sustainability

Article

# Assessment of Battery-Integrated Hybrid Wind–Solar Plants: A Spanish Case Study

**Santiago Alonso-del-Viejo** [1], **Juan José Graña-Magariños** [1], **Isabel C. Gil-García** [1,2] and **Ana Fernández-Guillamón** [1,2,*]

[1] Faculty of Engineering, Distance University of Madrid (UDIMA), C/Coruña, km 38500, 28400 Collado Villalba, Madrid, Spain; santiago.alonso.del.viejo@gmail.com (S.A.-d.-V.); juanjose.grana@udima.es (J.J.G.-M.); isabelcristina.gil@udima.es (I.C.G.-G.)
[2] Department of Applied Mechanics and Projects Engineering, Universidad de Castilla-La Mancha, 02071 Albacete, Castilla-La Mancha, Spain
* Correspondence: ana.fguillamon@uclm.es; Tel.: +34-926053251

## Abstract

The increasing penetration of variable renewable energy sources requires flexible solutions to ensure system stability and economic efficiency. In this context, this study presents a comprehensive assessment of hybrid plants combining wind farms (WF) and photovoltaic (PV) systems integrated with battery energy storage systems (BESS), using the Casetona project in Spain as a real-world study. Three configurations (PV + WF + BESS, PV + BESS, and WF + BESS) are evaluated based on 2024 operational data combined with simulation tools. Under the assumptions of this study (2024 data, Spanish market), the results indicate that WF generation outperforms PV, mainly due to higher capacity factors and better alignment with high-price periods, while PV output is affected by price cannibalization. Under current Spanish market conditions and at the assumed BESS cost (236 €/kWh), energy arbitrage is not economically viable, yielding negative net present value across all configurations. In contrast, participation in automatic frequency restoration reserve services provides higher revenues under current Spanish market conditions, with the WF + BESS configuration achieving the best performance. From the perspective adopted in this study, the sustainability analysis reveals that the hybrid system enables annual greenhouse gas emissions reductions between 13,695 and 49,195 $t_{CO_{2,eq}}$, depending on the displaced generation source. Although BESS does not directly reduce emissions, it enhances renewable integration, reduces curtailment, and improves grid flexibility. The results also highlight the importance of regulatory frameworks and market design in determining the economic viability of storage systems. While the quantitative results are specific to the case study and sensitive to regulatory parameters, this study provides a comprehensive and transferable methodology for evaluating hybrid renewable systems with storage, supporting informed decision-making in the transition toward low-carbon and resilient energy systems.

**Keywords:** wind-solar hybridization; sustainability; battery energy storage system; energy, economic, environmental assessment; frequency regulation (aFRR)

Academic Editor: Francesco Riganti Fulginei

Received: 30 April 2026
Revised: 19 May 2026
Accepted: 21 May 2026
Published: 29 May 2026

## 1. Introduction

The growing penetration of variable renewable energy sources (RESs) into modern power systems demands increasingly sophisticated solutions to ensure supply reliability and grid stability [1]. The hybridization of wind farms (WF), photovoltaic (PV), and battery energy storage systems (BESS) has emerged as one of the most promising strategies to advance the energy transition [2]. By combining technologies with complementary generation profiles and integrating storage capacity, hybrid plants can overcome the inherent limitations of individual RES while optimizing shared infrastructure and maximizing economic returns [3]. Beyond site-level benefits, hybrid plants also contribute to improving power system flexibility and stability under high renewable penetration scenarios [4–7]. In this context, battery energy storage systems (BESS) can provide fast-response balancing services and support grid reliability.

Against this background, this article presents a comprehensive assessment of hybridizing PV plants, WF, and BESS within a unified framework. The analysis is structured around the following dimensions aiming to answer the research questions shown below:

- Energy feasibility, assessing whether BESS integration can be effectively implemented within the existing infrastructure and grid access capacity of a real hybrid installation (including generation complementarity and grid integration). To what extent does wind–solar hybridization improve energy performance and grid utilization under real operating conditions?
- Economic feasibility, evaluating whether the optimization of generated energy, reduction of curtailment, and participation in electricity markets can yield sufficient long-term returns despite the high upfront cost of storage. Under current Spanish market conditions, can BESS integration be economically justified through energy arbitrage and/or aFRR services?
- Environmental impact, examining the greenhouse gas (GHG) emission reduction potential of the hybrid system and its contribution to a cleaner and more stable electricity supply. What is the environmental contribution of hybrid wind–solar–storage systems in terms of GHG emissions reduction?

While the quantitative results are case-specific and dependent on the Spanish regulatory and market framework, the contribution of this work lies in the transferability of the proposed methodological framework. It should be noted that the objective of this study is not experimental validation at laboratory scale, but rather a techno-economic and environmental feasibility assessment based on real operational data, simulation tools, and actual market conditions from the Spanish electricity system. Therefore, the proposed framework is intended as a decision-support methodology for evaluating large-scale hybrid renewable configurations.

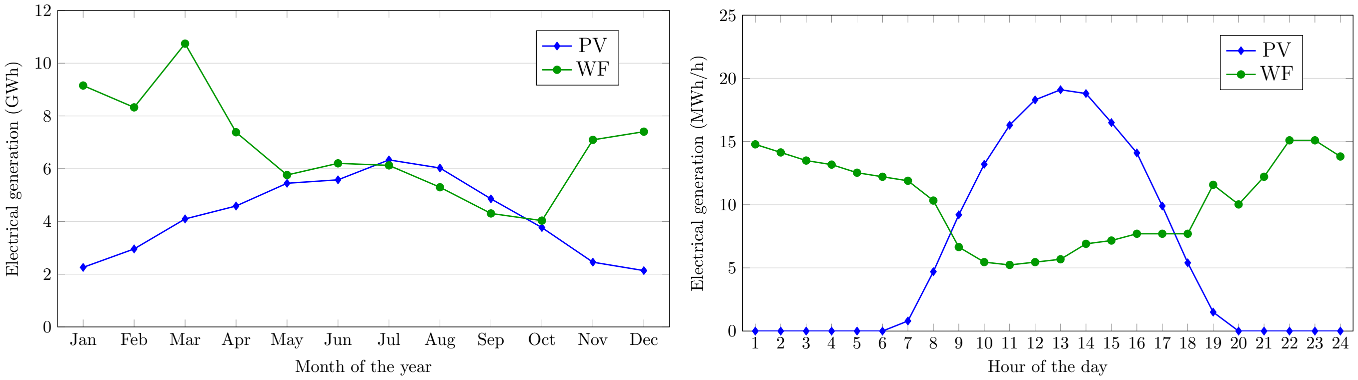
The rest of the paper is structured as follows: Section 3 presents the methodology and case study; results are detailed in Section 4 and discussed in Section 5; finally, the main conclusions are summarized in Section 6.

## 2. Background of Analysis

### 2.1. Wind–Solar Hybridization and Complementarity

The physical basis for wind-solar hybridization lies in the inverse correlation between their respective generation profiles, as seen in Figure 1. Solar generation peaks at midday and during summer months, whereas wind output tends to be stronger at dawn, dusk, and in winter [8]. This temporal complementarity enables a more balanced electricity supply across both daily and seasonal cycles, reducing periods of simultaneously low generation. Although the shared grid connection is used more efficiently as a result, the installation of higher aggregate capacity may also lead to curtailment when both resources coincide. This challenge can be addressed through careful capacity sizing, strategic turbine placement, appropriate selection of the grid connection point, and the integration of BESS [9].

From a technical and economic standpoint, hybrid plants offer a convergence of significant advantages [10]. Wind turbines occupy only approximately 3% of their allocated area, leaving substantial space for PV panel installation without interfering with wind turbine performance [11]. Sharing a single grid connection point between multiple technologies also improves the utilization of electrical assets such as transformers, converters, and transmission lines, distributing capital expenditure across a higher energy output [12]. The integration of BESS further strengthens the economic case by enabling energy arbitrage, reducing curtailment, and unlocking revenue through participation in ancillary service markets such as frequency regulation and capacity reserves [13].



(**a**) (**b**)

**Figure 1.** (**a**) Example of seasonal complementarity between wind and photovoltaic generation; (**b**) Example of daily complementarity between wind and photovoltaic generation. Own elaboration.

### 2.2. Grid Stability and Flexibility Services

Beyond site-level benefits, hybrid plants play an increasingly important role in supporting power system operation [4]. The complementarity between wind and solar generation attenuates short-term output variability and reduces reliance on dispatchable conventional sources [5], while BESS can respond within milliseconds to compensate for instantaneous imbalances between supply and demand [6]. This last capability is of particular relevance in the context of ongoing decarbonization: as thermal and nuclear power plants (traditionally responsible for supplying natural inertia through their rotating masses) are progressively decommissioned, grid-forming converters coupled with storage can emulate synchronous inertia, helping to maintain system security at high levels of RESs penetration [7].

### 2.3. International and Spanish Deployment of Hybrid Plants

Hybrid solar-wind-storage systems are already operational in a growing number of countries, including Australia, India, the United States, China, and several European nations [14]. Notable examples include the Haringvliet project in the Netherlands and Parc Cynog in the United Kingdom, both demonstrating the technical and commercial viability of integrated configurations [7]. In Europe, companies such as Vattenfall and EDP have pioneered hybrid development at scale [15], while in Spain, the National Integrated Energy and Climate Plan (PNIEC) explicitly targets significant growth in hybrid capacity by 2030 [16]. Two principal development approaches have been identified in practice: the retrofitting of existing installations (such as adding PV capacity to operational WF) which leverages existing infrastructure and reduces costs and administrative barriers [2]; and the greenfield development of fully integrated hybrid plants, designed from the outset to optimize the combined layout and shared connection capacity of multiple technologies [17].

### 2.4. Brief Literature Review

Recent literature has extensively analyzed the technical complementarity between wind and photovoltaic generation in hybrid renewable systems. Several studies have demonstrated that combining both technologies improves grid connection utilization and smooths renewable power output profiles [1,5].

