciones AC y DC convergen hacia el caso standalone: en DC, el impulso del clipping se ve parcialmente compensado por la limitación del inversor; en AC, al no existir carga directa desde PV, prevalece el recorte asociado al transformador/interconexión. Se discuten implicaciones para desarrolladores e inversores: evitar sobreestimar ventajas híbridas sin modelar límites físicos y priorizar comparaciones 'como-con-como' entre sitios.

7. RESULTADOS AJUSTADOS Y DISCUSION

Representar explícitamente sinergias y restricciones operativas mejora la credibilidad de la evaluación económico-financiera de híbridos PV+BESS. La metodología propuesta es trasladable y escalable, y apoya decisiones de inversión más rigurosas. Como trabajo futuro se sugiere integrar modelos horarios de despacho y profundizar en particularidades regulatorias por mercado.

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1. INTRODUCTION

1.1. GLOBAL ENERGY CONTEXT AND THE GROWING ROLE OF HYBRID SYSTEMS

In recent decades, the global energy system has undergone a profound transformation driven by international decarbonization commitments, increasing competitiveness of clean technologies, and the rise of decentralized electricity markets. Within this process, photovoltaic (PV) solar energy has emerged as one of the most relevant renewable sources worldwide, due to its modular nature, rapid cost decline, and ease of deployment.

However, PV generation presents structural limitations: its output is intermittent, depends on variable weather conditions, and is concentrated on specific hours of the day — typically during midday solar peaks — which often do not align with the periods of highest electricity demand. This mismatch can lead to low or even zero prices during certain hours, constrain the profitability of pure solar projects, and create challenges for the power grid in high-renewable penetration scenarios.

To address these issues, energy storage systems (BESS), particularly lithium-ion battery storage— have gained increasing relevance in recent years. Their ability to store energy when it is abundant and release it when it is more valuable from a technical or economic standpoint makes them key assets for mitigating renewable variability and providing system flexibility. Thanks to rapid technological improvements and declining costs, BESS has become a critical enabler in the transition toward a cleaner, more efficient, and resilient electricity system.

The natural evolution toward more efficient integration of both technologies has led to the rise of hybrid PV+BESS systems. These projects aim not only to share infrastructure and reduce development costs, but also to maximize the joint value of solar generation and storage through coordinated operation strategies. Their deployment has accelerated notably in markets such as the United States, Australia, and Spain, where regulatory and economic pressure is pushing the industry to develop increasingly optimized solutions from both technical and financial perspectives.

In this context, the correct evaluation of hybrid PV+BESS projects — considering both their technical configurations and their associated revenue and cost structures — becomes an essential tool to support investment decision-making and strategic planning for developers and investors in the renewable energy sector.

Image 1. PV + BESS coupled system

1.2. OBJECTIVES OF THE STUDY

The main objective of this Master's Thesis is to strategically analyze and evaluate the different integration scenarios between photovoltaic (PV) systems and battery energy storage systems (BESS), considering their technical configurations, revenue models, associated costs, and financial performance, to identify which setups offer the most efficient operation and are most attractive from an investment standpoint.

To support this overarching goal, the following specific objectives are defined:

- Identify and classify the main physical configurations for integrating PV and BESS systems, including AC coupling, DC coupling, shared inverter schemes, and both front-of-the-meter (FTM) and behind-the-meter (BTM) architectures.

- Evaluate the revenue models associated with each technical-commercial configuration, considering both traditional and advanced schemes:

  For PV systems: fixed-rate or indexed Power Purchase Agreements (PPA), as well as merchant spot market participation.

  For BESS: tolling agreements, energy arbitrage, participation in ancillary service markets, and capturing excess solar energy through clipping recapture.

- Estimate the cost structure (CAPEX, OPEX, interconnection, etc.) for each PV+BESS configuration to provide a comprehensive view of the required investment. Where relevant, elements specific to the U.S. market—such as tax equity incentives or project finance structures—will be briefly mentioned. However, these will not be incorporated into the analysis, as the conclusions will be evaluated on an unlevered basis.

- Model and compare the economic profitability of the identified hybrid configurations using key investment indicators such as Unlevered Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), Levelized Cost of Storage (LCOS), and payback period.

- Conduct sensitivity analyses on critical project variables (module degradation, solar irradiance, energy prices, etc.) in order to assess the financial robustness of each configuration.

- Propose a methodological enhancement to the financial model used for estimating merchant revenues in hybrid PV+BESS systems. The objective is to supplement standardized merchant revenue curves—such as those developed by specialized energy modeling firms (e.g., Aurora Energy Research, Wood Mackenzie, Ascend, or Energy Exemplar)—with an analytical adjustment that accounts for the operational synergies of hybridization. Specifically, the adjustment will capture the additional value generated by coordinating battery operation with PV output, considering both export limitations and the opportunity to charge the battery at zero marginal cost during clipping or solar overproduction events. *The detailed methodology is outlined in the following section.*

- Extract strategic recommendations for investors and developers based on the results, so that this work may serve as a practical decision-support tool for evaluating hybrid PV+BESS projects from both a technical and financial perspective.

1.3. JUSTIFICATION FOR IMPROVING HYBRID FINANCIAL MODELLING

In the current context of hybrid PV+BESS project development, financial models used by developers and investors are generally well-structured for evaluating standalone photovoltaic or storage assets. However, when both systems are co-located within the same project, it is common for the revenues and costs of each technology to be modeled in parallel but not in a coordinated manner, which limits the ability to capture the true operational value of a hybrid system.

In particular, the estimation of merchant revenues for BESS systems is typically based on long-term revenue curves provided by specialized energy modeling firms —such as Aurora Energy Research, Wood Mackenzie, Ascend, or Energy Exemplar— which express forecasted revenues in units of dollars per kilowatt per month ($/kW-month). While these curves serve as useful standardized inputs, they are generally built upon the assumption of standalone BESS operation, meaning the battery is charged exclusively from the grid.

Standard merchant curves do not capture the operational reality of hybrid configurations, where part of the battery's charging energy can be sourced directly from the PV plant. This occurs either during clipping events—when PV generation exceeds inverter capacity—or during periods of solar overgeneration. In these cases, the energy used for charging is effectively "free," as it does not require grid purchases. Consequently, revenues from arbitrage or ancillary services based on this energy yield higher net returns than those implied by conventional merchant curves. At the same time, the export constraints inherent to shared infrastructure must also be considered, as they can reduce the revenues achievable in hybrid systems.

This mismatch between the technical operation of hybrid systems and their financial representation can result in a systematic over- or underestimation of project profitability. To address this gap, the present study proposes a complementary adjustment to the merchant revenue curves employed in financial models, explicitly incorporating both the additional economic value of free PV-based charging and the constraining effect of export limitations.

This methodological adjustment is not intended to replace sophisticated modeling tools developed by third parties, but rather to supplement them with a transparent and exogenous estimation that more accurately reflects the real synergies of hybrid PV+BESS systems — with direct implications for evaluating their financial viability and investment attractiveness.

1.4. METHODOLOGY AND SCOPE OF STUDY

The methodology of this Master's Thesis is structured around a logical sequence of technical, economic, and financial analyses, aimed at comprehensively evaluating various configurations of hybrid projects combining photovoltaic generation (PV) with battery energy storage systems (BESS), and proposing a methodological improvement to increase the accuracy of the financial modeling involved.

The study is organized into four main sections:

1. **Identification and classification of technical configurations**

First, the different physical integration schemes between PV and BESS systems are analyzed. These are classified based on their coupling method (AC coupling, DC coupling, shared inverters), as well as their location relative to the grid connection point (front-of-the-meter or behind-the-meter). For each case, the main technical constraints, operational viability, and implications for energy flow and potential synergies—such as clipping recapture or shared infrastructure—are examined.

2. Analysis of revenue streams and cost structure

Next, the commercial operation models applicable to each technical configuration are identified, including revenue sources such as PPAs, merchant sales, tolling, ancillary services, and energy arbitrage. In parallel, a cost structure is developed for each case (CAPEX, OPEX, interconnection, degradation, maintenance, replacements). Financing structures that may vary depending on the region—such as the use of debt or specific mechanisms like tax equity in the U.S.— will be briefly mentioned. While such structures can offer relevant advantages for certain investors, they are not directly modeled, as this study focuses primarily on unlevered project-level metrics.

3. Financial evaluation of hybrid project scenarios

Representative hybrid PV+BESS configurations are defined and simulated by integrating the technical and economic data collected in the previous sections. Each scenario's profitability is assessed using key indicators such as IRR, LCOE, LCOS and payback period.

Methodological note: As mentioned in section 2, the financial analysis developed in this study is approached from a project-centric perspective, using unlevered metrics (at the project level), without considering specific debt structures or fiscal instruments such as US tax equity. This approach allows for a neutral and structural comparative evaluation of the economic impact of different technical configurations of PV+BESS hybridization. This methodological approach is useful for two types of decision-makers:

- **Developers**, who can use this analysis in the early stages of the project to determine the most appropriate technical architecture to maximize the profitability and operational efficiency of the hybrid system.

- **External investors**, who analyze already structured projects (e.g., at NTP or COD) to determine whether the configuration implemented is optimal and whether the economic value offered justifies its acquisition.

Therefore, although customized financial aspects such as capital structure or investor-specific tax rates are not modeled, the work provides a solid comparative basis for strategic decision-making from both the development and investment analysis sides.

4. **Proposed methodological improvement to financial modeling and sensitivity analysis**

Based on the findings, this study proposes an adjustment module to complement the merchant revenue curves commonly applied in BESS financial models when evaluating hybrid configurations. The first adjustment captures the additional value of free battery charging from the PV plant—whether through clipping or solar overgeneration—by quantifying the associated operational savings in a transparent and replicable way. The second adjustment, which complement the first, incorporates the revenue downgrade caused by co-export limitations. The combined impact of these adjustments is assessed through a realistic case study to evaluate their influence on key financial performance indicators.

Finally, a sensitivity analysis is conducted on critical variables (e.g., degradation, solar irradiance, market prices) to test the resilience of each configuration under uncertain external conditions.

Scope of the study

This study is primarily based on utility-scale projects in the United States, given the market's high maturity in PV+BESS hybrid development and its diversity of regulatory, contractual, and financial frameworks. However, the methodological approach and conclusions are fully transferable to other markets with similar technical and commercial conditions, such as Spain or other parts of Europe, which will be referenced when relevant to add comparative perspective.

The study does not include the implementation of a full hourly dispatch model for hybrid PV+BESS operation, nor the redevelopment of proprietary third-party financial models. Instead, a complementary, flexible, and transparent methodological approach is proposed—one that can be easily integrated into existing financial models to enhance the representation of real operational synergies between generation and storage in hybrid projects.

1.5. STRUCTURE OF THE STUDY

This master's Thesis is organized into seven main chapters, followed by a technical glossary and references. Each chapter corresponds to a distinct phase of the analysis, enabling a progressive and structured reading of the study:

Chapter 1 – Introduction: presents the general context, the objectives of the study, the motivation behind it, and the methodology followed.

Chapter 2 – Technical and conceptual framework: outlines the technological fundamentals of photovoltaic and storage systems, as well as the main hybridization configurations.

Chapter 3 – Revenue and cost analysis: identifies the possible revenue schemes and structures the cost components based on the system configuration.

Chapter 4 – Economic evaluation of hybrid scenarios: compares different PV+BESS combinations using standard financial metrics without the revenue stacking effect.

Chapter 5 – Methodological improvement proposal: develops an adjustment to financial modeling to reflect PV+BESS synergies not captured in standard merchant curves. Therefore, representing the revenue stacking effect and conducting a sensitivity analysis.

Chapter 6 – Discussion of results: analyzes the findings and highlights relevant considerations for decision-making.

Chapter 7 – Conclusions and recommendations toward investors: summarizes the key takeaways and suggests future areas of development or research.

The document is complemented by annexes and a glossary of terms to facilitate understanding of the concepts used throughout the study.

2. TECHNICAL AND FINANCIAL FUNDAMENTALS

2.1. OPERATION PRINCIPLES OF PHOTOVOLTAIC PLANTS (PV) AND BESS SYSTEMS

Photovoltaic (PV) generation systems and battery energy storage systems (BESS) are fundamental pillars in the move towards a decarbonized, resilient, and flexible electricity system. Their joint deployment, especially in large-scale (utility-scale) applications, not only increases the penetration of renewable energies but also optimizes their economic use through smarter and more coordinated operation. This section describes the operating principles of both systems and introduces the technical synergies that emerge from their integration.