In parallel, increasing attention has been devoted to the integration of battery energy storage systems (BESS) within hybrid plants, particularly for energy arbitrage and ancillary service provision. Previous studies have highlighted the growing relevance of balancing markets and frequency regulation services as key revenue streams for storage systems under high renewable penetration scenarios [6,7,13,14].

Nevertheless, despite the increasing number of studies on hybrid renewable systems, limited research has simultaneously addressed energy performance, economic profitability, and environmental impact under real market conditions using actual Spanish electricity market data. In addition, few studies compare the relative profitability of arbitrage and aFRR participation while incorporating profitability-limit and sensitivity analyses.

Therefore, this study aims to contribute to the existing literature by developing a comprehensive assessment framework for hybrid WF-PV-BESS systems based on a real Spanish case study.

## 3. Materials and Methods

To provide a clear overview of the methodological framework adopted in this study, Figure 2 summarizes the sequential workflow followed for the techno-economic and environmental assessment of the Casetona hybrid renewable plant. The methodology integrates real operational data, simulation tools, electricity market analysis, and economic feasibility indicators.

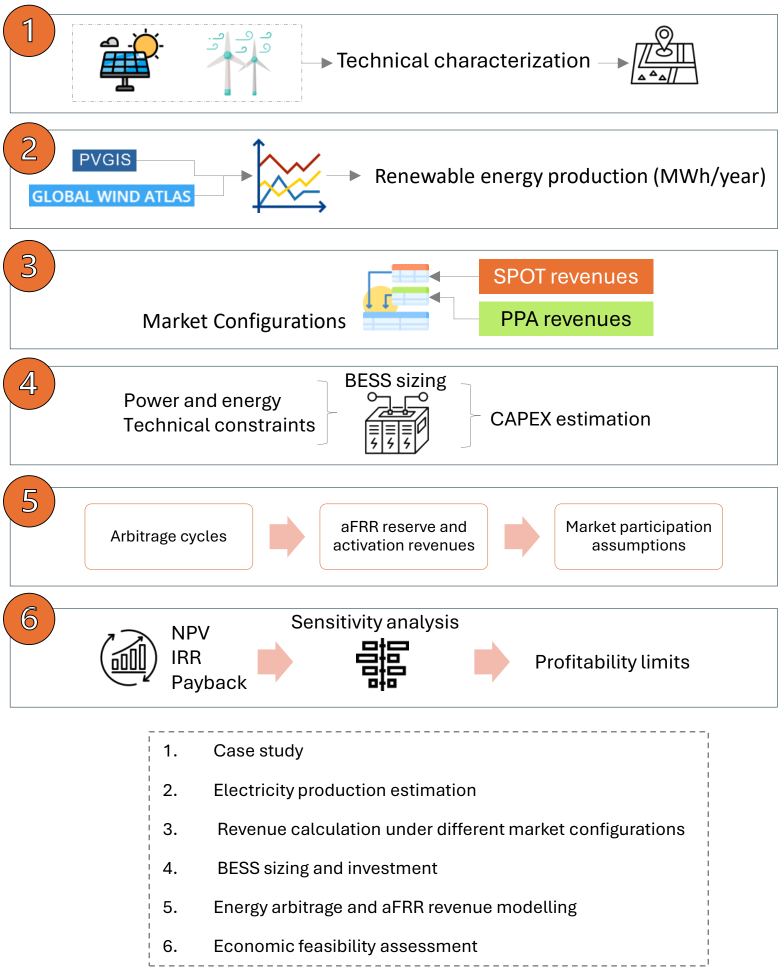


**Figure 2.** General methodological workflow. Own elaboration.

The process begins with the characterization of the hybrid WF-PV installation and the estimation of renewable electricity generation using PVGIS 5 [18] and Global Wind Atlas data [19]. Subsequently, electricity revenues are calculated under different market schemes, including PPAs, SPOT market participation, energy arbitrage, and aFRR ancillary services. Based on these operational scenarios, the BESS is sized considering technical constraints, storage capacity, state-of-charge limits, and investment costs. Finally, the economic feasibility of the three hybridization configurations is evaluated through NPV, IRR, payback indicators, and sensitivity analyses to determine profitability limits under different market conditions.

### 3.1. Case Study: The Casetona Hybrid Plant

The analysis is grounded in a real installation (the Casetona hybrid WF-PV plant) whose location is shown in Figure 3. The preliminary analysis draws on the technical characteristics of both the PV and WF components (installed capacity, equipment specifications, and geographical coordinates) to evaluate monthly and annual energy production for 2024, combining real operational data with simulation-based estimates. Of particular relevance are the peak and valley generation periods of each source and their seasonal patterns, which determine the degree of complementarity achievable at the shared grid connection point.

The PV plant consists of 61,509 monocrystalline modules of 540 Wp, arranged with a fixed tilt angle of 23° facing south, connected to 4 SUNGROW 6.8 MVA power stations, yielding a peak power of 33.21 MWp and a nominal power of 27.675 MW. The WF comprises 8 SIEMENS Gamesa G130 turbines of 3.465 MW each, with a rotor diameter of 132 m, a hub height of 114 m, and a ground elevation of approximately 910 m. The main technical specifications are summarized in Tables 1 and 2, and the overall scheme of the hybrid plant is presented in Figure 4.

**Table 1.** Technical specifications of the PV plant. Own elaboration based on [20].

| | | | |
|---|---|---|---|
| **PV modules** | Monocrystalline, 540 Wp | | |
| **N° of PV modules** | 61,509 | | |
| **Tilt angle** | 23° South (fixed) | | |
| **Power station** | SUNGROW 6.8 MVA | | |
| **N° of power stations** | 4 | | |
| **Peak power** | 33.21 MWp | | |
| **Nominal power** | 27.675 MW | | |
| **Situation (UTM)** | 30 T | 403,207.74 m E | 4,665,616.33 m N |

**Table 2.** Technical specifications of the WF. Own elaboration based on [20].

| | | | |
|---|---|---|---|
| **Wind turbine** | SIEMENS Gamesa G130, 3.465 MW | | |
| **N° of wind turbines** | 8 | | |
| **Turbine diameter** | 132 m | | |
| **Hub height** | 114 m | | |
| **Ground elevation** | 910 m | | |
| | **Situation (UTM)** | | |
| **WT 1** | 30 T | 405,340.83 m E | 4,674,615.84 m N |
| **WT 2** | 30 T | 405,599.77 m E | 4,674,492.51 m N |
| **WT 3** | 30 T | 405,807.70 m E | 4,674,295.92 m N |
| **WT 4** | 30 T | 405,925.71 m E | 4,674,048.27 m N |
| **WT 5** | 30 T | 406,266.69 m E | 4,673,973.32 m N |
| **WT 6** | 30 T | 406,315.14 m E | 4,673,597.46 m N |
| **WT 7** | 30 T | 406,396.66 m E | 4,673,340.59 m N |
| **WT 8** | 30 T | 406,487.43 m E | 4,673,063.98 m N |

**Figure 3.** Location of the Casetona WF-PV Hybridization Project. Red box shows the location of the hybrid power plant in Spain. Blue circles show the location of the WTs, red box shows the Own elaboration.

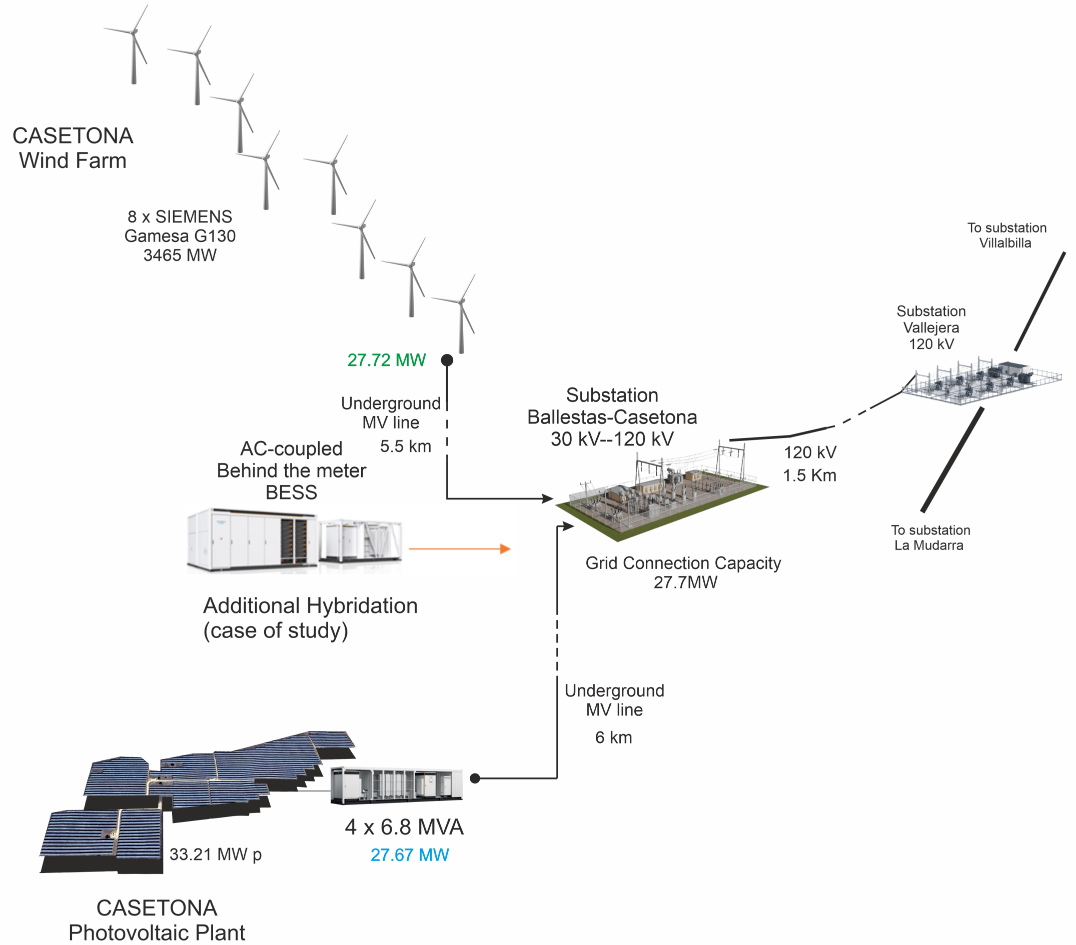


**Figure 4.** Scheme of existing hybrid plant of Casetona WF and PV plant and their main features; orange, green, and blue colors refer to the different sources of the hybrid plant connected to the grid (BESS, WF, and PV, respectively). Own elaboration based on [20].