Solar photovoltaic (PV) generation

A utility-scale solar photovoltaic plant consists of an array of solar modules (usually based on crystalline silicon), connected in series and parallel to achieve adequate voltage and current levels. These modules convert solar energy into direct current (DC), which is then transformed into alternating current (AC) by inverters for injection into the grid.

The daily generation profile follows a bell-shaped curve, with peak production around noon, when solar irradiation is at its maximum. However, the capacity of AC inverters is sized to limit the maximum power exported, which means that, under certain conditions of high irradiance, part of the potential generation is discarded. This phenomenon is known as clipping, and represents energy that, although generated by the modules, cannot be used due to inverter saturation.

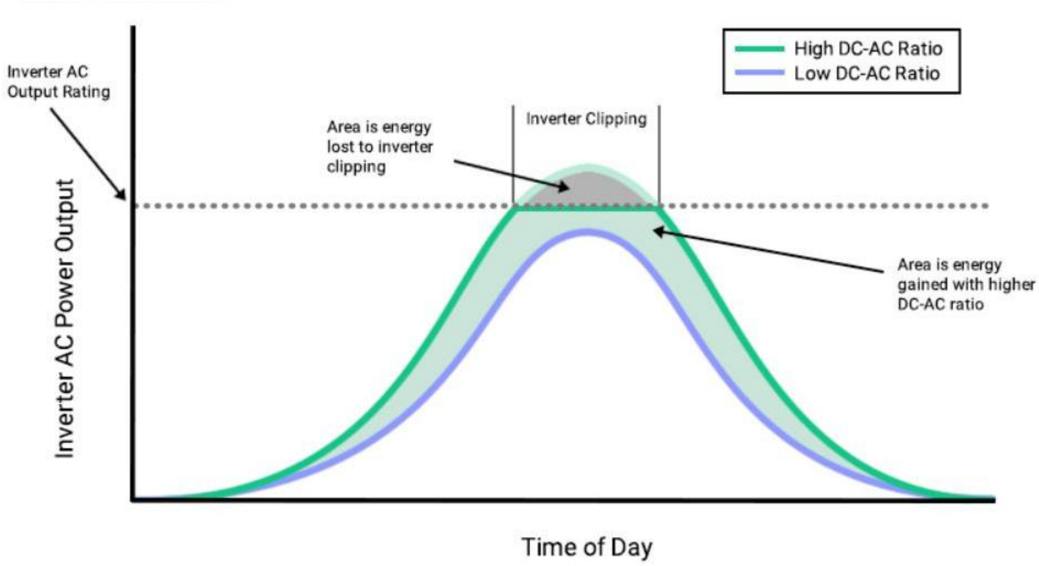


Figure 1. Clipping losses in a PV plant depending on the DC/AC ratio chosen

In addition to clipping, actual production is conditioned by various factors:

- **Atmospheric conditions:** direct and diffuse irradiance, ambient temperature (which reduces conversion efficiency), and wind speed (which contributes to module cooling) directly affect effective generation.

- **Module orientation and tilt:** the most common orientation in the northern hemisphere is south-facing, but east-west configurations can be useful for flattening the generation profile and thus having more hours of production but at lower power. The optimal tilt depends on the latitude; significant deviations can reduce annual yield. Too low an angle, for example, increases the accumulation of dirt and shadows.

- **Shadowing:** caused by nearby structures, trees, dense clouds, or even rows of modules depending on their distribution. It affects production in a non-linear way and can trigger additional losses due to the "hot spot" effect.

- **Electrical losses:** occur throughout the generation system. These include:

    Losses in conductors (Joule effect) depending on their resistance.

    Losses due to mismatch between modules or strings. If one of the modules in a row fails, it can affect the production of the entire row.

    Losses in inverters (DC/AC conversion efficiency)

    Transformation and gen-tie (transformers, internal lines, etc.). Cables, heating, noise, etc.

- **Module degradation:** caused by exposure to thermal cycles, humidity, UV, and mechanical failures. The main causes include:
    - PID (Potential Induced Degradation)
    - Microcracks in cells
    - Delamination of encapsulating materials
    - Hot spots generated by defective cells

- **Operational availability:** limited by scheduled or corrective maintenance activities, inverter failures, SCADA communication errors, or external events (storms, vandalism, gen-tie network failures, etc.).

- **Solar tracking systems** (single or dual axis tracking) can also improve solar capture and modify the hourly production profile, affecting the amount and distribution of clipping.

Battery Energy Storage Systems (BESS)

BESS (Battery Energy Storage Systems) allow electrical energy to be stored for use at a later time, temporarily decoupling generation and consumption. This is particularly valuable in environments with high renewable penetration or in markets with variable prices.

From a technical standpoint, batteries can only store energy in the form of direct current (DC). Therefore, when interacting with the grid (AC), they require bidirectional conversion systems. During charging, electrons are stored electrochemically within the battery cells; during discharging, this process is reversed to generate usable electricity.

In utility-scale projects, the most widely used technology is the lithium-ion battery, due to its energy density, efficiency, and decreasing cost. A BESS system consists of:

- **Cells and modules:** where the redox reactions that store energy take place.
- **Racks and containers:** integrate the modules with cooling systems, fire protection, and thermal insulation.
- **PCS (Power Conversion System):** bidirectional inverters that convert energy between AC and DC and allow dispatch to the grid.
- **BMS (Battery Management System):** manages the health of the system, monitors temperature, individual voltages, cell balancing, and prevents catastrophic failures.

Key technical characteristics include:

- **Capacity (kWh):** total amount of energy that can be stored.
- **Power (kW):** maximum speed at which it can be charged or discharged.

- **Nominal duration:** result of the quotient between energy and power (e.g., 100 MW / 400 MWh = 4h).
- **Round-trip efficiency:** ratio of energy recovered to energy stored, between 85% and 92%.
- **Life cycles:** varies depending on depth of discharge (DoD), operating temperature, and number of daily cycles. Typically ranges between 6,000 and 10,000 cycles.
- **Degradation:** linked to chemical aging, thermal stress, deep cycles, and overloads.

Unlike a PV plant, a battery does not depend on solar radiation to generate power. Its output depends on the available storage capacity and can be actively controlled, making it a tool for energy management and participation in short-term markets.

BESS can operate in different modes:

- **Arbitrage:** they buy energy when it is cheap (low demand) and sell it when it is expensive.
- **Firming:** they smooth out the variability of solar production, i.e., they try to make the combined energy output (PV+BESS) as consistent as possible throughout the different hours of the day.
- **Ancillary services:** they provide frequency and voltage regulation services. These are services required from time to time by the regulatory agency of the electricity market in which the battery is located to keep the grid stable.
- **Capacity market:** they ensure firm and available power at critical times when shortages are possible.

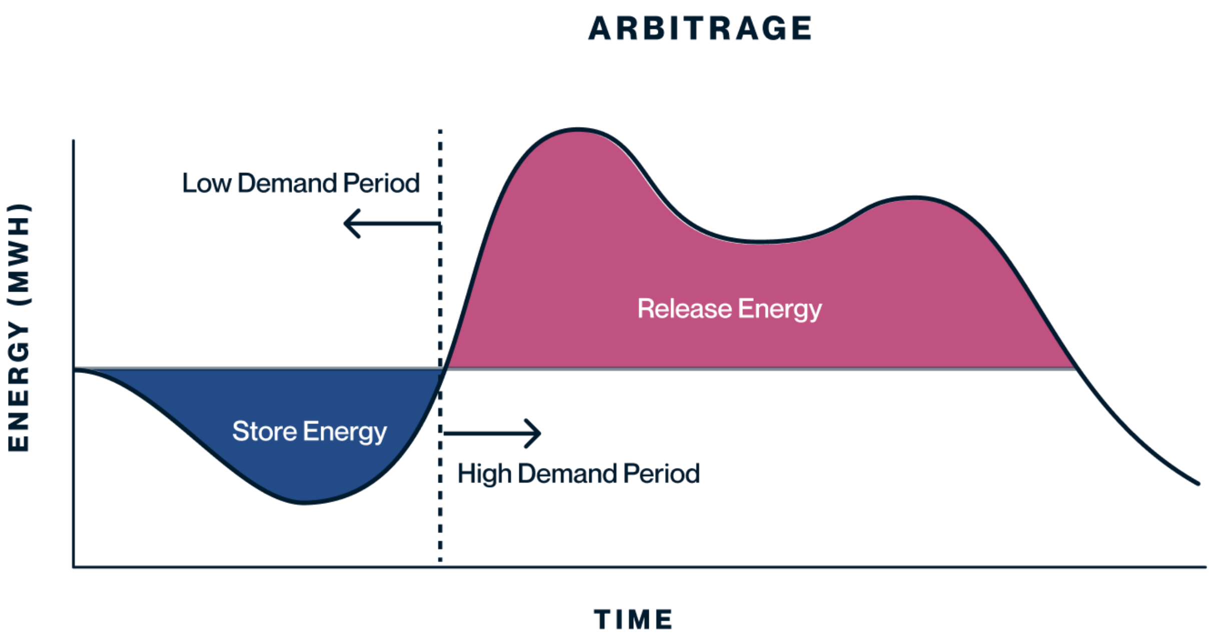


Figure 2. Arbitrage as a BESS revenues

Technical synergies between PV and BESS

When both systems are integrated at the same site, significant operational and technical synergies arise:

1. **Clipping recapture:** since the battery operates in DC, it can absorb energy directly from the PV modules without passing through the saturated inverter. This allows the use of energy that would otherwise be lost to be harnessed.

2. **Curtailment reduction:** in systems with injection restrictions or in congested markets where the market operator restricts the output of the plant at certain times, the battery can sometimes store excess energy instead of wasting it.

3. **Shared use of infrastructure:** transformers, interconnection systems, and grid access points are things that can be shared between both technologies, therefore reducing total combined CAPEX.

4. **Joint dispatch management:** in centralized control configurations, combined operation can be optimized to maximize revenue based on market prices.

5. **Operational flexibility:** allows for a combined or adaptive response to different market products (merchant, PPA, tolling).

These synergies are mentioned here as a technical basis, but some of them will be developed in depth in chapters 3 and 5, where their impact on the revenue structure and optimization of the hybrid project's financial model will be analyzed.

2.2. HYBRID SYSTEM CONNECTION TYPES (AC AND DC COUPLING)

The physical integration between a photovoltaic (PV) system and a battery energy storage system (BESS) can be carried out using different technical configurations. These directly influence system efficiency, operational flexibility, design complexity, and both CAPEX and OPEX costs. The two main architectures are: AC coupling and DC coupling. These are explained in detail below.

AC Coupling

AC coupling architecture can be divided into two main variants: AC coupled standalone, and AC coupled co-located, depending on whether the PV and BESS systems are located independently or share a location and infrastructure.

- **AC coupled standalone**

In this configuration, the photovoltaic plant and the battery system are physically and operationally independent. Each has its own grid connection point, specific inverters, and separate control logic. The energy generated by the PV is fed directly into the grid, while the battery is charged **exclusively from the grid** and has no direct connection to solar production.

This variant does not allow the battery to be recharged from solar surplus or clipping to be recaptured, as the energy flows are not interconnected in the AC domain. However, it offers advantages in terms of permits, independent operation, and contractual flexibility, as the two assets are completely decoupled.

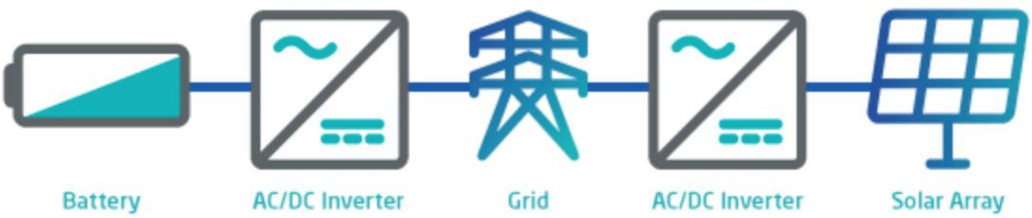


Figure 3. AC Coupled standalone PV + BESS configuration

- **AC coupled co-located**

In the case of co-located systems, both the solar plant and the battery share the same **interconnection point and part of the infrastructure** (such as transformers, protection systems, and gen-tie). Although each system still has its own inverter, there is greater coordination between the two energy flows.

In this variant, the battery can be charged from the PV in certain scenarios, provided that the appropriate technical and contractual conditions are met. For example, if the control allows it and the EMS system is configured for it, part of the energy generated by the solar plant can be redirected to the battery through the shared AC bus. However, as it passes through both inverters (PV and BESS), this energy suffers additional losses due to double conversion (DC→AC→DC).