### 3.2. Electricity Production Estimation

Energy production is estimated using two freely accessible simulation tools widely employed in the RESs sector. Solar irradiation and PV electricity production are modelled with PVGIS [18], while wind energy production is calculated using Global Wind Atlas [19]. These tools provide sufficient accuracy for the purposes of this feasibility study, where a high level of detail is not required.

In PVGIS, the plant input parameters are entered to obtain the annual production and average monthly irradiance profiles, from which average daily power curves are derived for each month. These curves are subsequently used for both production calculations and revenue estimations. From the average daily irradiance curves, daily, monthly, and annual PV production is calculated according to the expressions given in Equations (1)–(5):

$$P_{n,PV}(t) = G_n(t) \cdot A \cdot \eta \cdot \lambda \tag{1}$$

$$P^{corr}_{n,PV}(t) = P_{n,PV}(t) \cdot \left[1 + \gamma \cdot (T_c - 25)\right] \tag{2}$$

$$E^{day}_{n,PV} = \int_0^{23} P^{corr}_{n,PV}(t)\, dt \tag{3}$$

$$E^{month}_{n,PV} = E^{day}_{n,PV} \cdot D_n \tag{4}$$

$$E^{year}_{PV} = \sum_{n=1}^{12} E^{month}_{n,PV} \tag{5}$$

where $G_n(t)$ is the solar irradiance (W/m$^2$), $A$ is the PV area (m$^2$), $\eta$ is the panel efficiency, $\lambda$ is the loss factor, $\gamma$ is the temperature coefficient, $T_c$ is the cell temperature (°C), and $D_n$ is the number of days in month $n$.

In Global Wind Atlas, the annual production per turbine is obtained directly, and average monthly wind speed curves are exported and processed to derive corresponding power curves using the expressions in Equations (6)–(10):

$$P_{n,WT}(t) = v_n(t) \cdot PC \tag{6}$$

$$P^{net}_{n,WF}(t) = P_{n,WT}(t) \cdot N \cdot \eta_{tot} \tag{7}$$

$$E^{day}_{n,WF} = \int_0^{23} P^{net}_{n,WF}(t)\, dt \tag{8}$$

$$E^{month}_{n,WF} = E^{day}_{n,WF} \cdot D_n \tag{9}$$

$$E^{year}_{WF} = \sum_{n=1}^{12} E^{month}_{n,WF} \tag{10}$$

where $v_n(t)$ is the hourly average wind speed (m/s), $PC$ represents the turbine power curve (MW per m/s), $N$ is the number of turbines, $\eta_{tot}$ is the total efficiency of the system, and $D_n$ is the number of days in month $n$.

Once the power curves for both technologies are obtained, they are plotted together with their sum $E_{RESs} = E_{PV} + E_{WF}$ and the grid connection capacity limit (Figure 5), making it possible to identify periods of simultaneous generation and potential curtailment.

The analysis also includes the capacity factors of each plant and an estimation of the reduction in GHG emissions. For the Spanish energy mix, GHG savings are calculated as the product of renewable electricity production (MWh) and the average emission factor of the mix ($t_{CO_{2,eq}}$/MWh). To assess the maximum mitigation potential, a reference scenario based on the most carbon-intensive technology (natural gas combined cycle plants) is also evaluated using their specific emission factor. The corresponding expressions are given in:

$$GHG = E^{year}_{RESs} \cdot \alpha \tag{11}$$

https://doi.org/10.3390/su18115467

where $E_{RESs}^{year}$ is the annual renewable energy sources production (MWh/year), and $\alpha$ is the reference emission factor ($t_{CO_{2,eq}}$/MWh).

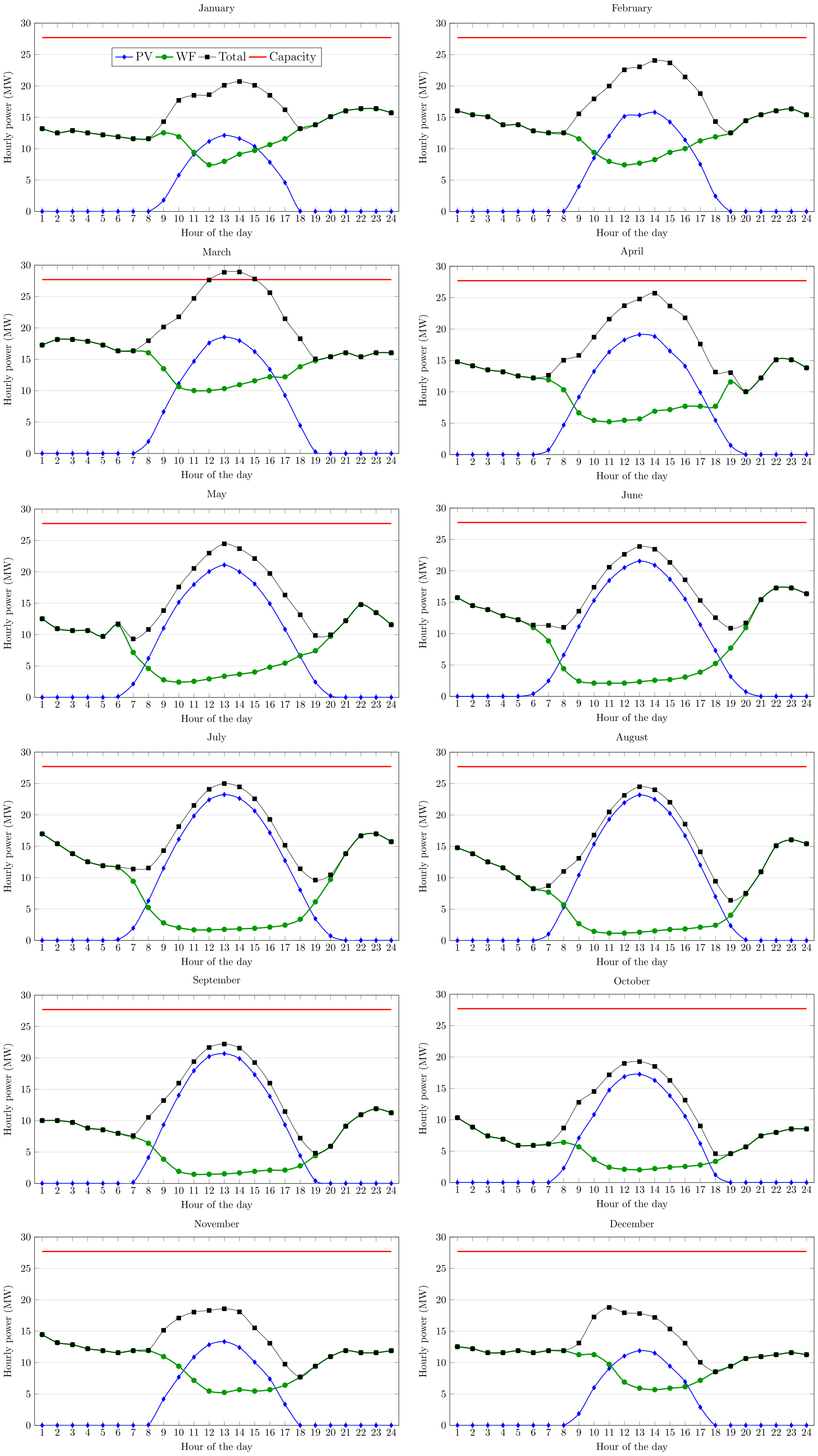


**Figure 5.** Daily average hourly power curves for each month of 2024 (PV, WF, and PV + WF). Own elaboration.

### 3.3. Revenue Calculation Under Different Market Configurations

Three revenue streams are considered: long-term power purchase agreements (PPAs), sales in the SPOT wholesale market, and BESS derived revenues from energy arbitrage and secondary frequency regulation services.

PPA revenues represent the baseline scenario, calculated as the product of the contracted energy volume and the fixed agreed price:

$$R_{WF}^{year} = \mathrm{PPA}_{WF} \cdot E_{WF}^{year} \tag{12}$$

$$R_{PV}^{year} = \mathrm{PPA}_{PV} \cdot E_{PV}^{year} \tag{13}$$

In Equations (12) and (13), $R_{WF}^{year}$ and $R_{PV}^{year}$ are the annual revenues (€/year) from WF and PV generation, respectively, and $\mathrm{PPA}_{WF}$ and $\mathrm{PPA}_{PV}$ are the PPA prices (€/MWh). However, PPA contracts restrict the operational flexibility required for energy arbitrage, and are therefore evaluated separately from the BESS scenarios.

SPOT market revenues are calculated based on hourly delivered power and the corresponding market-clearing prices determined by the system operator (OMIE in the Iberian Peninsula). To obtain representative monthly price curves, hourly SPOT price data for 2024 are sourced from the official OMIE database [21]. Monthly averages are computed, and a moving average removes inter-day variability while keeping intraday fluctuations. Then, for each month, a representative day is selected based on matching the monthly mean and standard deviation, denoted as $\overline{\pi}$ (€/MWh) and $\sigma$ (€/MWh), respectively. The resulting values are summarized in Table 3. The hourly revenue is then obtained by multiplying each hourly power value ($P_n(t)$, MW) by the corresponding hourly electricity price ($\pi_n(t)$, €/MWh), and daily, monthly, and yearly revenues ($R_n^{day}$, $R_n^{month}$, $R^{year}$, respectively) are computed by integrating along the time period under consideration:

$$R_n^{day} = \int_0^{23} P_n(t) \cdot \pi_n(t)\, dt \tag{14}$$

$$R_n^{month} = R_n^{day} \cdot D_n \tag{15}$$

$$R^{year} = \sum_{n=1}^{12} R_n^{month} \tag{16}$$

**Table 3.** Energy price records for 2024. Own elaboration based on [21].

| **2024** | | **JAN** | **FEB** | **MAR** | **APR** | **MAY** | **JUN** | **JUL** | **AUG** | **SEP** | **OCT** | **NOV** | **DEC** | **MEAN** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MONTHLY SPOT RECORD | $\overline{\pi}$ (€/MWh) | 74.1 | 40.0 | 20.3 | 13.7 | 30.4 | 56.1 | 72.3 | 91.1 | 72.6 | 68.6 | 104.4 | 112 | |
| | $\sigma$ (€/MWh) | 18 | 21 | 21.7 | 15.9 | 23 | 30.3 | 29.7 | 32.5 | 39.8 | 29.4 | 23.7 | 29 | |
| SELECTED DAY RECORD | $\overline{\pi}$ (€/MWh) | 70.9 | 40.7 | 22.4 | 15.2 | 33 | 56.7 | 73.2 | 82.2 | 72.9 | 76.4 | 109.5 | 117.6 | 64.2 |
| | $\sigma$ (€/MWh) | 10.1 | 19.8 | 15.9 | 13.5 | 25.4 | 34.4 | 28.1 | 28.9 | 41.9 | 30.1 | 27.3 | 18.5 | 24.5 |
| **DAY** | | 19/01 | 19/02 | 22/03 | 19/04 | 18/05 | 18/06 | 8/07 | 17/08 | 22/09 | 25/10 | 22/11 | 06/12 | |

### 3.4. BESS Sizing and Investment

The integration of a BESS is evaluated as the primary improvement measure over the baseline hybrid configuration. The system is designed to increase economic revenues through energy arbitrage and participation in the secondary frequency regulation market (aFRR), with the target of recovering the investment within half the battery's operational lifetime. The BESS is configured as an AC-coupled, behind-the-meter system.

The power capacity is set at 10 MW to avoid exceeding the grid connection limit during simultaneous peak generation and discharge. The energy capacity is sized to shift approximately 30 MWh over a 3-h window to capture peak price periods. The selected system is a Sungrow Power Titan 2.0 (model ST5015UX-4H, 8 units) [22], with a total capacity of 10 MW/40 MWh at a 0.25 C rate. For the $\text{LiFePO}_4$ chemistry adopted, a depth of discharge (DoD) of 80% is assumed, with state of charge (SoC) limits set between 10% and 90% of nominal capacity. A conservative round-trip efficiency (RTE) of 0.88 is adopted within the manufacturer's specified range of 0.85–0.95, and a lifetime of 20 years is assumed. At a 50% SoC, 1.4 h are available for charging and discharging for aFRR up and down regulation, while 2.8 h are available for energy arbitrage within the full SoC operating window. The investment cost is estimated at 9,280,000 € (236.25 €/kWh including transformers), based on comparable projects and published reference data [23].

### *3.5. Energy Arbitrage and aFRR Revenue Modelling*

Energy arbitrage revenue is modelled by simulating daily charge/discharge cycles based on actual 2024 SPOT market prices (Figure 6). The BESS stores energy during low-price hours (typically associated with excess renewable generation or low demand) and injects it during peak price periods, with the margin determined by the price spread between valley and peak hours. Each cycle applies the RTE factor, and a limit of one charge/discharge cycle per day is imposed. To prevent premature capacity degradation, two months per year are excluded from arbitrage operation. This yields approximately 300 cycles over the remaining ten months. The SoC is maintained between 10% and 90% throughout. Revenue is calculated by multiplying the BESS-modified power curve ($P(t)$, hourly power generation in MW) by the daily SPOT price curve ($\pi^{spot}(t)$ in €/MWh) and integrating the resulting profit curve ($R(t)$, hourly revenue curve (€/h)) over the 24-h period:

$$R^{day} = \int_0^{23} P(t) \cdot \pi^{spot}(t)\, dt = \int_0^{23} R(t)\, dt \tag{17}$$

Regarding secondary frequency regulation, the BESS is evaluated for participation in the aFRR market under the PICASSO platform [24], which provides access to European-level activation volumes (Figure 7). Eligibility requires a minimum offered capacity of 1 MW, participation within a balance group with at least 100 MW qualified for secondary regulation, and compliance with the technical and certification requirements established by Red Eléctrica (the transmission system operator of Spain, REE), including real-time control, telemetry, and qualification testing [25]. Primary frequency response is excluded, as it carries no remuneration in Spain. Tertiary regulation and replacement reserve are also excluded from this analysis due to the high unpredictability of their activation volumes, which precludes reliable annual revenue estimation. More information regarding the different frequency control responses can be found in [26].

The aFRR capacity reserve prices for 2024–2025 are taken as 34.6 €/MW·h for upward band and 25.3 €/MW·h for downward band, while activation prices are 70 €/MWh for upward and 22 €/MWh for downward energy. Reserve and activation revenues are calculated according to the expressions defined by REE:

$$R_n^{up} = H_n^{up} \cdot P^{up} \cdot \pi^{up} \tag{18}$$

$$R_n^{down} = H_n^{down} \cdot P^{down} \cdot \pi^{down} \tag{19}$$

$$R^{act} = P^{band} \cdot T^{act} \cdot \pi^{act} \tag{20}$$

where $R_n^{up}$ and $R_n^{down}$ are the monthly revenues (€) from the upward and downward bands, respectively, $H_n^{up}$ and $H_n^{down}$ are the monthly hours accepted by the TSO (h), $P^{up}$ and $P^{down}$ are the available upward and downward power (MW), $\pi^{up}$ and $\pi^{down}$ are the band prices

(€/MW·h), $R^{act}$ is the activation revenue (€), $P^{band}$ is the activated power (MW), $T^{act}$ is the activation time (h), and $\pi^{act}$ is the activation price (€/MWh).

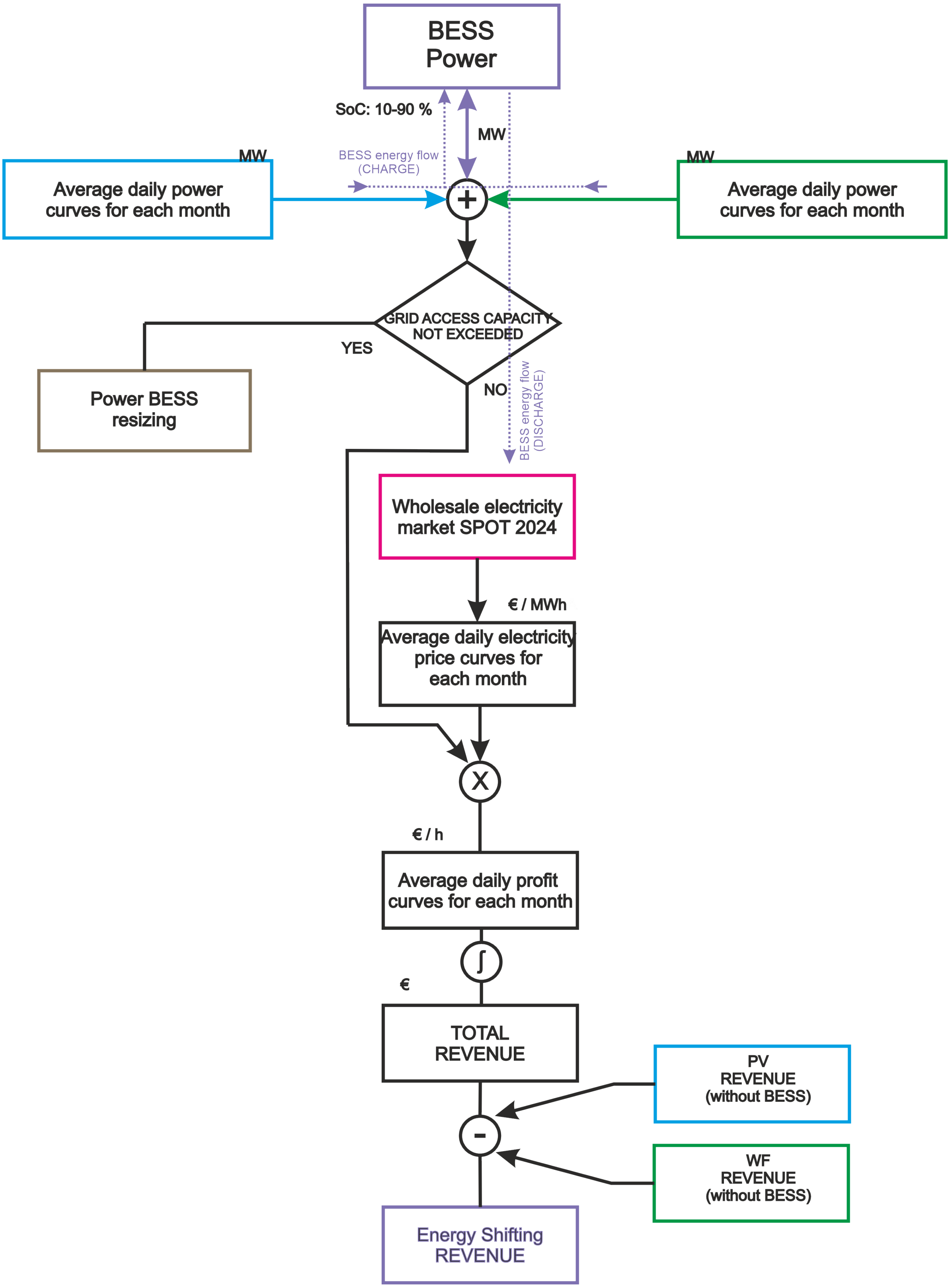


**Figure 6.** Flowchart for the calculation of energy arbitrage revenue; purple, green, and blue colors refer to the different sources of the hybrid plant (BESS, WF, and PV, respectively) Own elaboration.