This configuration is particularly useful for projects that want to benefit from sharing CAPEX in infrastructure, but without assuming full integration as in the case of DC coupled systems.

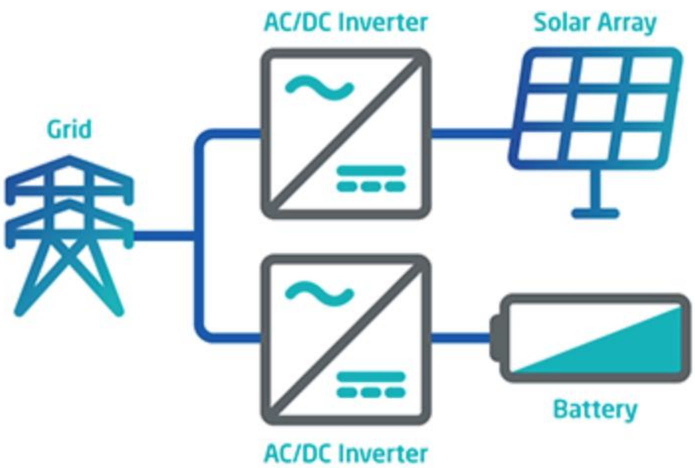


Figure 4. AC Coupled Co-located PV + BESS configuration

In general, AC coupling, whether standalone or co-located, allows for great operational and contractual flexibility, but has limitations in terms of energy efficiency and the ability to capture synergies between PV and BESS.

DC Coupling

Unlike AC coupling, direct current coupling allows for closer integration of the systems, as both share the same DC bus prior to the inverter. This architecture offers superior energy efficiency and allows for direct storage of excess solar energy. There are two main variants of DC coupling: the classic configuration and the shared inverter configuration.

- **Classic DC Coupling**

In this configuration, both the PV plant and the BESS system are connected to the DC bus through separate components. Energy from the solar panels is delivered directly to the DC bus, while the battery is integrated via a DC-DC converter that adjusts its operating voltage. All energy then flows to a central inverter that converts it to AC for evacuation to the grid.

This architecture allows excess solar production to be captured directly, especially during clipping—and stored in the batteries without the need for intermediate AC conversion, improving the overall efficiency of the system. It also means a reduction in the total number of inverters compared to AC coupling, which translates into lower costs. However, it requires a more sophisticated energy management system (EMS) to coordinate the interactions between the photovoltaic plant and the battery system.

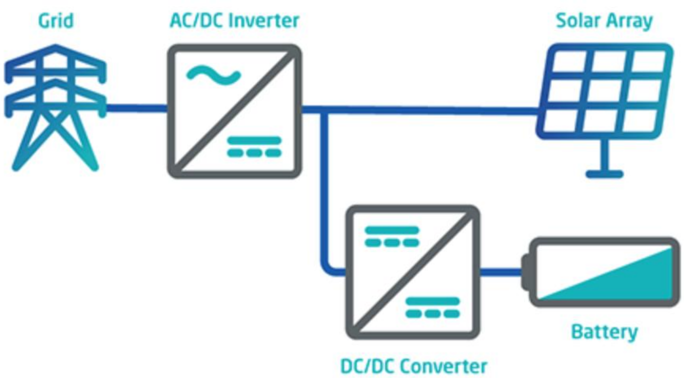


Figure 5. Classic DC Coupled PV + BESS configuration

- **DC Coupling with Shared Inverter**

The shared inverter configuration can be considered an evolution of the previous model. Instead of designing and integrating each subsystem independently, the manufacturer provides a compact hybrid device that integrates inputs for the PV field, an embedded DC-DC converter for the batteries, a bidirectional DC/AC inverter, and an all-in-one energy management system.

This solution offers advantages in terms of efficiency, design simplicity, footprint, and speed of implementation. By centralizing energy management and flows, the joint operation of both systems is optimized. However, it has certain limitations in terms of scalability and technical flexibility, as it is a closed solution with predefined parameters. It also creates a significant dependence on the supplier for maintenance and future system updates.

<u>**General comparison**</u>

Feature	AC Coupling Standalone	AC Coupling Co-located	Classic DC Coupling	DC Coupling with Shared Inverter
Inverters	Independent and uncoordinated inverters	Independent for PV and BESS	One common inverter for both systems	Single hybrid unit
Energy conversion (PV)	Only DC → AC	DC → AC DC→AC→DC	Only DC→AC	Only DC→AC
Energy efficiency	Medium (no double conversion for BESS charging, but no synergy)	Low (double conversion when BESS charging from PV)	High	Very high

CAPEX cost	High (two separate systems, no shared infrastructure)	High (dual inverter)	Medium	Low (fewer components)
Flexibility / scalability	Very high (independent systems, easy to replicate)	High	Medium	Low (closed system)
Requires external EMS	Yes (for coordination of site, if needed)	Not necessarily	Yes	No (integrated)
Clipping recapture capability	No	No	Yes	Yes

Table 1. General hybrid structures comparison

Note: *The "Energy conversion" row refers to the primary flow of energy generated by the photovoltaic system. In some DC Coupling configurations, the battery may also be charged from the grid, which would involve an AC→DC conversion not reflected in this table.*

The choice between these configurations not only has technical implications, but also direct consequences on operating income and integration costs, aspects that will be analyzed in depth in the following chapters of this paper.

2.3. OPERATION TYPOLOGIES (BTM & FTM)

The operation of hybrid photovoltaic systems with batteries (PV+BESS) can be classified into two main structural types according to their connection point: **Front-of-the-Meter (FTM)** and **Behind-the-Meter (BTM)**. These determine their relationship with the electricity grid and with the agents in the system (market, customers, operators), as well as the possible revenue streams. Based on this classification, different functional modes of operation are deployed that respond to specific technical and economic objectives.

2.3.1. Types of operation

- **Front-of-the-Meter (FTM)**

FTM systems are connected directly to the transmission or distribution grid, operating as independent generators that are not associated with a specific consumer. Their main objective is to sell energy or services to the market. This approach is typical of large-scale (utility-scale) projects, in which the PV plant and the BESS system actively participate in electricity markets through PPAs, merchant operations, provision of ancillary services, among others. In this case, the battery can be charged from the grid or from the solar plant if there is physical integration between the two.

- **Behind-the-Meter (BTM)**

BTM systems, on the other hand, are located downstream from a consumer's metering point. Their purpose is to optimize local energy consumption and reduce the costs associated with the electricity bill. This type of scheme is common in commercial, industrial, or residential installations, where the solar energy generated is directly self-consumed, and the BESS system allows for the storage of surpluses or strategic charging from the grid at times of lower cost. In this case, the economic benefit comes from direct savings rather than from the sale of energy to third parties.

2.3.2 Examples of functional modes of operation

Within FTM and BTM schemes, different operational strategies can be implemented to maximize the economic and technical value of the hybrid system. Some of the most relevant are described below:

Peak Shaving: typical mode in the BTM environment. The BESS system discharges energy during times of peak consumer demand, thus reducing charges for contracted power. The battery can be charged either from the grid (at low-cost times) or from the PV if there is a surplus.

Energy Arbitrage: a strategy applicable to both FTM and BTM schemes. It consists of charging the battery during low-price hours and discharging it during high-price times, generating a profit margin. In hybrid configurations, this arbitrage can be further optimized when the battery is charged for free from the PV, avoiding grid energy costs.

Solar generation firming: the BESS system is used to smooth out variations in solar production, generating a more stable and predictable delivery profile. This modality is particularly useful in PPAs with penalty clauses for deviations or in markets (FTM) where supply reliability is valued (more detail in next chapter).

Ancillary services: applicable only in FTM schemes. The BESS provides services such as frequency regulation, voltage control, or spinning reserve, contributing to the stability of the electrical system. Its implementation requires specific technical certifications and real-time communication systems.

Given that the operational and economic synergies between PV and BESS systems have a greater impact on Front-of-the-Meter (FTM) configurations, especially in terms of revenue optimization and resource sharing, this paper will focus its analysis exclusively on **FTM scenarios**. This approach allows for a more representative assessment of hybridization opportunities in utility-scale projects and greater comparability between configurations.

Specifically, the following main configurations will be considered for analysis:

- **AC Coupling – Co-located**
- **DC Coupling – Classic**

Additionally, the following configuration will be maintained:

AC Coupling – Standalone: not as an optimal case from the point of view of synergies, but as a base case for comparison, as it allows a clear reference to be established with two independently modeled and operated systems.

However, the following is excluded from the main analysis:

DC Coupling – Shared Inverter: as this is a more common solution in BTM or smaller-scale environments, with little applicability in utility-scale FTM projects.

This filtering allows the study to focus on scenarios where the technical and economic synergies of hybridization are more relevant to investment decision-making.

2.4. COST AND CAPEX STRUCTURE PER CONFIGURATION

The type of technical connection in a hybrid PV+BESS system has a direct impact on its cost structure and the level of investment required (CAPEX). Differences in design, quantity of equipment, control complexity, need for additional infrastructure, and level of integration determine significant variations in initial costs. This section analyzes the typical cost structure, with special attention to how it varies according to the three technical configurations that will be studied: AC Coupled Standalone (as the base scenario), AC Coupled Co-located, and classic DC Coupled. The main cost categories are the following:

- **PV system**

Photovoltaic modules: these represent between 25% and 35% of the total CAPEX in standalone PV projects. They are the core energy generator.

Tracking structures (trackers): mechanical structures that allow the sun's movement to be tracked in order to maximize energy capture. They account for 8–12% of CAPEX in utility-scale PV, if used. They are not always used, as it can sometimes be more cost-effective to have fixed modules and achieve significant savings in CAPEX by dispensing with trackers.

PV system-specific BOS: includes wiring between modules (strings), specific electrical protection in direct current, and connection boxes. This set of elements ensures the physical and electrical connection of the modules to the rest of the system.

- **BESS system**

Battery cells: main storage component. They can represent 30–50% of the cost of the BESS system depending on the technology used and the duration (4h or 8h).

BESS-specific BOS: includes the containment system (racks or containers), the BMS (battery management system), the cooling system, the PCS (power conversion system), among others. These elements ensure the safe and efficient operation of the storage system.

- **Generic Balance of System (BOS)**

This includes internal AC cabling, all LV/MV equipment, all civil work, the SCADA and security systems necessary to operate the project, etc. This is the most expensive part of the overall CAPEX. It can represent between 30% and 40% of the total CAPEX in traditional configurations, reaching up to 60% in cases of complex work.

- **Inverters (Normally included inside BOS)**

These represent between 5% and 10% of the total CAPEX of the project. They can be solar inverters, bidirectional inverters for BESS, or shared hybrid inverters. The number and type of inverters for each project depends directly on the chosen connection architecture.

- **Interconnection / HV**

This block represents between 10% and 20% of the total CAPEX, depending on the location and interconnection point. The main elements in this section are: HV substation, transformer, evacuation line (Gen-Tie), and HV breaker.

In standalone configurations, each technology may require its own transformer. In co-located hybrid projects or those with DC coupling, the use of a single shared transformer (with greater capacity) can result in important savings in this block, thanks to economies of scale and a reduction in duplication of protections and civil works.

The HV substation and Gen-Tie can also reduce their total cost significantly if shared, although the design must be adapted to meet the combined technical requirements.

- **Soft costs and associated services**

Miscellaneous costs include engineering, permits, insurance, legal and financial costs, guarantees, and EPC margins. These typically represent slightly less than 10% of total CAPEX.

- **DEVEX (Development Expenses)**

These costs encompass all expenses incurred during the development phase of the project prior to the Notice to Proceed (NTP), the official milestone indicating the project is ready for construction. They range from real estate–related items, such as land option payments, geotechnical studies, and land acquisitions, to other costs such as legal fees (including title work, permitting, and related services), or mineral work.

- **Network upgrades**

Network upgrade costs are those associated with the improvements needed to the electricity grid to accept the project's interconnection. These may include reinforcements to existing lines, new control equipment, or adjustments to upstream substations, among others. Although they can represent a significant component of CAPEX in certain projects (up to tens of millions in some cases), they do not depend on the type of internal technical configuration (AC vs. DC) but rather on the total power to be injected at the point of interconnection (POI) and the state of the local grid. Therefore, they will be included as a relevant mention in the general CAPEX analysis but will not be considered in the specific comparison between configurations.

Depending on the **type of configuration**, there is a different impact on the cost structure:

2.4.1. AC Coupled – Standalone

This configuration, which operates the PV and battery separately, requires two completely independent inverters and interconnection systems. It is important to note that the substation, transformer, Gen-Tie lines, and HV protections are also duplicated, with a significant impact on interconnection costs. The total CAPEX is usually the highest of all configurations due to this duplication.