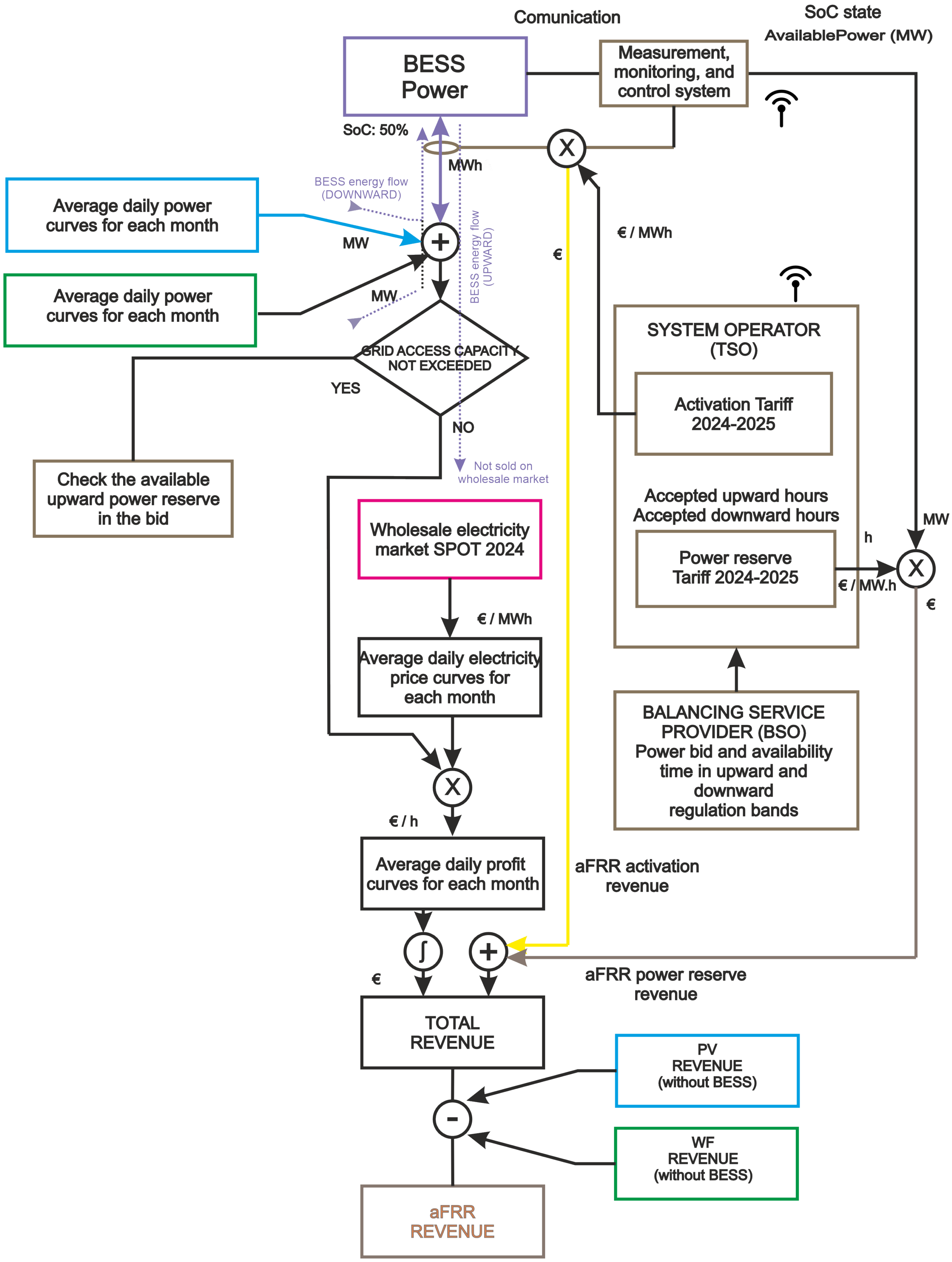


**Figure 7.** Flowchart for the calculation of revenues from aFRR; purple, green, and blue colors refer to the different sources of the hybrid plant connected to the grid (BESS, WF, and PV, respectively). Own elaboration.

Given the uncertainty in actual activation frequency, we assume one upward and one downward activation per available hour, each lasting 15 min, with a TSO acceptance rate of 70%. The available power limits for both regulation directions are established relative to the plant's operating point in each of the three hybridization scenarios considered, accounting for the maximum grid connection capacity constraint. The BESS is assumed to offer reserve capacity during all available hours at a 50% SoC. Upward activated energy is settled exclusively at the aFRR activation price; the opportunity cost of foregone SPOT revenue is internalized into the net revenue calculation, with incremental profitability attributed primarily to upward activations.

### *3.6. Economic Feasibility Assessment*

The economic viability of the three hybridization configurations (PV + WF + BESS, PV + BESS, and WF + BESS) is assessed using net present value (NPV), internal rate of return (IRR), simple payback, and discounted payback indicators, complemented by a sensitivity analysis that defines clear profitability boundaries. A discount rate of 6% is applied. Both revenue streams are modelled over the BESS lifetime of 20 years, incorporating an annual revenue growth rate of 1% and a battery degradation rate of 1% per year. The revenue inputs considered for each configuration are: energy arbitrage over ten months per year, and aFRR secondary regulation market participation over twelve months per year.

All economic indicators are calculated in real terms using a constant-euro approach. Therefore, inflation is not explicitly modelled in the cash flows. This approach is standard for energy assets with lifetimes below 25 years, but it implies that the results do not capture potential revenue erosion under high and persistent inflation (e.g., in fixed-price PPAs).

All economic indicators (NPV, IRR, payback) are calculated in real terms using a constant-euro approach. Inflation is therefore not explicitly modelled, as its expected effect is embedded in the real discount rate. This approach is standard in feasibility studies of energy assets with lifetimes below 25 years and allows a clearer comparison between revenue streams. Nevertheless, we acknowledge that under high and persistent inflation scenarios (particularly for fixed-price PPAs) real revenues could be eroded. This limitation is explicitly acknowledged and discussed.

## 4. Results

### *4.1. Electricity Generation*

The Casetona hybrid system achieves a total annual production of 132.96 GWh, with the WF contributing 82.96 GWh and the PV plant 50 GWh. Despite having similar installed capacity, the WF generates 66% more energy than the PV plant, a difference attributable to the limited daily generation window of solar technology and the higher capacity factor typically associated with wind generation. In this regard, Table 4 presents the classification criteria used to evaluate the capacity factors of both technologies, providing a reference framework to interpret the observed production levels. The monthly and annual production figures for each component and for the combined system are presented in Table 4 and the corresponding generation profiles are illustrated in Figures 8 and 9, which also show the temporal complementarity between both sources discussed in Section 1.

**Table 4.** Capacity factors of photovoltaic and wind power generation. Prepared by the authors.

| | | **PV** | | | | **WF** | |
|---|---|---|---|---|---|---|---|
| | **CF (%)** | **Evaluation** | **Rate (%)** | | **CF (%)** | **Evaluation** | **Rate (%)** |
| | <12% | Very Low/Not Viable | 0 % | | <20% | Very Low/Not Viable | 0 % |
| | 12–15% | Low | 25% | | 20–24% | Low | 25% |
| → | 16–18% | Moderate | 50% | | 25–29% | Moderate | 50% |
| | 19–21% | Good | 75% | | 30–34% | Good | 75% |
| | ≥22% | Excellent | 100% | → | ≥35% | Excellent | 100% |

The arrows represent the CF of the PV and the WF.