2.4.2 AC Coupled – Co-located

In this case, the two inverters remain separate, but the downstream infrastructure is shared, i.e., infrastructure elements such as the transformer, HV substation, fencing, security systems, etc. The use of a single transformer and substation allows for significant savings in equipment, engineering, and permits. Although the shared transformer is more expensive than an individual one, it can be estimated that the net savings are usually 10–15% compared to duplicating equipment.

Despite sharing all these elements, this configuration allows separate contracts to be maintained for PV and BESS, which can be beneficial from a commercial or regulatory point of view depending on the strategy sought.

2.4.3. DC Coupled – Classic

The only case evaluated in DC coupling uses a single shared hybrid inverter, which significantly reduces the total cost of inverters in much the same way as the transformer in the previous configuration. By also reducing AC cabling and physical space, the full BOS cost can be reduced by up to 20% in certain cases.

As it is DC coupled, the system requires a DC-DC converter to control the battery charge to the shared inverter and a more sophisticated EMS.

A single interconnection infrastructure is maintained, as in the co-located case, with the same savings in transformer and substation, and with the additional benefit of energy synergies (such as the use of **solar clipping**).

Below is a comparison table which simplifies the CAPEX structure for the three proposed scenarios.

Cost Category	AC Standalone	AC Co-located	Classic DC Coupled
Inverters	High	High	Medium
DC-DC Converter	No	No	Yes
EMS (Energy Management System)	Basic	Basic	Complex
BOS (Balance of System)	High	Medium	Low
Interconnection / HV	High (double)	Medium-Low	Medium
Soft Costs	High	Medium	Medium
Estimated Total CAPEX	High	Medium-High	Medium

Table 2. CAPEX comparison per technical structure

As can be deducted, the type of connection significantly influences the total CAPEX of the system. Standalone AC configurations have the highest costs due to the duplication of equipment and infrastructure. Co-located AC architecture allows for a partial reduction by sharing interconnection, while classic DC coupling offers an efficient combination of shared components and energy synergies (interconnection, inverters, etc.), although it requires greater technical complexity. This CAPEX comparison will be key to contextualizing the profitability analyses that will be addressed in the following chapters.

2.5. KEY EVALUATION INDICATORS: IRR, LCOE, LCOS, Payback period, etc.

To evaluate the financial and comparative viability of the different PV+BESS hybrid configurations, a series of standardized metrics in the energy industry are used. These allow the profitability, efficiency, and payback period of the investment to be quantified, thus facilitating strategic decision-making. This section describes the main metrics used in the study:

- **Internal Rate of Return (IRR)**

The unlevered post-tax IRR measured from the Commercial Operation Date (COD) will be used, as it reflects the return on the project without taking into account the debt structure and from the start of the operational life. This metric is particularly suitable for comparing the relative efficiency of different configurations from a project finance perspective. A higher IRR implies a higher expected return on the initial investment.

- **Levelized Cost of Energy (LCOE)**

LCOE represents the average cost per MWh of energy delivered over the life of the project, including CAPEX, OPEX, and replacements. It is useful for comparing the competitiveness of technologies or configurations purely from the perspective of cost per unit of energy. In the case of hybrid systems, it is adjusted to consider only the energy exported to the system.

LCOE formula:

LCOE = [CAPEX + 40Y OPEX] / Total PV Energy

- **Levelized Cost of Storage (LCOS)**

LCOS is analogous to LCOE but applied to storage systems. It allows the levelized cost per MWh delivered from the battery to be estimated, considering charge/discharge efficiency and operating cycles. It is particularly relevant for evaluating the profitability of incorporating BESS and its net contribution to the hybrid system.

LCOS formula:

LCOS = [CAPEX + 40Y OPEX] / Total BESS discharged energy

Where discharged energy essentially refers to the useful energy delivered by the battery.

- **Payback Period**

The payback period measures the time required to recover the initial investment from the project's net cash flows. Although it does not capture the total profitability like IRR or NPV, it does provide a useful reference for the return horizon, especially in contexts of regulatory or financial risk.

These metrics will be used together in Chapter 4 to compare the hybrid scenarios under study, identify optimal configurations, and perform sensitivity analyses on the main impact factors.

3. TECHNICAL-COMMERCIAL COMBINATIONS: ANALYSIS OF HYBRID SCENARIOS

3.1. REVENUE STREAMS ANALYSIS

In hybrid PV+BESS projects aimed at the Front-of-the-Meter (FTM) market, revenue can come from multiple sources depending on the technology involved, the type of connection, and the regulatory framework in place. The main revenue streams for both photovoltaic generation and the storage system, which will be evaluated in this paper, are described below.

Revenue associated with photovoltaic (PV) generation

- **Fixed Power Purchase Agreement (PPA):**

A long-term contractual agreement whereby a buyer (offtaker) purchases the energy generated at a predetermined price. This type of contract provides stability and predictability of revenue for the project and is particularly valued for its bankability.

There are different PPA structures, including:

- Physical PPA: the producer physically delivers the energy to the buyer.
- Financial (or virtual) PPA: settled by differences between the market price and the agreed price.
- Sleeved PPA: where an intermediary utility acts as a bridge between the generator and the end buyer.

Although this paper does not analyze the differences between these modalities in detail, a generic fixed-price PPA structure is assumed as the main source of income for the PV part.

- **Merchant / Spot Market:**

Direct sale of energy to the wholesale market at variable prices. This option entails greater exposure to the market price risk but can be more profitable in scenarios of high volatility or high prices.

In hybrid projects, the PV component generally favors long-term PPAs, as the stable production profile of solar ensures predictable revenues, even when merchant returns look higher. In co-located or DC-coupled configurations, however, any surplus not covered under the PPA can be monetized through merchant sales.

- **Capacity Revenue:**

In some markets, PV projects may also receive capacity payments as compensation for contributing to the system's resource adequacy, even if their output is variable. These payments are typically based on the project's accredited capacity and provide an additional, though generally smaller, revenue stream compared to energy sales.

- **Renewable Energy Credits (RECs):**

PV generation may also create tradable renewable energy credits or certificates, which can be sold separately from the electricity itself to entities looking to meet renewable portfolio standards or sustainability goals. *However, REC revenue is not considered in this paper due to its market-dependent nature and frequent price fluctuations.*

Revenue associated with the storage system (BESS)

- **Tolling (or tolling agreement):**

A contract whereby a third party pays for the use of the BESS system, assuming its operation and obtaining the associated benefits. The battery owner receives fixed or variable income, without having to be involved in the operation of the asset. This modality offers a stable income stream and reduces operational risk.

- **Energy arbitrage (BESS Merchant):**

A strategy that consists of charging the battery when prices are low and discharging it when prices are high, thus maximizing the price differential. Although the system does not generate energy itself, it acts as a temporary market optimizer. In hybrid configurations, charging can be done from the grid or directly from the PV plant (e.g., during surplus hours), which directly influences the profitability of the process.

(Note: Energy arbitrage refers purely to energy sales and purchases in the wholesale market.)

- **Ancillary Services:**

Participation of the BESS system in network service markets such as frequency regulation, voltage support, or reserve capacity. In this case, the asset does not sell energy for consumption but is available to contribute to the stability and reliability of the electrical system when required by the system operator. Response speed and technical availability are key factors for eligibility in these markets.

- **Capacity/Scarcity Revenue:**

In certain markets, BESS assets can receive capacity payments as compensation for their accredited capacity value in contributing to system reliability. This revenue is typically structured as a fixed payment per kW-month or similar metric, and provides an additional, relatively predictable revenue stream separate from energy market operations.

- **Clipping Recapture:**

In DC-coupled systems, the BESS is able to capture clipped energy that would normally be curtailed by inverter limits at peak irradiance. This recovered energy is subsequently exported to the grid, providing incremental revenues without requiring a larger solar facility. From a financial perspective, the benefit may be treated either as additional revenue (this case) or as a reduction in energy costs.

- **DART Revenue:**

In some markets, BESS assets can also earn revenue from market convergence activities between the Day-Ahead (DA) and Real-Time (RT) markets. This is known as **DART revenue** and includes income from mechanisms such as price convergence bidding and certain uplifts related to reducing differences between DA schedules and RT operations. It is considered a separate stream from pure energy arbitrage, as it captures value from improving price alignment rather than just buying and selling energy.

Access to these streams depends on:

- The technical configuration of the system (AC standalone, AC Coupled, DC coupled).
- The operational and contractual compatibility between generation and storage.
- The commercial flexibility allowed by the offtaker (in the case of PPAs) and market regulation.

These compatibilities will be analyzed cross-sectionally in the following section using a revenue matrix by configuration, which will serve as the basis for determining which are technically and economically viable for subsequent modeling.

3.2. MATRIX OF TECHNICAL CONFIGURATIONS VS COMPATIBLE REVENUE STREAMS

The possibility of accessing certain revenue streams in a hybrid PV+BESS project depends directly on the technical configuration of the system. This configuration determines both the energy routes and the operational and contractual limitations that influence eligibility for certain markets. Below is a comparative analysis of the three configurations under study:

Revenue stream	AC Coupled Standalone	AC Coupled Co-located	Classic DC Coupled
PV – Fixed PPA	Yes	Yes	Yes
PV – Merchant spot	Yes	Yes	Yes
PV - Capacity market	Yes	Yes	Yes
PV - RECs	Yes	Yes	Yes
BESS – Tolling	Yes	Yes	Limited (*)

BESS – Energy arbitrage	Yes	Yes	Limited (*)
BESS – Ancillary services	Yes	Yes	Limited (*)
BESS - Capacity market	Yes	Yes	Limited (*)
BESS - DART	Yes	Yes	Limited (*)
BESS – Clipping recapture	No	Partial (***)	Yes

Table 3. Technical configurations vs compatible revenue streams

AC Coupled – Standalone:

Since they are physically separated, PV and BESS operate as independent assets. This allows separate commercial contracts to be established for each technology, providing greater flexibility. However, it is not possible to recapture energy through clipping, as the BESS system does not have direct access to the energy flow from the solar plant.

AC Coupled – Co-located:

There is some synergy in infrastructure through the shared use of the transformer and substation, but the energy flows of PV and BESS remain independent. As a result, revenue streams are essentially the same as in standalone systems, with the only adjustment being that the transformer may curtail exports once its nameplate capacity is reached. This setup helps optimize certain costs but does not generate new energy revenues.

(***) In AC Coupled Co-located configurations, some specific cases could allow part of the clipping to be exploited if the BESS inverters are sized to charge from the common point, although this is not common or optimal.

DC Coupled – Classic:

This configuration allows for deeper integration between PV and BESS, facilitating direct charging of the storage system from the energy generated by the plant (especially at times of clipping). This enables income from “Clipping Recapture” and improves the efficiency of energy arbitrage by reducing the cost of charging.

(*) Nevertheless, in the case of classic DC Coupled the battery's ability to inject energy into the system is subject to the **availability of the inverter shared with the PV**. This may restrict simultaneous participation in certain markets (merchant, ancillary) when the PV is generating at full capacity. Therefore, although they can technically access these streams, actual revenues may be limited by this physical constraint.

This matrix should be interpreted not only as the basis for selecting the technical and commercial combinations of the different configurations, but as a tool to identify the technical barriers that limit full access to revenue streams, which will be essential for the financial analysis in the following chapter.

3.3. OPEX AND STRUCTURAL COSTS

To complement the CAPEX analysis discussed in the previous chapter, this section examines the OPEX (operating expenses) associated with the different PV+BESS configurations. Unlike CAPEX, which is incurred initially, OPEX is recurring throughout the life of the project and can have a significant impact on long-term profitability.

The main components of OPEX in hybrid projects typically include:

- **Operation and maintenance (O&M):** Includes routine tasks such as inspections, PV module cleaning, replacement of minor components, and remote monitoring.
- **Insurance:** Cost of policies covering technical, meteorological, or financial risks.
- **Asset management and technical administration:** Expenses related to performance monitoring, regulatory compliance, and contract management.
- **Land lease costs:** Periodic payments for land use, which are usually indexed to a specific rate.

Depending on the technical architecture of the system (AC coupled standalone, AC coupled co-located, classic DC coupled), significant OPEX synergies can be observed that directly affect the operational efficiency of the project:

AC Coupled Standalone:

As this is the base case, no significant synergies are observed in OPEX, as the PV and BESS systems operate separately. Each technology requires its own O&M contract, SCADA system, insurance, and technical management.