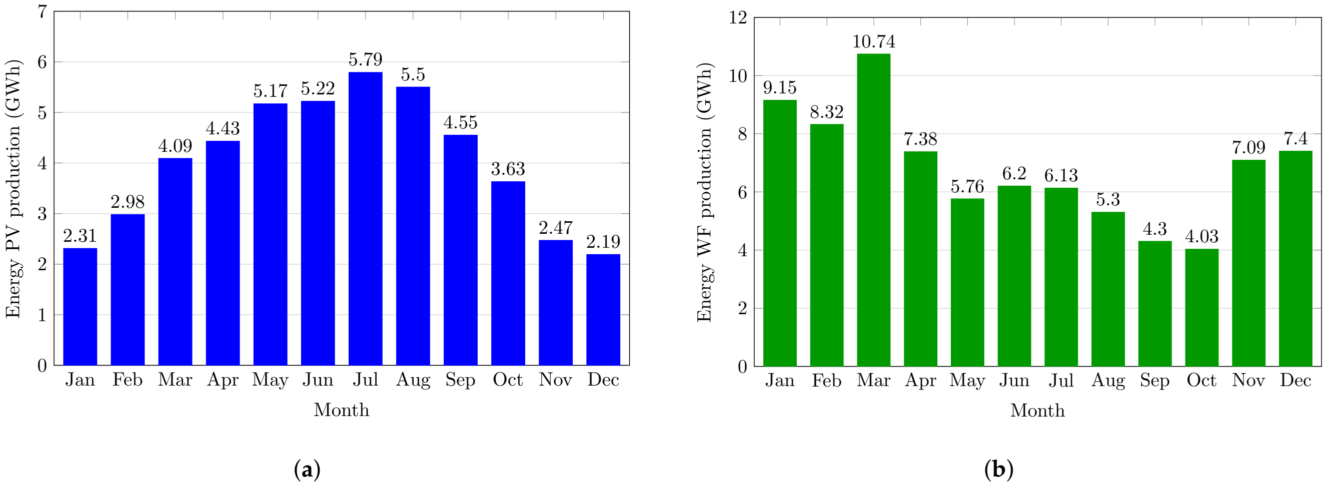


**Figure 8.** (**a**) Monthly energy production (PV); (**b**) Monthly energy production (WF). Own elaboration.

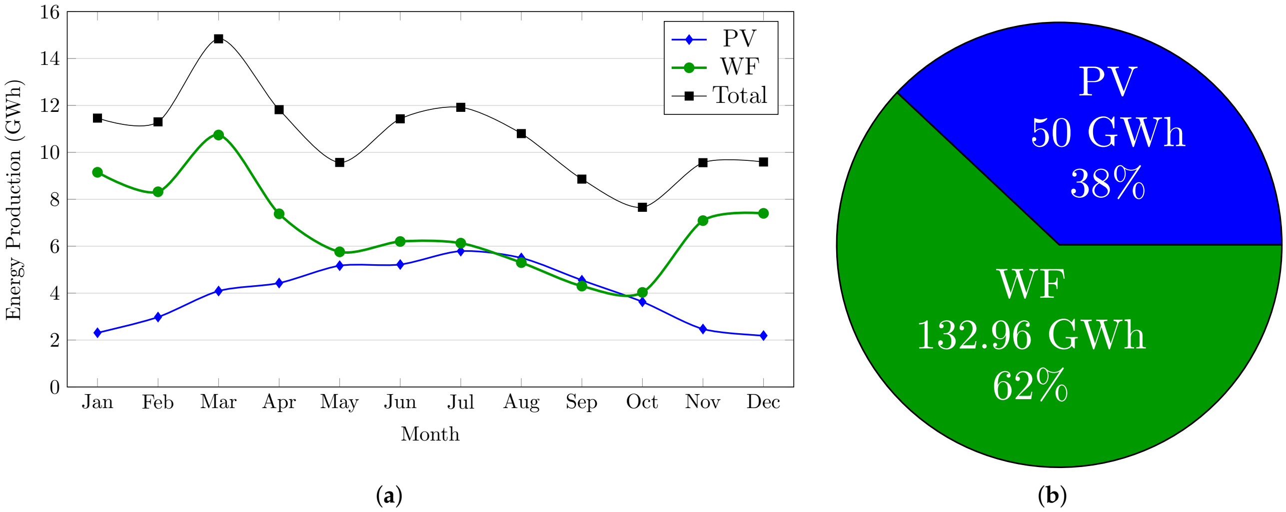


**Figure 9.** (**a**) Monthly energy production of photovoltaic and wind power generation (**b**) Energy contribution of the hybrid configuration. Own elaboration.

### 4.2. GHG Emissions Reduction

The estimated GHG emissions avoided by the proposed system were calculated using emission factors from the Spanish electricity system. According to the 2024 report by REE [27], the average emission factor of the peninsular electricity mix was $\alpha = 0.103\ t_{CO_{2,eq}}/\text{MWh}$. Considering an annual renewable electricity generation of 132,960 MWh, the corresponding GHG emissions reduction following Equation (11):

$$\Delta GHG_{mix} = 132{,}960 \cdot 0.103 = 13{,}695\ t_{CO_{2,eq}}/\text{year} \tag{21}$$

Additionally, if the generated renewable energy displaces electricity from combined-cycle power plants, which are among the most carbon-intensive technologies in the current mix, a higher emissions reduction can be estimated. Using a specific emission factor of $\alpha = 0.37\ t_{CO_{2,eq}}/\text{MWh}$ for combined-cycle generation, the avoided emissions would be:

$$\Delta GHG_{CCGT} = 132{,}960 \cdot 0.37 = 49{,}195\ t_{CO_{2,eq}}/\text{year} \tag{22}$$

These two values define the lower and upper bounds of the system's mitigation potential, depending on the marginal technology displaced in the grid.

https://doi.org/10.3390/su18115467

### *4.3. Revenue Calculation and Feasibility Study*

#### 4.3.1. PPA Revenues

Under the long-term power purchase agreement scenario, revenues are calculated by applying the contracted fixed price to the total annual energy delivered, yielding the results summarized in Table 5. This scenario serves as the baseline reference for comparison with the BESS-enhanced configurations.

**Table 5.** Revenues from Power Purchase Agreement (PPA). Own elaboration based on [28,29].

| Power Plant | €/MWh | GWh/year | €/year |
|---|---|---|---|
| WF | 57.60 | 82.96 | 4,728,720 |
| PV | 38.97 | 50.00 | 1,948,500 |
| Hybrid | | 132.96 | 6,677,220 |

#### 4.3.2. SPOT Market Revenues

Applying the methodology described in Section 3.3 to the representative daily price curves for each month of 2024, the annual revenues from electricity sales in the SPOT wholesale market are obtained for each plant and for the combined hybrid system (Table 6).

**Table 6.** Revenues calculation from sales in the wholesale SPOT market. Own elaboration.

| Power Plant | €/year |
|---|---|
| WF | 2,135,893 |
| PV | 5,535,202 |
| Hybrid | 7,671,096 |

In Figure 10, a comparison between the revenues obtained from PPA and SPOT market are shown. These results establish the revenue baseline prior to BESS integration and highlight the months with the greatest potential for price arbitrage.

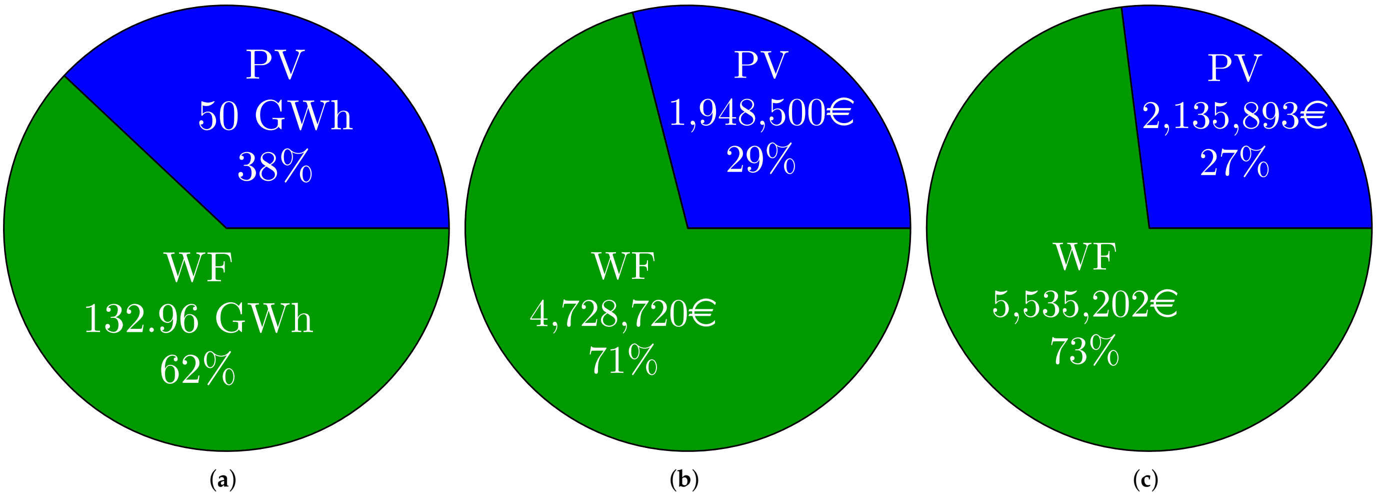


**Figure 10.** (**a**) Energy contribution of the hybrid configuration; (**b**) PPA contract revenue; (**c**) SPOT market revenue. Prepared by the authors.

#### 4.3.3. Energy Arbitrage Revenues

The simulation of daily charge/discharge cycles over ten months, based on actual 2024 SPOT prices and subject to the SoC and RTE constraints defined in Section 3.3, yields the arbitrage revenues for each of the three hybridization configurations: PV + WF + BESS, PV + BESS, and WF + BESS. The annual results are presented in Table 7. Across all configurations, the revenue increment over the baseline SPOT scenario reflects the price spread captured through shifting generation from valley to peak hours, net of round-trip efficiency losses.

**Table 7.** Feasibility assessment of the hybridization system depending on the different configurations under analysis. Prepared by the authors.

| Configuration | NPV | IRR | Payback | Discounted Payback |
|---|---|---|---|---|
| PV + WF + BESS | −7,537,271 € | −5.85% | 31 years | 54 years |
| PV + BESS | −8,308,494 € | −7.8% | 34.7 years | 55 years |
| WF + BESS | −8,845,243 € | −9.40% | 37.5 years | 55 years |

### 4.3.4. aFRR Revenues

The revenue from secondary frequency regulation services is calculated for all three configurations over twelve months of operation, combining capacity reserve remuneration and a reference activation unit of 15 min per direction per available hour, at a TSO acceptance rate of 70%. The monthly and annual results are presented in Table 8. The aFRR revenue stream consistently exceeds the arbitrage revenue across all configurations, reflecting the higher remuneration associated with reserve capacity provision relative to price-spread exploitation under current market conditions.