AC Coupled Co-located:

In this configuration, it is possible to combine O&M and insurance contracts, as they share the same location and access. In addition, there is also a certain reduction in administration and technical personnel costs due to joint supervision. Finally, in terms of land, savings can also be achieved when negotiating it in a unified manner if it belongs to the same owner.

Classic DC Coupled:

In this case, synergies in terms of operating costs are maximized since inverters, cabling, and control systems are shared, which drastically reduces the O&M costs associated with BESS in terms of maintenance and monitoring.

In terms of technical personnel and the simplification of the SCADA system, some optimization is also possible.

Below is a comparison table with an estimation of the **expected savings** for each configuration:

Configuration	O&M shared contract	Shared SCADA	Shared insurance	Potential land lease rate reduction
AC Coupled Standalone	No	No	No	No
AC Coupled Co-located	Partial (5–10%)	Partial (10%)	Partial (5%)	Partial (5–10%)
Classic DC coupled	Yes (15–20%)	Yes (20–25%)	Yes (10–15%)	Yes (10–15%)

Table 4. Expected OPEX savings per configuration

Physical integration between technologies has a direct impact on operating expenses. While standalone systems require duplicate contracts and resources, co-located configurations, and especially classic DC Coupled, allow for greater operational efficiency. This efficiency can significantly contribute to improving project profitability, especially in long investment horizons where cumulative OPEX represents a significant fraction of the total system cost.

4. PROFITABILITY ASSESSMENT AND SENSITIVITY ANALYSIS

Although DC Coupled configurations can offer significant structural advantages in terms of cost reduction (both CAPEX and OPEX), these configurations also impose certain technical and contractual limitations arising from the shared use of inverters and joint operational control design. These limitations can restrict operational flexibility and hinder simultaneous access to multiple revenue streams (**revenue stacking**), negatively affecting capturable revenue.

In contrast, AC Coupled configurations, although less cost-efficient, allow for greater operational independence between the PV plant and the storage system. This independence can facilitate the exploitation of various revenue mechanisms in a more flexible manner, including separate PPA and tolling contracts, differentiated strategies for participation in spot markets and ancillary services, and independent management of merchant curves for each technology.

These next two chapters aim to evaluate which of these configurations offers greater overall profitability and financial viability, integrating the three key pillars of technical-economic analysis:

- **Total investment cost (CAPEX)**
- **Operating expenses (OPEX)**
- **Potential revenue per configuration (revenue stack)**

Based on this evaluation, it will be determined whether the structural efficiencies of DC configurations offset operational constraints, or whether AC configurations—despite their higher costs—allow for more profitable and versatile revenue strategies, especially from an investment decision-making perspective.

4.1. BASELINE CAPEX, OPEX & REVENUE INPUTS PER SCENARIO

To comparatively evaluate the profitability of different PV+BESS hybrid configurations, an internal financial model of the company where this work was developed has been used. This model is not reproduced or attached for confidentiality reasons, but it has allowed for the simulation of comparable technical scenarios and the analysis of cash flows, as well as the main profitability metrics.

The approach followed and the key elements included in the simulation are detailed below:

- Specific CAPEX per configuration: Based on representative estimates of the current US market and the results analyzed in chapter 2.4. It includes the different investment components associated with each technology and technical configuration (PV, BESS, BOS, HV, synergies, etc.).

- Estimated annual OPEX: Adapted to the operational synergies observed in chapter 3.3. The total operating cost incorporates O&M, insurance, asset management, and land fees values from the US market, differentiating between AC standalone, AC co-located, and Classic DC Coupled configurations.

- Revenue curves by stream:

For PV: fixed PPA prices, spot and capacity (merchant) prices where applicable. No RECs.

For BESS: revenue from tolling, arbitrage (merchant), ancillary, capacity services, DART, and clipping recapture.

Price curves for PV are represented in $/MWh (USD/energy dispatch), just as a vanilla PV PPA price. They are direct replicas of third parties specializing in PV electricity markets (ABB, Wood Mackencie, etc.)

For the BESS price curves, they are given in average annual values (**$/kW-month)** for energy arbitrage / BESS ancillary services / BESS DART /BESS Capacity and are direct replicas of third parties specializing in BESS electricity markets (e.g., Ascend Analytics, Aurora, etc.).

- Time horizon of the analysis: Base case of 20-year useful life for BESS and 40-year useful life for PV, with cash flow updated based on factors such as annual degradation of PV modules and changes in battery efficiency.

- Output metrics: Unlevered IRR, NPV, LCOE, and LCOS. Profitability is assessed from the perspective of an external investor at time of acquiring a project, or an early-stage developer, as specified in the methodological note in chapter 1.4.

- Comparable scenarios: All configurations are based on the same PV and BESS system size (in MW and MWh), thus allowing a direct comparison between configurations in terms of costs, revenues, and profitability.

The CAPEX/DEVEX inputs used for the three scenarios in this first study are the following:

100MWp PV + 50MWac/200MWh BESS	AC Standalone		AC Coupled Co-located			Classic DC Coupled		
	Cost (USD)	% Base Case	Cost (USD)	% Base Case	Explanation	Cost (USD)	% Base Case	Explanation
CAPEX PV	**110 M**		**110 M**			**110 M**		
PV Modules (100Wp) - 0.35USD/Wp	35 M	-	35 M	100%	-	35 M	100%	-
PV BOS - 0.75USD/Wp	75 M	-	75 M	100%	-	75 M	100%	-
CAPEX BESS	**43 M**	-	**43 M**			**41,6 M**		
BESS Modules (200kWh) - 180USD/KWh	36 M	-	36 M	100%	-	36 M	100%	-
BESS BOS - Equipment - 35USD/KWh	7 M	-	7 M	100%	Same system size, partial infra sharing	5,6 M	80%	Inverter sharing reduces BOS cost
CAPEX HV	**14,2 M**	-	**12,16 M**			**11,76 M**		
HV Substation	6,8 M	-	6,8 M	100%	-	6,6 M	97%	Optimized design, less redundancy
Transformer	5,8 M	-	4,06M	70%	Shared transformer, reduced oversizing	3,94 M	68%	Shared transformer and optimized inverter dispatch
Gen-Tie Equipment	1,2 M	-	900k	75%	Single gen-tie for hybrid export	840k	70%	Single gen-tie with less oversizing
HV Breaker	400k	-	400k	100%	-	380k	95%	Less HV protection redundancy
Soft Costs (CAPEX)	**4,15M**	-	**3,62 M**			**3,44 M**		
Project Management/Oversight	500k	-	425k	85%	Partially shared dev/soft costs	400k	80%	More integrated soft cost effort
Engineering	1,8 M	-	1,53M	85%	Partially shared dev/soft costs	1,44 M	80%	More integrated soft cost effort
Legal: Construction & EPC	50k	-	42,5k	85%	Partially shared dev/soft costs	40k	80%	More integrated soft cost effort
Other Consultants	800k	-	680k	85%	Partially shared dev/soft costs	640k	80%	More integrated soft cost effort
Miscellaneous Fees	400k	-	340k	85%	Partially shared dev/soft costs	320k	80%	More integrated soft cost effort
Mowers	600k	-	600k	100%	-	600k	100%	-
DEVEX + Nus	**16 M**	-	**15,7 M**			**15,2 M**		
Development Expenses	6 M	-	5,7 M	95%	Partial permitting/process overlap	5,4 M	90%	-
Network Upgrades	10 M	-	10 M	100%	-	9,8 M	98%	Operative coordination in DC
TOTAL CAPEX:	**265 M**	**100%**	**259 M**	**97.83%**	**-**	**254 M**	**95.96%**	**-**

Table 5. CAPEX breakdown per configuration

The table above presents the disaggregated capital expenditures (CAPEX) associated with each hybrid configuration. Although the system size (100 MWp PV + 200 MWh BESS) is identical across all three scenarios, the total CAPEX varies slightly due to differences in component sharing and system integration.

The AC Standalone configuration, used as the base case, involves two fully independent systems. Transformer sizing reflects realistic AC outputs: approximately 85 MVA for the PV system, assuming a DC/AC ratio of 1.2, and 50 MVA for the BESS system, resulting in a total of 135 MVA of installed transformer capacity.

100MWp + 200MWh	AC Standalone		AC Coupled Co-located			Classic DC Coupled		
	Cost (USD/year)	% Base Case	Cost (USD/year)	% Base Case	Explanation	Cost (USD/year)	% Base Case	Explanation
General OPEX Item	**2,475,000**	-	**2,322,000**			**2,223,000**		
Land lease (800acres base)	800,000	-	720,000	90%	Shared transformer, less land required	680,000	85%	Shared transformer+inverter, less land required
Telecom Service Expense	25,000	-	25,000	100%	-	25,000	100%	-
Entity Licenses & Misc.	40,000	-	36,000	90%	Shared hybrid OPEX tasks	34,000	85%	Optimized shared operations
Scheduling and Forecasting	100,000	-	100,000	100%	-	100,000	100%	-
Auditing Fees and Tax Filing	50,000	-	45,000	90%	Shared hybrid OPEX tasks	42,500	85%	Optimized shared operations
Asset Management	350,000	-	315,000	90%	Shared hybrid OPEX tasks	280,000	80%	Optimized shared operations
NERC Compliance	60,000	-	54,000	90%	Shared hybrid OPEX tasks	51,000	85%	Optimized shared operations
Cybersecurity	100,000	-	90,000	90%	Shared hybrid OPEX tasks	85,000	85%	Optimized shared operations
IX Facilities Maintenance	30,000	-	27,000	90%	Shared hybrid OPEX tasks	25,500	85%	Optimized shared operations
Insurance (0.6% CAPEX)	920,000		910,000			900,000		
Specific OPEX	**3,260,000**	-	**3,224,500**			**3,189,000**		
PV Covered& Non-Covered O&M	2,000,000	-	2,000,000	100%	-	2,000,000	100%	-
BESS Covered & Non-Covered O&M	350,000	-	332,500	95%	BESS co-location reduces split cost	315,000	90%	BESS integration reduces cost further
LTSA BESS	550,000	-	550,000	100%	-	550,000	100%	-
Aux load BESS	360,000	-	342,000	95%	BESS co-location reduces split cost	324,000	90%	BESS integration reduces cost further
TOTAL OPEX:	**8,995,000**	**100%**	**8,771,000**	**97.51%**	-	**8,601,000**	**95.62%**	-

Table 6. OPEX breakdown per configuration

The AC Co-located configuration achieves a 1.5% reduction in total CAPEX by consolidating part of the electrical infrastructure—most notably by using a single shared transformer of ~120–125 MVA instead of two separate units. Minor efficiencies in permitting and soft development costs further contribute to this reduction, although inverters and operational systems remain mostly separate.

The DC Coupled configuration reaches the highest level of integration, using a single transformer of ~110–115 MVA, made possible by joint inverter control and optimized dispatch of PV and battery output. This allows for more efficient use of electrical equipment and reduces duplication of permitting, engineering, and balance-of-system components. As a result, total CAPEX is reduced by nearly 3% compared to the standalone baseline.

While these differences may appear moderate in percentage terms, they translate into absolute savings of **$2–5 million** at utility scale—savings that become increasingly relevant when combined with operating cost reductions and enhanced revenue capture, which are addressed in the following sections.

In terms of annual operating costs (OPEX), the differences between configurations are primarily driven by shared operational tasks, equipment integration, and reduced physical footprint. While the AC Standalone configuration presents the highest OPEX—serving as the base case—the AC Co-located setup achieves a 3.7% reduction, mainly due to the use of a single transformer, a slightly reduced land footprint, and the partial overlap of permitting, compliance, and administrative tasks.

The DC Coupled configuration shows the greatest OPEX savings (−6.3%), reflecting its higher degree of technical integration. The shared inverter and transformer not only reduce the physical land use but also simplify asset management, compliance efforts, and auxiliary power consumption for BESS. Furthermore, the integration allows for slight cost optimization in BESS-specific O&M, given the tighter operational control enabled by DC coupling.

Despite these differences, the O&M costs associated with the PV system remain unchanged across all configurations, as the solar asset is assumed to operate independently from the BESS system in terms of maintenance requirements.

These operational savings, while not transformative in percentage terms, are material when scaled over a 40-year project horizon—and further reinforce the strategic relevance of hybrid integration from a long-term cost-efficiency perspective.

When it comes to revenues, in chapter 4 we will not measure the effect of merchant revenue stacking in order to isolate the effect of CAPEX+OPEX in the three scenarios. Therefore, the same toll and curves for BESS will be used for the three scenarios along with the same PPA and curves for PV:

- For the PV Plant - PPA price for the first 15 years: **$60/MWh**

  Initial yield=1565 MWh/MWp/year

- For the battery - Toll price for the first 15 years: **$16/kW BESS-mo.**

PV MERCHANT REVENUES			
Year	Annual average $/MWh merchant (US CPI Indexed)	Annual average Capacity recognition	Annual average $/MWac - capacity price (US CPI Indexed)
16	75.61	14.79%	105.90
17	74.30	12.40%	111.19
18	78.41	10.71%	117.79

19	84.50	9.17%	124.77
20	84.24	7.88%	128.80
21	83.53	7.10%	135.84
22	85.98	6.56%	143.62
23	87.10	6.20%	149.60
24	88.93	5.89%	158.24
25	90.80	5.60%	172.32
26	92.71	5.30%	184.37
27	94.65	5.05%	191.34
28	96.64	4.79%	196.14
29	98.67	4.67%	196.79
30	100.74	4.59%	199.60
31	102.86	4.54%	203.79
32	105.02	4.47%	208.07
33	107.22	4.44%	212.44
34	109.48	4.41%	216.90

35	111.78	4.37%	221.45
36	114.12	4.32%	226.10
37	116.52	4.34%	230.85
38	118.97	4.33%	235.70
39	121.46	4.33%	240.65
40	121.93	4.33%	245.70
AVG	**97.85**	-	-

Table 7. PV Merchant revenue profile

BESS MERCHANT REVENUES				
Year	Annual average $/kW-month - Energy	Annual average $/kW-month - Ancillary	Annual average $/kW-month - Capacity	Annual average $/kW-month DART
16	14.78	0.22	4.80	0.91
17	15.48	0.55	4.62	0.92

18	15.14	0.56	4.58	0.92
19	15.39	0.79	4.73	0.93
20	14.85	0.43	4.88	0.88
AVG	**15.13**	**0.51**	**4.72**	**0.91**

Table 8. BESS Merchant revenue profile

4.2. BASELINE FINANCIAL RESULTS PER SCENARIO

Having specified all the relevant inputs to model the three scenarios, the financial metrics evaluated are the following:

- **Unlevered rate of return at COD (model output):**

Scenario	AC Standalone	AC Coupled Co-located	Classic DC Coupled
UIRR from COD	8.31%	8.69%	8.99%

Table 9. Unlevered IRR results per scenario (before adjustment)

- **LCOE / LCOS:**

To obtain the LCOE and LCOS of the project, there are certain calculations that need to be done prior to it:

Total PV energy:

Initial yield=1565 MWh/MWp/year

PV MWdc=100 MWp

d=0.5%=0.005 (annual degradation)

n = 40 years

Energy year 1 = Initial yield × PV MWdc = 156,500 MWh

Energy year n = [Energy year 1] × (1−d) ^ (n−1)

where

Total PV energy = [∑ PV Energy year n] (from Y1 to Y40)

Or using the formula of a geometric progression:

Total PV energy = Energy year 1 × [1−(1−d)^40]/d =

156,500 MWh * [1-(1-0.005)^40]/0.005 = **5,686,580 MWh**

Total PV related CAPEX

Total PV related CAPEX = PV specific CAPEX + (Shared CAPEX) * (PV % of the shared capex)

Shared CAPEX = HV CAPEX + Soft Costs CAPEX + DEVEX + NUs

PV specific capex = PV Modules + PV BOS

[PV % of the shared capex] is calculated based on the PV MWac in the interconnection point (POI) over the total. Therefore, 85MWac out of the (85MWac PV + 50MWac BESS) = 63%.

Total PV related OPEX = PV Covered & Non-Covered O&M

LCOE = [CAPEX + 40Y OPEX] / Total PV Energy

	AC Standalone	**AC Coupled Co-located**	**Classic DC Coupled**
Energy (MWh)	5,686,580	5,686,580	5,686,580

Table 10. PV energy for LCOE calculation

PV Specific CAPEX ($)	110,000,000	110,000,000	110,000,000
Shared CAPEX ($)	34,350,000	31,477,500	30,400,000

% Shared CAPEX	63%	63%	63%
PV related CAPEX ($)	131,640,500	129,830,825	129,152,000

Table 11. PV specific CAPEX for LCOE calculation

PV specific OPEX ($)	80,000,000	80,000,000	80,000,000
Shared OPEX ($)	49,500,000 (Y1-Y20) 49,500,000 (Y21-Y40)	46,440,000 (Y1-Y20) 46,440,000 (Y21-Y40)	44,460,000 (Y1-Y20) 44,460,000 (Y21-Y40)
% Shared OPEX	63% of first 20years 100% of last 20years	63% of first 20years 100% of last 20years	63% of first 20years 100% of last 20years
PV related OPEX ($)	160,685,000	155,697,200	152,469,800

Table 12. PV specific OPEX for LCOE calculation

LCOE ($/MWh)	**51.41**	**50.21**	**49.52**

Table 13. PV LCOE results

Total BESS energy:

BESS MWac = 50 MWac

Cycles in a year (total discharges) = around 300 cycles.

Cycle duration = 4hours

Degradation = 0.5%

Round trip efficiency = 90%

BESS energy year n = BESS MWac * cycles in a year * cycle duration * (1 − year degradation) * round trip efficiency

Total BESS energy = [∑ BESS Energy year n] (from Y1 to Y20)

Or using the formula of a geometric progression:

Total BESS energy = BESS MWac * cycles in a year * cycle duration * [1-(1- year degradation)^20]/(year degradation) = 50 MWac * 300 cycles * 4hours * [1-(1-0.005)^20]/0.005 = 1,140,000 MWh

Total BESS related CAPEX

Total BESS related CAPEX = BESS specific CAPEX + (Shared CAPEX) * (BESS % of the shared capex)

Shared CAPEX = HV CAPEX + Soft Costs CAPEX + DEVEX + NUs

BESS specific capex = BESS Modules + BESS BOS

[BESS % of the shared capex] is calculated based on the PV MWac in the interconnection point (POI) over the total. Therefore, 50MWac out of the (85MWac PV + 50MWac BESS) = 37%.

Total BESS-related OPEX = BESS Covered & Non-Covered O&M + LTSA BESS + Aux Load BESS

LCOS = [CAPEX + 20Y OPEX] / Total BESS Energy

	AC Standalone	**AC Coupled Co-located**	**Classic DC Coupled**
Energy (MWh)	1,140,000	1,140,000	1,140,000

Table 14. BESS discharged energy (throughput) for LCOS calculation

BESS Specific CAPEX ($)	43,000,000	43,000,000	43,000,000
Shared CAPEX ($)	34,350,000	31,477,500	30,400,000
% Shared CAPEX	37%	37%	37%
BESS related CAPEX ($)	55,709,500	54,646,675	52,848,000

Table 15. BESS specific CAPEX for LCOS calculation

BESS specific OPEX ($)	25,200,000	24,490,000	23,780,000
Shared OPEX ($)	49,500,000	46,440,000	44,460,000
% Shared OPEX	37% of first 20 years	37% of first 20 years	37% of first 20 years
BESS related OPEX ($)	43,515,000	41,672,800	40,230,200

Table 16. PV specific CAPEX for LCOS calculation

LCOS ($/MWh)	**87.03**	**84.49**	**81.63**

Table 17. BESS LCOS results

- **Payback period:**

Point in time when the accumulated cash flows turn positive.

Payback period (years)	**16.83**	**16.33**	**15.83**

Table 18. Payback period results per scenario

4.3. SENSITIVITY ANALYSIS

Scope and metrics.

To test the robustness of the baseline results, three material sources of uncertainty are evaluated: **PV degradation, solar yield, and market price levels.** For each sensitivity, the variation is applied consistently across the three configurations (AC Standalone, AC Coupled, Classic DC Coupled). Results are reported as ΔUnlevered IRR (basis points), ΔPayback (months), and %ΔLCOE (PV) relative to each scenario's own baseline. LCOS is not reported unless the BESS throughput assumption changes (see note below).

Implementation details.

- **PV degradation (non-uniform rates).**

  The project uses a non-uniform annual degradation path $r1, r2,\ldots,rt$. The sensitivity is implemented as an absolute bump of Δr to each annual rate:

  $rt' = rt + \Delta r$

  Annual PV performance multipliers are recomputed as $Mt = \prod(1-ri)$, $Mt' = \prod(1-ri-\Delta r)$,

yielding stressed energy $Et'=E0\cdot Mt'$. Cash flows, Unlevered IRR (at COD), and payback are recalculated with Et'. This approach preserves the original curve shape while providing a transparent, scenario-consistent stress.

- **Solar yield.**

  A uniform scalar is applied to the P50 net yield (e.g., −5%) across all years and scenarios. Energy, revenues, and KPIs are recalculated accordingly.

- **Market price level.**

A uniform scalar is applied to merchant price levels (e.g., −10%) across all years. **Note:** LCOE/LCOS are cost-side metrics (energy denominators), so they **do not** change with price-only sensitivities; only IRR and payback are reported for this case.

Perturbations used.

- PV degradation: +Δr= [**+0.5 pp**] absolute per year.
- Solar yield: [**−2%**].
- Market price level: [**−10%**].

All results are deltas vs. each scenario's baseline (Chapter 4.2 base case without stacking).

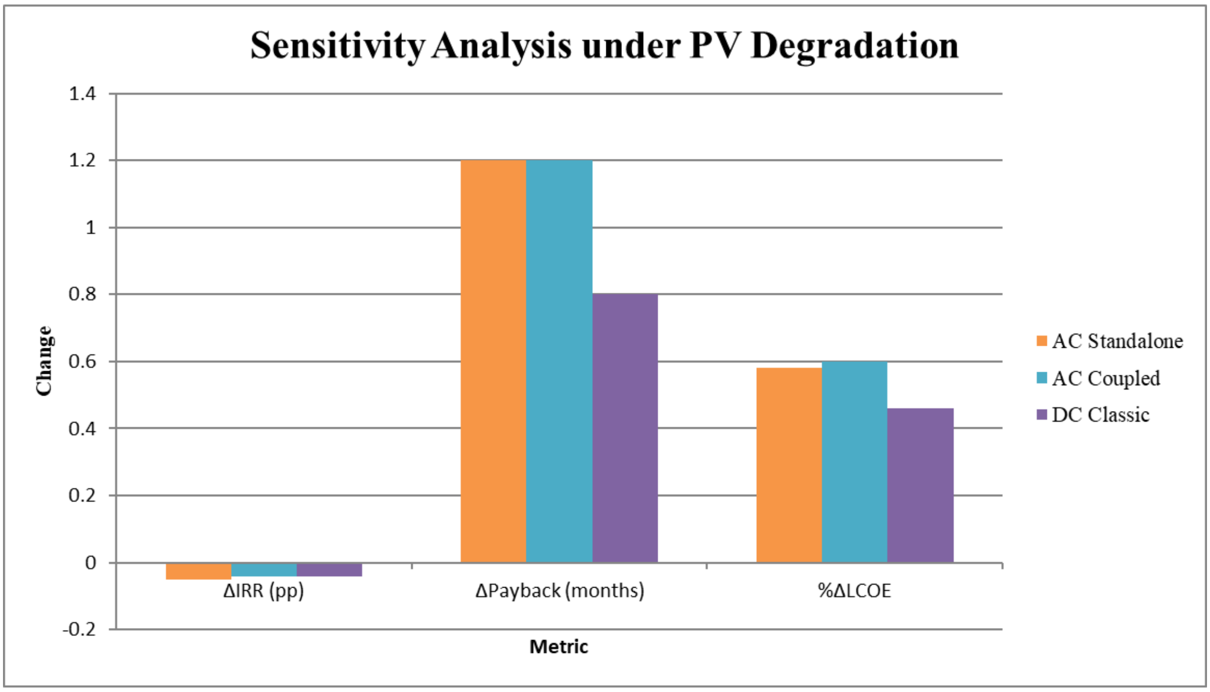
ΔLIRR (bps)=(IRRsens−IRRbase),

ΔPayback (months)=(Paybacksens−Paybackbase)×12,

%ΔLCOE=(LCOEsens/LCOEbase−1)×100%

Sensitivity (change)	**Metric**	**AC Standalone**	**AC Coupled Co-located**	**Classic DC Coupled**
PV degradation (+0.5 pp)	ΔLIRR (bps)	-0.05%	-0.04%	-0.04%
	ΔPayback (months)	+1.2	+1.2	+0.8
	%ΔLCOE (PV)	0.58%	0.60%	0.46%
Solar yield −2%	ΔLIRR (bps)	-0.17%	-0.17%	-0.17%
	ΔPayback (months)	+4.2	+2.6	+3.6
	%ΔLCOE (PV)	2.04%	2.03%	2.04%
Market price level −10%	ΔLIRR (bps)	-0.27%	-0.26%	-0.25%
	ΔPayback (months)	+6.6	+5.9	+5.3

Table 19. Sensitivity results (no revenue stacking/export limit effect)



Graph 1. Sensitivity Analysis under PV degradation

4.4. COMMENTS AND CONCLUSIONS

The sensitivity analysis confirms that, under conventional merchant assumptions (i.e., without considering hybrid revenue stacking), all three configurations move consistently in the same direction when stressed. The magnitude of the impact remains moderate across the tested cases.