**Table 8.** Feasibility assessment of the hybridization system depending on the different configurations under analysis. Own elaboration.

| Configuration | NPV | IRR | Payback | Discounted Payback |
|---|---|---|---|---|
| PV + WF + BESS | 17,522,341 € | 23.8% | 4.2 years | 5 years |
| PV + BESS | 23,316,008 € | 29.3% | 3.5 years | 4 years |
| WF + BESS | 26,065,844 € | 32% | 2.8 years | 3.6 years |

### 4.3.5. Sensitivity Analysis and Profitability Limits

A sensitivity analysis of the NPV is performed for the PV + WF + BESS configuration under both revenue streams (energy arbitrage and aFRR) by varying CAPEX, discount rate, price spread, and aFRR reserve price within a ±20% range. The annual average spread is derived from the mean of the monthly standard deviations of 2024 SPOT prices (Table 3), using the expression:

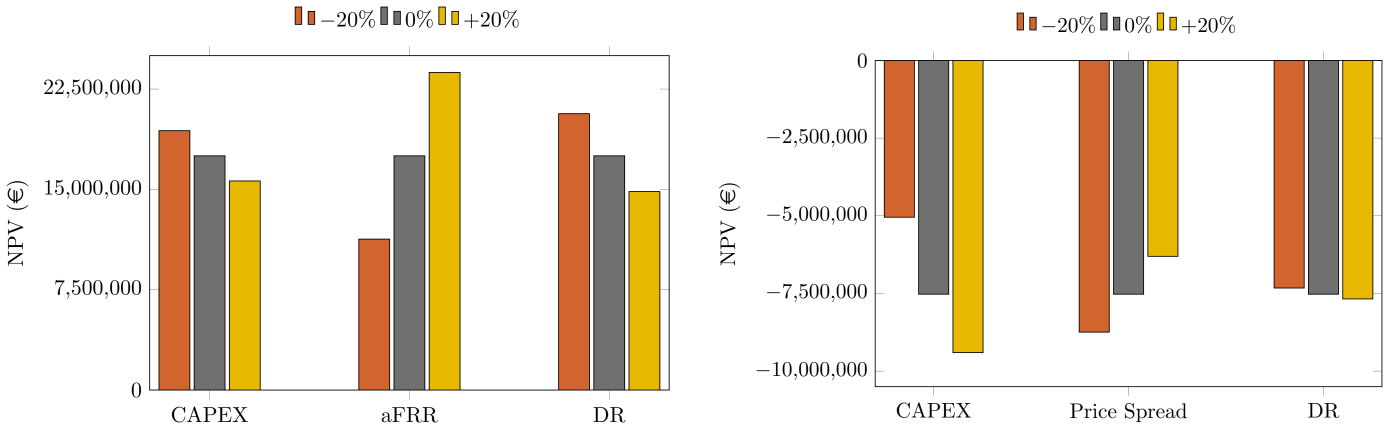
$$\text{Spread}_{avg} = 2\sqrt{2} \cdot \overline{\sigma}_{monthly} \tag{23}$$

The corresponding NPV response surfaces resulting from the sensitivity analysis are shown in Figure 11.

Under the energy arbitrage business model, the sensitivity analysis allows identification of the CAPEX threshold at which the NPV equals zero, as well as the investment cost consistent with a 10-year payback period (Table 9). The results show that current storage costs (estimated at 236.25 €/kWh including transformers) remain significantly above the level required for arbitrage-only profitability. Even under the zero-NPV threshold, the 20-year NPV is comparatively modest, underscoring the limited revenue potential of this strategy under 2024 market conditions.

**Table 9.** Energy arbitrage profitability limits—PV + WF + BESS. Own elaboration.

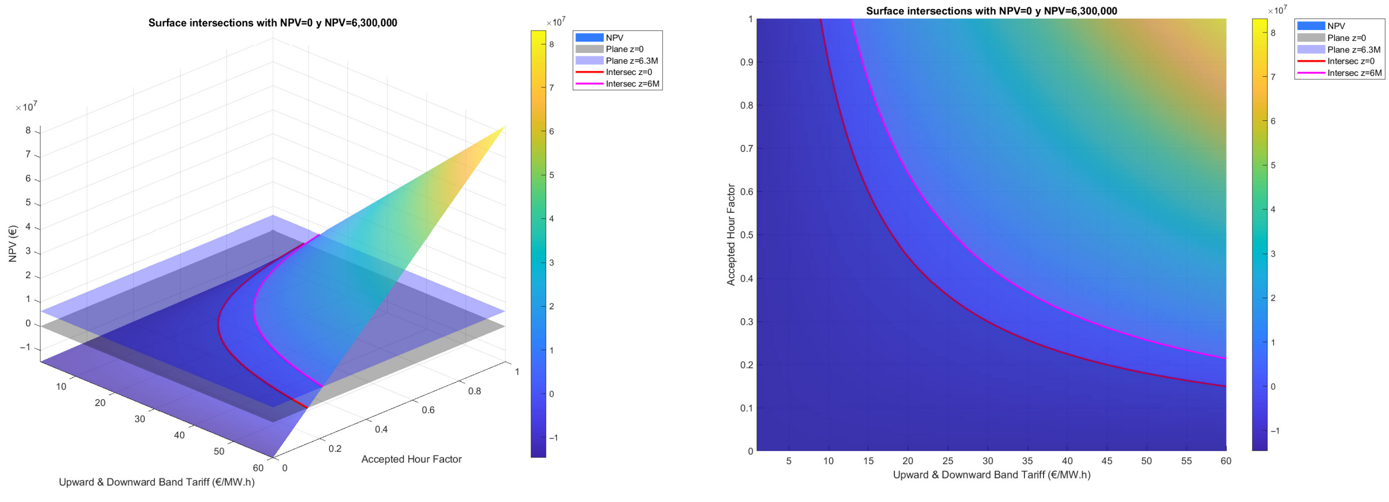
| Energy Arbitrage (WF + PV + BESS) | Storage Cost | NPV | Discounted Payback |
|---|---|---|---|
| Limit A | 80 €/kWh | 0 | 20 years |
| Limit B | 55 €/kWh | 1,300,253 € | 10 years |



(**a**) (**b**)

**Figure 11.** (**a**) Sensitivity analysis for aFRR (10 months—WF + PV + BESS); (**b**) Sensitivity analisys for energy arbitrage (10 months—WF + PV + BESS). The discount rate is varied between 4% and 8% (real) to capture uncertainty in the cost of capital and long-term inflation expectations.

Under the aFRR business model, the sensitivity analysis is extended to cover iterations on both the marginal reserve price and the fraction of offered hours accepted by the TSO (accepted hours factor, AHF). The AHF is defined as the percentage of submitted hours that the system operator contracts, applied symmetrically to upward and downward bands. Given the asymmetry between the upward and downward reserve contributions in the PV + WF + BESS configuration (with a downward-to-upward ratio of approximately 1.4), a weighted average price is computed for both bands based on their respective revenue shares. The resulting NPV map as a function of marginal price and AHF is presented in Figures 12 and 13, with iso-curves corresponding to NPV = 0 (20-year payback) and NPV = 6,300,000 € (10-year payback). The analysis identifies the price and acceptance-hour combinations that satisfy the target profitability condition, providing a reference framework applicable to future scenarios of market evolution. This is particularly relevant given that, as participation in the aFRR market grows, marginal prices are expected to decline, and the conditions assumed in this case study may prove optimistic over the longer term.



(**a**) (**b**)

**Figure 12.** (**a**) Matlab 25.2.x NPV map as a function of iterations on marginal price and hours accepted, with intersections curves NPV = 0—payback = 20 years and NPV = 6,300,000—payback = 10 years (three dimensional view) (**b**) (upper view). Own elaboration.

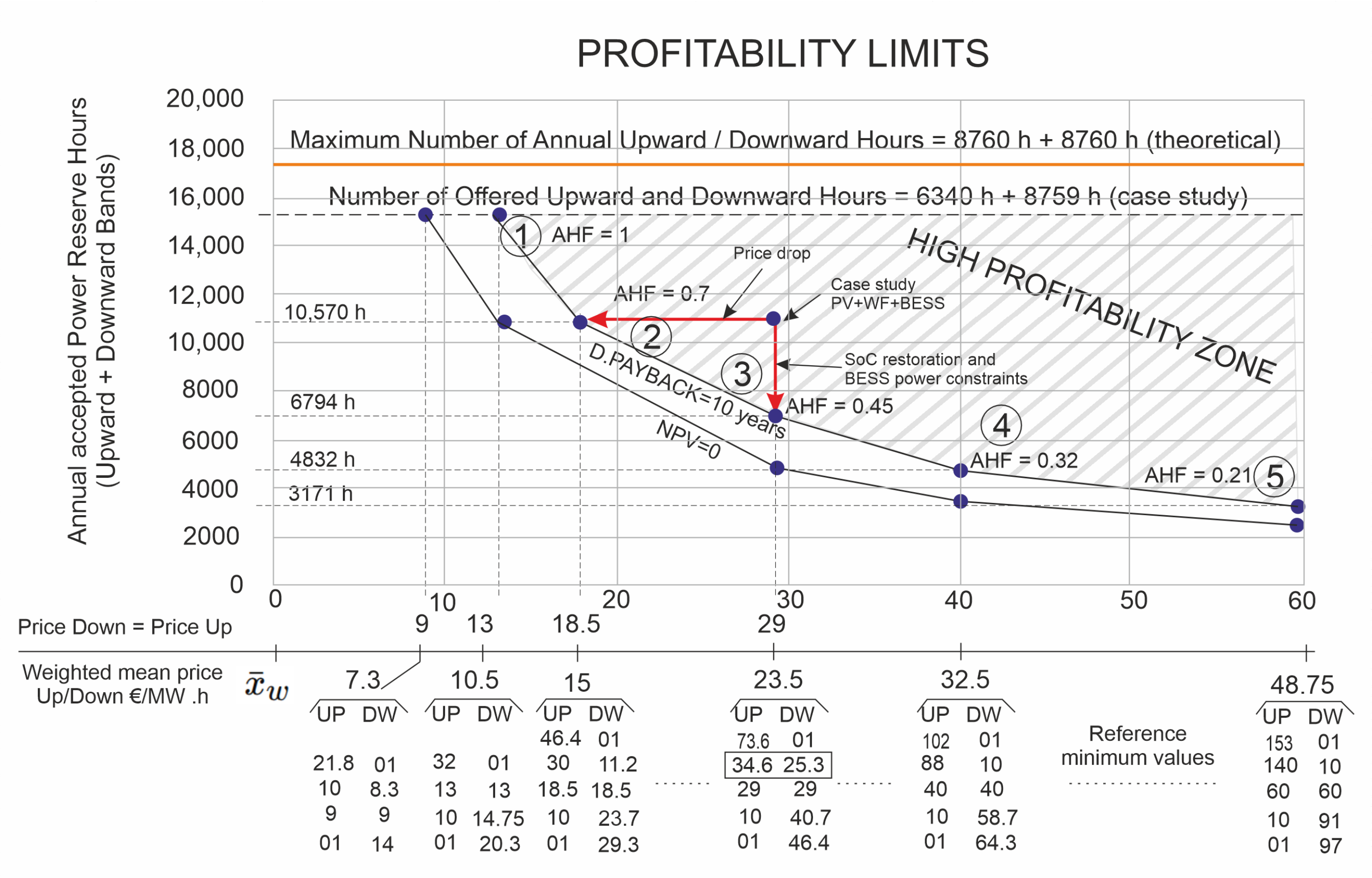


**Figure 13.** Detailed profitability limits with curves NPV = 0 and payback = 10 years. Own elaboration.

## 5. Discussion

The techno-economic assessment of the Casetona hybrid plant provides results that are broadly consistent with recent literature, while also offering specific insights within the context of the Spanish electricity market.

First, the findings confirm the well-established temporal complementarity between WF and PV generation, as reported in previous studies [1,5]. As expected, the hybrid configuration improves the utilization of the grid connection point and smooths the aggregate generation profile. However, the present study highlights that this technical complementarity does not automatically translate into economic gains, particularly under real market conditions. This observation is consistent with [10], who emphasize that hybrid system optimization must explicitly account for market price dynamics rather than relying solely on production synergies.

While the quantitative results presented here are specific to the Spanish market (OMIE price patterns, REE aFRR rules, and the Casetona site), the methodological framework is entirely transferable. To apply the same assessment to another country or region, one would need to recalibrate the following key inputs: hourly market prices (or PPA levels), aFRR reserve and activation prices, wind/solar capacity factors based on local resource data, BESS capital costs (which vary globally), and grid connection limits. The profitability limit maps (Figures 11 and 12) are particularly useful for this purpose, as they allow an investor to input local reserve prices and acceptance rates to assess viability. As an illustration, studies in Germany [30] and the UK [31] have similarly found that energy arbitrage alone is insufficient to justify BESS investment, while frequency regulation provides the dominant revenue stream—suggesting that the main conclusion (aFRR > arbitrage) may hold across several European markets, even if absolute NPV figures differ.

A key result is the PV price cannibalization, which significantly reduces PV revenues despite its substantial energy contribution. This effect, widely discussed in the literature [15], is particularly pronounced in systems with high solar penetration, where midday generation coincides with depressed wholesale prices. The Casetona case provides empirical support for this phenomenon, showing that WF generation achieves revenues due to its better alignment with peak-price periods. This reinforces the argument that technology value depends not only on energy yield but also on temporal price correlation.

Regarding storage, the results for energy arbitrage are fully aligned with prior research [13,14], which generally concludes that arbitrage alone is insufficient to justify BESS investments in markets with limited price spreads. The negative NPV obtained across all configurations confirms that, under current Spanish market conditions, arbitrage revenues are constrained by reduced intraday volatility and the flattening of price curves. This finding reflects a broader European trend, where arbitrage has shifted from being a primary revenue stream to a secondary component within multi-service strategies.

In contrast, participation in aFRR emerges as a major revenue source for BESS. This result is consistent with studies highlighting the strong economic potential of ancillary services for storage systems [6,7]. However, this study adds an important layer of analysis by demonstrating the high sensitivity of profitability to regulatory parameters, particularly reserve prices and the fraction of accepted hours. This introduces a structural uncertainty that is often underrepresented in the literature.

International experience further contextualizes these findings. In more mature markets such as Germany and the United Kingdom, increasing BESS penetration has led to progressive saturation of frequency regulation markets, reducing revenues over time and shifting value toward arbitrage and capacity mechanisms [30,31]. The results obtained for Spain suggest a similar trajectory may occur, particularly given the current concentration of revenues in aFRR due to the absence of remuneration for primary frequency control [32].

An additional contribution of this study is the development of a profitability limits map, which allows the identification of viable operating regions as a function of reserve prices and accepted hours. This approach extends beyond static economic indicators and aligns with recent optimization-based frameworks for hybrid systems, providing a more flexible and forward-looking tool for investment assessment.

The comparison between configurations further shows that WF + BESS consistently outperforms PV + BESS, a result that is not always explicitly addressed in the literature. This outcome can be explained by the higher capacity factor of wind generation and its more favorable correlation with market prices. It also supports conclusions from studies such as [17], which highlighted the importance of generation profile characteristics in hybrid system design.

Beyond these techno-economic findings, the results have important sustainability implications. From an environmental perspective, the hybrid system enables substantial GHG emissions reductions, estimated between 13,695 and 49,195 $t_{CO_{2,eq}}$/year depending on the displaced generation source. These values are consistent with previous studies highlighting the role of hybrid renewable systems in decarbonization pathways. However, the contribution of storage to emissions reduction is primarily indirect: BESS does not generate renewable energy but enhances its effective integration by reducing curtailment and enabling temporal shifting. Its sustainability value therefore lies in facilitating higher renewable penetration and improving system efficiency, rather than in direct emissions avoidance.

From a system-level perspective, BESS integration contributes significantly to grid stability and flexibility, which are critical in power systems with high shares of variable renewable energy. Fast-response storage technologies can partially substitute conventional sources of inertia and provide essential balancing services, reinforcing system reliability. The strong performance of aFRR observed in this study supports the view that storage is evolving from a purely economic optimization tool into a core enabler of secure and resilient low-carbon power systems.

However, sustainability must also be assessed in light of economic and regulatory constraints. The lack of profitability of arbitrage under current conditions may delay storage deployment, indirectly slowing the integration of renewable energy and associated emissions reductions. In this sense, sustainability is not only a technological or environmental issue but also a market design challenge, where regulatory frameworks and incentive mechanisms play a decisive role.

Finally, the results highlight a potential trade-off between short-term profitability and long-term sustainability. While aFRR currently provides strong economic signals, its dependence on market conditions and risk of future saturation may limit its long-term stability. This suggests that diversified revenue strategies (revenue stacking), combining arbitrage and ancillary services, will be essential to ensure that storage deployment remains aligned with long-term decarbonization objectives.

Overall, the findings confirm that hybrid wind–solar–storage systems are valuable not only for their emissions reduction potential but also for their contribution to a more flexible, efficient, and resilient electricity system.

A caveat on profitability claims: The positive NPVs obtained for aFRR (Table 8) are based on a 70% acceptance rate and 2024 reserve prices (34.6 €/MW·h upward, 25.3 €/MW·h downward). As more BESS capacity enters the Spanish aFRR market, both the acceptance rate and reserve prices are likely to decline, which would reduce future profitability. The profitability limit maps (Figures 11 and 12) explicitly show that below a certain weighted reserve price (≈20 €/MW·h) or acceptance rate (≈40%), NPV becomes negative. Therefore, our conclusions should be interpreted as upper-bound estimates under current favourable conditions, not as guaranteed long-term outcomes.

## 6. Conclusions

The analysis of the Casetona hybrid plant leads to the following conclusions:

- WF generation outperforms PV in both annual energy production and hourly value due to higher capacity factors (35% vs. 19–21%) and better alignment with peak-price periods. The hybrid configuration improves grid connection utilization, though curtailment persists during coincident wind–solar peaks.
- Energy arbitrage is not profitable under current Spanish market conditions due to limited price spreads and PV-induced price cannibalization. In contrast, aFRR ancillary services provide higher revenues under current favourable market and regulatory conditions (≈23.3–26.1 M€ NPV), with WF + BESS achieving the best performance. Inflation effects are not explicitly modelled and may affect long-term real revenues, particularly under fixed-price contractual schemes.
- The hybrid system enables annual GHG reductions of 13,695–49,195 $t_{CO_{2,eq}}$ depending on the displaced generation source, supporting Spain's decarbonization targets.
- BESS profitability will depend on lower storage costs (<80 €/kWh for arbitrage), regulatory reforms (primary frequency control, capacity mechanisms), and revenue stacking strategies.

The proposed methodology—combining real operational data, simulation tools, and profitability mapping—is generic and can be readily adapted to other geographical and regulatory contexts by replacing the input parameters (price series, resource profiles, BESS costs).

**Author Contributions:** Conceptualization, S.A.-d.-V.; methodology, S.A.-d.-V.; software, S.A.-d.-V.; validation, J.J.G.-M. and A.F.-G.; formal analysis, S.A.-d.-V.; investigation, S.A.-d.-V. and J.J.G.-M.; resources, I.C.G.-G.; data curation, J.J.G.-M.; writing—original draft preparation, S.A.-d.-V.; writing—review and editing, I.C.G.-G. and A.F.-G.; visualization, I.C.G.-G. and A.F.-G.; supervision, I.C.G.-G. and A.F.-G.; project administration, A.F.-G.; funding acquisition, I.C.G.-G. and A.F.-G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by MICIU/AEI/10.13039/501100011033 and FEDER (UE) through the Ministry of Science, Innovation and Universities, Spain (Ref. PID2024-157436OB-C22).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data available in a publicly accessible repository, being the link to such repository the following: https://github.com/anafguillamon/sustainability-4321939 (accessed on 1 April 2026).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| aFRR | Automatic frequency restoration reserve |
| BESS | Battery energy storage system |
| GHG | Greenhouse gas |
| PV | Photovoltaic |
| RES | Renewable energy source |
| WF | Wind farm |
| WT | Wind turbine |

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