- **Unlevered IRR** declines slightly, by approximately −5 bps under the degradation stress (+0.05% annual), and up to −27 bps under yield and price reductions (−2% annual yield and −10% merchant price level, respectively).

- The **payback period** extends by only 0.1–0.5 years across the different sensitivities, remaining within a narrow band around the base case values.

- **LCOE** increases modestly under technical stresses, rising by about +0.3–0.6% when degradation is accelerated and up to +2% when yield is reduced by 2%. By contrast, LCOE remains unchanged under merchant price sensitivities, as it is a cost-side metric independent of market revenues.

- **LCOS** does not vary under the tested stresses, since the methodology applied assumes a fixed battery throughput path independent of PV output. Only if throughput were explicitly linked to PV clipping or charging conditions would LCOS exhibit changes; this is intentionally left out here to avoid misleading interpretations.

Overall, AC Standalone tends to appear marginally less sensitive, reflecting its simpler structure and lower capital intensity, whereas AC and DC Coupled cases show similar behavior at this stage. However, the limited differentiation between the three configurations highlights that conventional merchant revenue curves are not able to capture the operational synergies of hybrid projects.

This limitation provides motivation for the next chapter, where hybrid-specific effects such as clipping recapture and free PV-based charging are incorporated into financial modeling. By repeating one targeted sensitivity (degradation) under stacking assumptions, the analysis demonstrates how non-linear responses emerge and alter the relative competitiveness of AC and DC coupled configurations.

5. ENHANCING THE FINANCIAL MODEL: ANALYSIS OF HYBRID SCENARIOS

5.1. LIMITATIONS OF STANDARD MERCHANT CURVES: CLIPPING/CURTAILMENT NOT REFLECTED AND EXPORT CAPABILITY OVERESTIMATED

The baseline and sensitivity results presented in Chapter 4 demonstrate that, when relying on conventional merchant revenue curves, hybrid PV+BESS projects exhibit only moderate variations across scenarios. Although AC Standalone, AC Coupled, and DC Coupled differ in their capital intensity, the overall financial responses remain broadly aligned. This convergence is not due to a genuine lack of differentiation, but rather to a limitation of the revenue curves commonly used in financial models.

Standard merchant revenue curves are typically derived from standalone BESS simulations that assume grid-based charging and therefore neglect project-specific synergies present in co-located PV+BESS configurations. As a result, they fail to account for two critical hybrid dynamics: (i) the ability to store PV energy that would otherwise be lost through clipping or curtailment, and (ii) the export limitations that arise when PV and BESS share common infrastructure such as inverters or transformers. In practice, curtailed PV generation can be redirected to the battery and later discharged to the grid, enhancing project revenues; however, these gains may be fully or partially offset by export constraints imposed by the shared interconnection capacity.

The omission of both clipping recapture and export constraints can lead to a misrepresentation of the relative competitiveness of hybrid configurations compared to the AC Standalone case. Standalone projects, by definition, do not experience these synergies—neither the upside of recapturing curtailed PV nor the downside of interconnection limitations.

To overcome this modeling gap, a corrective adjustment is introduced in Section 5.2, explicitly incorporating both positive (clipping recapture) and negative (export limitations) hybrid dynamics into the revenue streams.

5.2. ADJUSTMENT IN METHODOLOGY

To address these limitations, the following adjustment to merchant energy revenues is proposed:

For AC Coupled Co-located systems:

$$C\_AC(s,t) = C\_base(s,t) \times (1 - H\_AC\_s)$$

For DC Coupled systems:

$$C\_DC(s,t) = C\_base(s,t) \times (1 - H\_DC\_s) + U\_clip$$

where:

- H_s are haircut factors by revenue stream (Energy, Ancillary, Capacity, DART).
- U_clip is the uplift from clipped PV energy that can be captured by the battery.

Haircuts are computed as the product of availability, losses, binding factors, and market rule effects. The clipping adder U_clip is estimated from the PV AC/DC ratio (≈1.2) for the DC Coupled case, which implies ~2% annual clipping (table attached).

AC/DC ratio	Annual clipping fraction (aprox.)
1.10	0.3–0.6%
1.15	0.8–1.5%
1.20	1.5–2.5%
1.30	2.5–6%
1.40	6–10%

Table 20. Clipping fraction vs PV AC/DC ratio

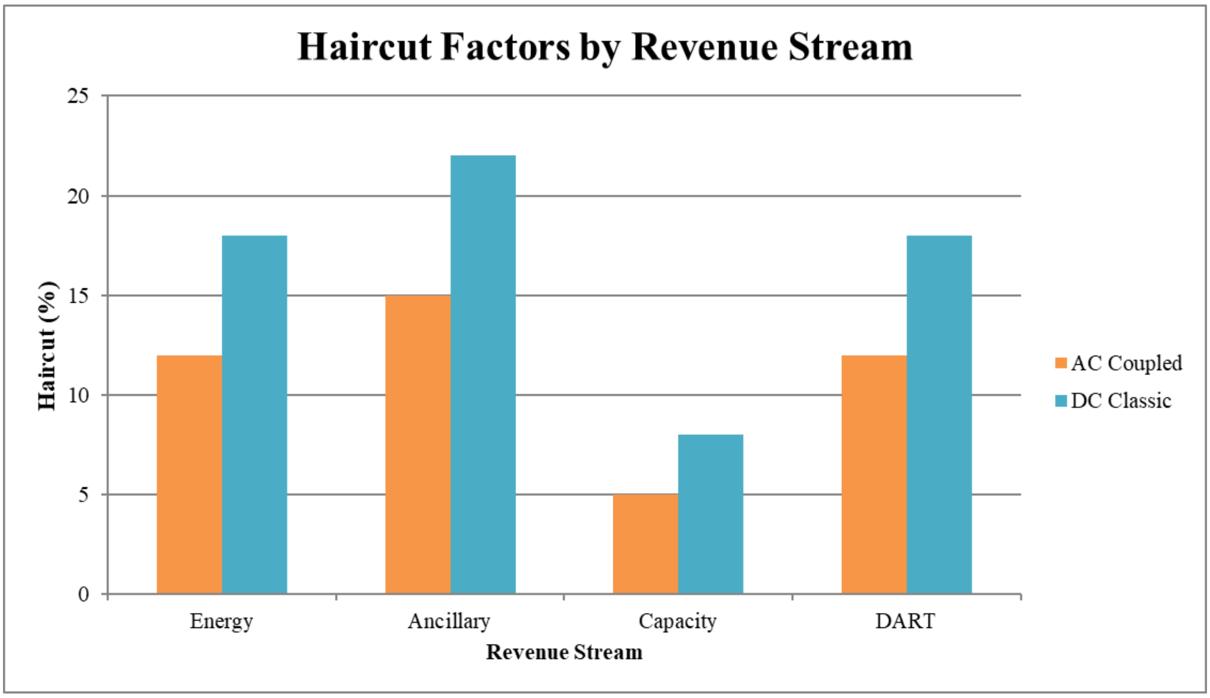
In the following table, AC haircut parameters correspond to AC coupled Co-located scenarios and therefore reflect curtailment at the transformer level, while DC haircut parameters correspond to DC-coupled scenarios and capture clipping at the inverter level.

Parameter	Value	Units	Rationale / Justification
AC_Energy_H	0.12	fraction	Binding 6% + losses 3% + availability 3% ⇒ ≈12%.

AC_Ancillary_H	0.15	fraction	Energy haircut + 6% for ancillary saturation ⇒ ≈15%.
AC_Capacity_H	0.05	fraction	Availability 2% + duration effect 3% ⇒ ≈5%.
AC_DART_H	0.12	fraction	Same as Energy ⇒ ≈12%.
DC_Energy_H	0.18	fraction	Binding 8% + losses 5% + availability 5% ⇒ ≈18%.
DC_Ancillary_H	0.22	fraction	Energy haircut + 10% for ancillary saturation ⇒ ≈22%.
DC_Capacity_H	0.08	fraction	Availability 3% + duration 3% + inverter share 2% ⇒ ≈8%.
DC_DART_H	0.18	fraction	Same as Energy ⇒ ≈18%.
U_clip	0.211	$/kW-month	Clipping ≈2% of PV export, adjusted by

			RTE=0.9 and spread 79.4 $/MWh.

Table 21. Haircut fractions per configuration and revenue stream



Graph 2. Haircut factors by revenue stream

The difference in haircut factors between AC coupled co-located and DC-coupled configurations arises from the stage of the energy chain at which limitations occur. In DC-coupled systems, inverter clipping happens upstream, meaning that a portion of the PV energy is lost before conversion and therefore unavailable for all downstream revenue streams. This amplifies the haircut applied to revenues, since the effect is embedded at the source of energy conversion. By contrast, in AC coupled co-located systems, the PV and BESS each have independent inverters, and the only shared bottleneck is at the transformer. Curtailment at this stage occurs later in the chain and typically has a smaller impact, which explains why the haircut factors for AC coupled co-located scenarios are consistently lower.

5.3. APPLICATION TO REVENUE CURVES

The adjustment methodology has been applied to the base merchant curves (Years 16–20). For AC Coupled co-located systems, only the negative adjustments (haircuts) are applied as there is no positive regarding the clipping gains. For DC Coupled systems, both haircuts and the clipping uplift are incorporated, with the uplift applied only to the Energy stream. The adjusted values are presented in the following tables (AC Adjusted and DC Adjusted).

AC Standalone - Base case

Year	Energy	Ancillary	Capacity	DART	Total
16	14.78	0.220	4.80	0.910	20.71
17	15.48	0.550	4.62	0.920	21.57
18	15.14	0.560	4.58	0.920	21.20
19	15.39	0.790	4.73	0.930	21.84
20	14.85	0.430	4.88	0.880	21.04

Table 22. Base case AC Standalone BESS revenues ($/kW-month.)

AC Coupled co-located adjusted

Year	Energy	Ancillary	Capacity	DART	Total
16	13.01	0.187	4.56	0.801	18.55
17	13.62	0.468	4.39	0.810	19.29
18	13.32	0.476	4.35	0.810	18.96
19	13.54	0.672	4.49	0.818	19.53
20	13.07	0.366	4.64	0.774	18.84

Table 23. Adjusted AC Coupled co-located BESS revenues ($/kW-month.)

Classic DC Coupled adjusted

Year	Energy	Ancillary	Capacity	DART	Total
16	12.60	0.172	4.42	0.746	17.93

17	13.17	0.429	4.25	0.754	18.61
18	12.89	0.437	4.21	0.754	18.30
19	13.10	0.616	4.35	0.763	18.83
20	12.66	0.335	4.49	0.722	18.20

Table 24. Adjusted Classic DC Coupled BESS revenues ($/kW-month.)

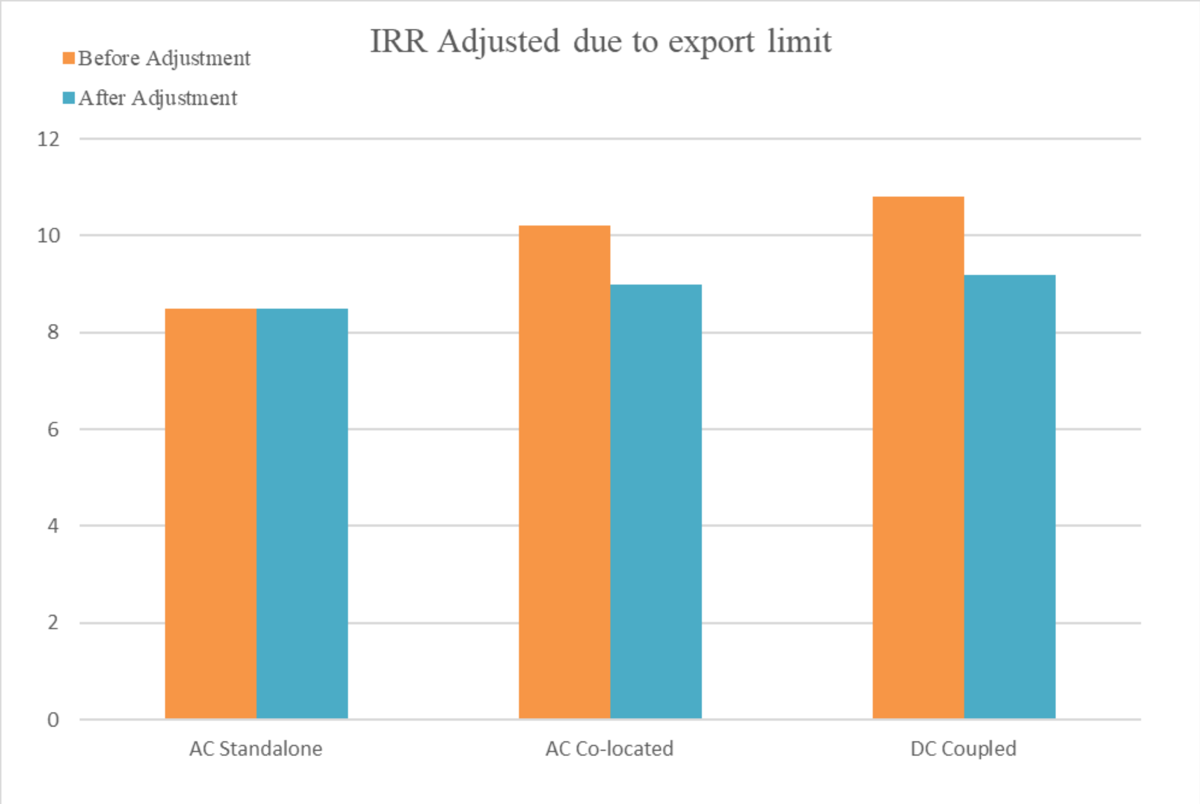
5.4. UPDATED FINANCIAL RESULTS WITH ADJUSTED REVENUE CURVES (AC COUPLED CO-LOCATED & CLASSIC DC COUPLED)

To summarize the overall effect of the adjusted merchant curves on project performance, Table 5.4 presents the final set of financial metrics (IRR, LCOE, LCOS, Payback) for all three scenarios. Values prior to adjustment (Chapter 4) are compared against the updated results after applying the methodology described in Sections 5.3–5.5. Although AC Coupled co-located and Classic DC Coupled initially showed higher IRRs than the Standalone case, the adjusted revenues compress these differences. All three scenarios now converge to similar levels of profitability, supporting the conclusion that hybrid competitiveness should not be overstated without accounting for clipping recapture and export limitations.

Scenario	Metric	Unadjusted (Ch.4)	Adjusted (Ch.5)	Observation
AC Standalone	IRR	8.31%	8.31%	Baseline, unchanged
AC Coupled Co-located	IRR	8.69%	8.35%	Reduced by transformer haircut
Classic DC Coupled	IRR	8.99%	8.40%	Clipping uplift offsets part of inverter haircut
AC Standalone	LCOE ($/MWh)	51.41	51.4	No change
AC Coupled Co-located	LCOE ($/MWh)	50.21	51.2	Slightly higher due to adjusted revenues
Classic DC Coupled	LCOE ($/MWh)	49.52	51.1	Approaches standalone after adjustment
AC Standalone	LCOS ($/MWh)	87.03	87.0	No change

AC Coupled Co-located	LCOS ($/MWh)	84.49	86.8	Reduced advantage after adjustment
Classic DC Coupled	LCOS ($/MWh)	81.63	86.5	Nearly converges with AC and standalone
AC Standalone	Payback (years)	16.83	16.8	Unchanged
AC Coupled Co-located	Payback (years)	16.33	16.7	Longer payback after haircut
Classic DC Coupled	Payback (years)	15.83	16.6	Payback converges with other cases

Table 25. Adjusted financial metrics



Graph 3. Variation in IRR when adjustments applied to BESS revenues

5.5. COMMENTS AND CONCLUSIONS

The adjusted curves show that both AC and DC Coupled scenarios experience lower merchant revenues compared to the standalone baseline once physical and operational constraints are considered. Although DC Coupled benefits from clipping recapture, the inverter limitation results in a net haircut that keeps revenues below the unadjusted baseline. AC Coupled co-located does not benefit from clipping recapture, and the transformer limitation applies to a smaller but still material haircut. Overall, the adjustments reduce the apparent financial advantage of hybrid configurations and align their IRRs more closely with the standalone case. This provides a more realistic and robust basis for investment comparison.

6. DISCUSSION AND STRATEGIC RECOMMENDATIONS

6.1. KEY INSIGHTS FROM THE ANALYSIS

The comparative evaluation of AC Standalone, AC Coupled Co-located, and Classic DC Coupled configurations demonstrates that hybridization can substantially enhance the operational and financial performance of solar-plus-storage projects. Standalone systems remain a reliable baseline and serve as a reference point for assessing the incremental value of hybridization. Co-located and DC-coupled options unlock additional synergies, particularly through clipping recapture, reduced balance-of-system (BoS) costs, and the potential to maximize site utilization under constrained interconnection agreements.

A key finding is that, when generic merchant revenue curves are used, hybrid systems may appear to deliver substantially higher returns than standalone alternatives. However, once revenue stacking effects are properly adjusted to account for free PV charging and export constraints, the profitability gap narrows. This suggests that the true advantage of hybridization lies less in short-term revenue uplift and more in strategic positioning for grid integration, land optimization, and long-term market flexibility.

6.2. IMPLICATIONS FOR INVESTMENT DECISION-MAKING

For investors, the results highlight the need to move beyond standard merchant revenue curves derived from standalone BESS simulations. Investment decisions should incorporate hybrid-specific dynamics such as transformer sizing, operational curtailment, and the opportunity to capture clipped PV generation. Overlooking these factors may lead to inaccurate valuation, potentially resulting in misallocation of capital or incorrect pricing of power purchase agreements (PPAs).

The sensitivity analysis further indicates that hybrid project returns are significantly influenced by external factors including market price evolution, solar yield variability, degradation rates, and interconnection costs. For decision-makers, this reinforces the importance of financial models capable of integrating both technical constraints and market volatility. Moreover, lenders and equity providers should demand scenario-based modeling to ensure bankability and reduce exposure to downside risks.

6.3. LIMITATIONS AND FUTURE WORK

This study acknowledges several limitations. First, the adjustment of merchant curves to reflect hybrid revenues was based on simplified assumptions regarding clipping availability and transformer constraints. While sufficient for comparative purposes, more granular dispatch modeling using chronological simulations would yield greater accuracy. Second, the analysis excludes regulatory and policy changes, such as evolving ancillary service markets or potential revisions to interconnection rules, both of which could materially affect hybrid economics.

Third, the study focused on three representative configurations. Alternative setups, such as shared inverter designs or advanced DC topologies, may further alter the balance between costs and revenues. Future research could extend the framework by incorporating stochastic market simulations, advanced degradation modeling, and the integration of policy-driven incentives (e.g., U.S. tax equity, IRA adders, or European capacity remuneration mechanisms).

6.4. RECOMMENDATIONS FOR DEVELOPERS AND INVESTORS

Developers should prioritize hybrid designs in contexts where interconnection capacity or land availability is scarce, as shared infrastructure reduces CAPEX and unlocks incremental revenues. However, hybridization should not be pursued blindly: transformer and inverter sizing must be optimized to minimize export bottlenecks. Furthermore, dispatch optimization strategies, supported by accurate forecasting, are critical to maximizing the value of stored energy.

Investors should require project models that explicitly account for hybrid dynamics, rather than relying on standardized standalone assumptions. In addition, hybrid projects should be strategically positioned to capture not only arbitrage but also ancillary services, capacity payments, and flexible contracting opportunities. Ultimately, PV+BESS projects should be framed as multi-service platforms capable of adapting to shifting market conditions while delivering stable long-term returns.

7. FINAL CONCLUSIONS

7.1. CONTRIBUTIONS TO THE STUDY

This thesis contributes to bridging the gap between theoretical modeling and practical investment appraisal for PV+BESS projects. It offers one of the first structured comparisons of AC Standalone, AC Coupled Co-located, and Classic DC Coupled configurations within a unified techno-economic framework. By developing a methodology to adjust merchant revenue curves to include hybrid-specific effects, the study provides a more realistic representation of financial performance. The detailed breakdown of CAPEX and OPEX structures, alongside investment metrics such as IRR, NPV, LCOE, and LCOS, equips stakeholders with a transparent basis for evaluating hybrid versus standalone alternatives.

7.2. VALIDATION OF OBJECTIVES

The objectives set at the beginning of the thesis were successfully achieved. The work clarified the operational principles of PV and BESS systems, analyzed the technical and economic implications of different hybridization configurations, and proposed a methodological adjustment to revenue modeling. The results validate the hypothesis that hybridization offers tangible benefits but also demonstrate that its financial advantage is context-dependent and sensitive to technical constraints. These insights emphasize the need for tailored project-specific modeling.

7.3. RELEVANCE OF THE PROPOSED MODELING FRAMEWORK

The proposed modeling framework enhances the robustness of investment evaluation for solar-plus-storage assets. By explicitly accounting for clipping recapture and interconnection limits, it provides a more accurate projection of project revenues, thereby reducing the risk of over- or under-estimating hybrid competitiveness. The approach is directly applicable to real-world decision-making processes, offering developers, investors, and financial institutions a valuable tool for strategic planning.

Looking ahead, the framework can serve as a foundation for more advanced models that integrate stochastic price forecasts, evolving policy environments, and multi-market participation strategies. As such, it contributes not only to academic literature but also to the practical advancement of bankable hybrid energy projects.

Glossary of terms

- **PV (Photovoltaic):** Technology that converts sunlight into DC electricity via semiconductor modules.
- **BESS (Battery Energy Storage System):** Utility-scale battery system used to store/release energy and provide grid services.
- **AC-coupled:** PV and BESS connected on the AC side with separate inverters; PV-to-BESS charging requires AC/DC-AC conversions.
- **DC-coupled:** PV and BESS share the DC bus prior to inversion; enables direct PV charging and clipping recapture.
- **Shared inverter:** Hybrid unit integrating PV inputs, DC-DC stage for batteries, and a bidirectional inverter governed by an EMS.
- **Clipping:** PV energy lost when DC output exceeds the AC inverter rating.
- **Curtailment:** Operational reduction of plant exports below available generation due to system or market constraints.
- **Export limit:** Site cap (e.g., transformer or interconnection) on simultaneous PV+BESS export.
- **DC/AC ratio:** PV array DC nameplate divided by inverter AC rating; a driver of clipping behavior.
- **EMS (Energy Management System):** Control/optimization layer managing PV+BESS dispatch and market participation.
- **PPA (Power Purchase Agreement):** Long-term contract for energy offtake with fixed or indexed pricing.
- **Merchant revenues:** Income from spot/ancillary markets without a long-term contract.
- **Tolling:** Contract where the battery provides capacity/throughput for a fee or agreed schedule.

- **Arbitrage:** Charging at low prices and discharging at high prices to capture price spreads.
- **Ancillary services:** Grid support products such as frequency regulation and reserves.
- **Capacity market:** Mechanism paying resources for availability during system stress.
- **IRR (Internal Rate of Return):** Discount rate setting NPV to zero for a series of cash flows.
- **NPV (Net Present Value):** Present value of inflows minus outflows discounted at a chosen rate.
- **Payback period:** Time for cumulative net cash flows to recover initial investment.
- **LCOE:** Levelized cost of energy: discounted total system costs divided by discounted energy output.
- **LCOS:** Levelized cost of storage: discounted storage costs divided by discounted discharged energy throughput.
- **CAPEX:** Upfront capital expenditures to build the plant.
- **OPEX:** Ongoing operating expenditures such as O&M, land lease, and insurance.
- **Gen-tie:** High-voltage line connecting the plant to the interconnection point.
- **HV substation:** High-voltage step-up and protection yard interfacing with the grid.
- **Revenue stacking:** Combining multiple revenue streams to maximize value (e.g., arbitrage+ancillary).
- **DART:** Day-Ahead vs Real-Time price spread used for arbitrage valuation.
- **Degradation:** Year-over-year decline in PV or battery performance.
- **Solar yield:** Annual energy per installed capacity, e.g., MWh/MWp-year.
- **Tax equity (US):** Financing structure monetizing tax credits and accelerated depreciation.

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