Project in Engineering and Management I

Hybrid solutions for renewable energy systems:

Application to Moinho do Salto System

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Abstract

This study conducts a pre-feasibility techno-economic assessment of a hybrid renewable energy system at Moinho do Salto, located on the Sousa River in Portugal. It focuses on optimizing the integration of micro-hydropower with complementary solar photovoltaic, wind, and battery storage technologies to meet energy demand across five different consumption scenarios, including residential homes, a restaurant, and a church. By applying data analysis and financial evaluation methods such as LCOE and NPV, the project aims to identify the most efficient and economically viable system configurations that maximize self-sufficiency and minimize energy losses. In addition to technical and economic metrics, the study also includes a CO_2 emissions analysis to assess the environmental benefits of each scenario. This research reflects a multidisciplinary approach aimed at delivering sustainable, innovative solutions that balance technical performance, economic feasibility, and community impact, providing valuable insights for decentralized renewable energy implementation in rural settings.

Content

1. Introduction and literature review

1.1. Context of the project

Hybrid renewable energy systems have become increasingly relevant as they combine multiple energy sources to overcome the intermittency and variability issues typical of renewables. By integrating different technologies, such systems improve reliability and stability of power supply, which is especially valuable for small or remote communities that lack access to reliable grid electricity.

The Moinho do Salto is an old water mill situated on the right bank of the Sousa River, within the natural area of Senhora do Salto, in the parish of Aguiar de Sousa, municipality of Paredes, district of Porto, Portugal. The site features abundant water availability and favorable topographic conditions, making it suitable for developing a small-scale renewable energy system.

This study is conducted as part of HY4RES – Hybrid Solutions for Renewable Energy Systems, in partnership with the mill's owner, who seeks to restore the site and achieve energy self-sufficiency for the small surrounding community. This community includes eight residential houses, a restaurant, and a church, all of which currently depend entirely on conventional energy sources without local renewable generation.

This project complies with the Portuguese legal framework for renewable energy self-consumption, following Decree-Law No. 49/2015, which regulates production units for self-consumption (UPAC). According to installed capacity, such units require prior communication, registration, and certification to ensure grid safety and legal compliance. The UPAC concept allows consumers to generate renewable electricity primarily for their own use, with the possibility of storing excess energy or injecting it into the public grid.

The proposed micro-hydropower installation will use a cross-flow turbine, adapted to the existing 2.8-meter hydraulic head and infrastructure, aiming to maximize energy production efficiency while respecting environmental and legal requirements. This decentralized energy generation supports local sustainability, reduces grid losses, and promotes economic benefits for the community.

To estimate electricity demand, typical consumption profiles were assumed for each building type. From these, five consumption scenarios were defined, representing different combinations of users. These scenarios form the foundation for evaluating the technical performance and economic feasibility of various hybrid system configurations.

The proposed hybrid solution integrates micro-hydropower, utilizing the site's existing 2.55-meter head and hydraulic infrastructure, together with solar photovoltaic panels, small wind turbines, and battery storage. Each system configuration is analyzed in terms of energy self-sufficiency, technical performance, and environmental impact, including CO_2 emissions reductions.

Economic assessment employs financial metrics such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period to determine the investment needed and the economic viability for each scenario. The overall goal is to provide actionable recommendations for the most efficient, cost-effective, and sustainable renewable energy solution tailored to this rural community.

1.2. Study Objective

The main objective of this study is to perform a pre-feasibility techno-economic assessment of hybrid renewable energy systems at Moinho do Salto. Specifically, it aims to:

- Evaluate different configurations integrating micro-hydropower, solar PV, wind turbines, and battery storage to supply energy for diverse community consumption scenarios.
- Identify the optimal system designs that maximize energy self-sufficiency while minimizing costs and environmental impact.
- Provide clear investment requirements and economic viability indicators to support decision-making for sustainable local energy solutions.

1.3. Literature Review

Literature establishes that hydro-solar-wind hybrid systems offer technically and economically viable pathways for rural electrification, achieving high energy autonomy at competitive levelized costs in Iberian contexts (Ghimire et al., 2022). Portugal-focused studies highlight the operational synergy between seasonal hydropower and solar generation, significantly reducing storage dependencies (Kaundinya et al., 2020). Nevertheless, applications in rehabilitated heritage infrastructure—particularly water mills—remain understudied, especially regarding optimization under spatial constraints and ecological flow regulations (Esteves et al., 2023). This project addresses this research gap through a site-specific techno-economic model for Moinho do Salto.

2. Methodology

This chapter outlines the methodology used to evaluate the technical and economic feasibility of hybrid renewable energy systems tailored to the specific context of Moinho do Salto. The approach integrates environmental data collection, energy generation modeling, demand estimation, and detailed financial analysis. By combining hourly simulations with system optimization and sensitivity testing, the method aims to identify the most suitable configurations under various consumption patterns and constraints.

2.1 Renewable Energy Production Models

This study follows a structured methodology to assess the techno-economic feasibility of hybrid renewable energy systems adapted to the local conditions of Moinho do Salto. The approach begins with the collection of environmental and meteorological data from open-access sources such as Open-Meteo, used to estimate hydro flow availability (through soil moisture and runoff depth), solar irradiation, and wind speed profiles. These data inputs are processed on an hourly basis to simulate the potential energy production of micro-hydropower, photovoltaic (PV) panels, and small wind turbines, applying standard performance equations and technology-specific assumptions.

In parallel, five distinct hourly electricity demand scenarios are created based on the consumption profiles of nearby residential, commercial, and institutional buildings. For each scenario, a detailed hourly energy balance is computed throughout the year, comparing generation and consumption. This balance identifies periods of energy surplus and deficit, which in turn determine the behavior of the battery system—whether it charges, discharges, or triggers grid imports/exports.

2.1.1 Hydropower Generation Equations

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \tag{1}$$

where:

- P: Hydraulic power output (W)

- ρ: Water density (1,000 kg/m³)
- g: Gravitational acceleration (9.81 m/s²)
- Q: Flow rate (m³/s)
- H: Net head (m)
- η: Overall system efficiency (dimensionless)

2.1.2 Solar PV Output Calculation

$$EPV = Gtilted \cdot PPV \cdot PRE \quad (2)$$

where:

- EPV : Daily energy output (kWh)
- Gtilted: Daily global tilted irradiation (kWh/m²)
- PPV: Installed PV capacity (kW)
- PR: Performance ratio (typically 0.75)

2.1.3 Wind Turbine Yield Modeling

$$Pwind = PW \cdot \frac{1}{2} \cdot \rho air \cdot A \cdot v^3 \cdot C_p \cdot \eta \quad (3)$$

where:

- Pwind: Instantaneous wind power output (W)
- ρair: Air density (1.225 kg/m³)
- PW: Installed W capacity (kW)
- A: Swept area of the turbine (m²)
- v: Wind speed (m/s)
- Cp: Power coefficient (typically ~0.3–0.4)
- η: System efficiency (electrical/mechanical losses)

2.1.4 Battery Storage Dynamics

Battery Storage: State of Charge (SoC) Update

$$SoCt = SoC_{t-1} + \left(\frac{Echar \quad \cdot \eta charge}{Cbat}\right) - \left(\frac{Edischarge}{\eta discharge \cdot Cbat}\right) \quad (4)$$

where:

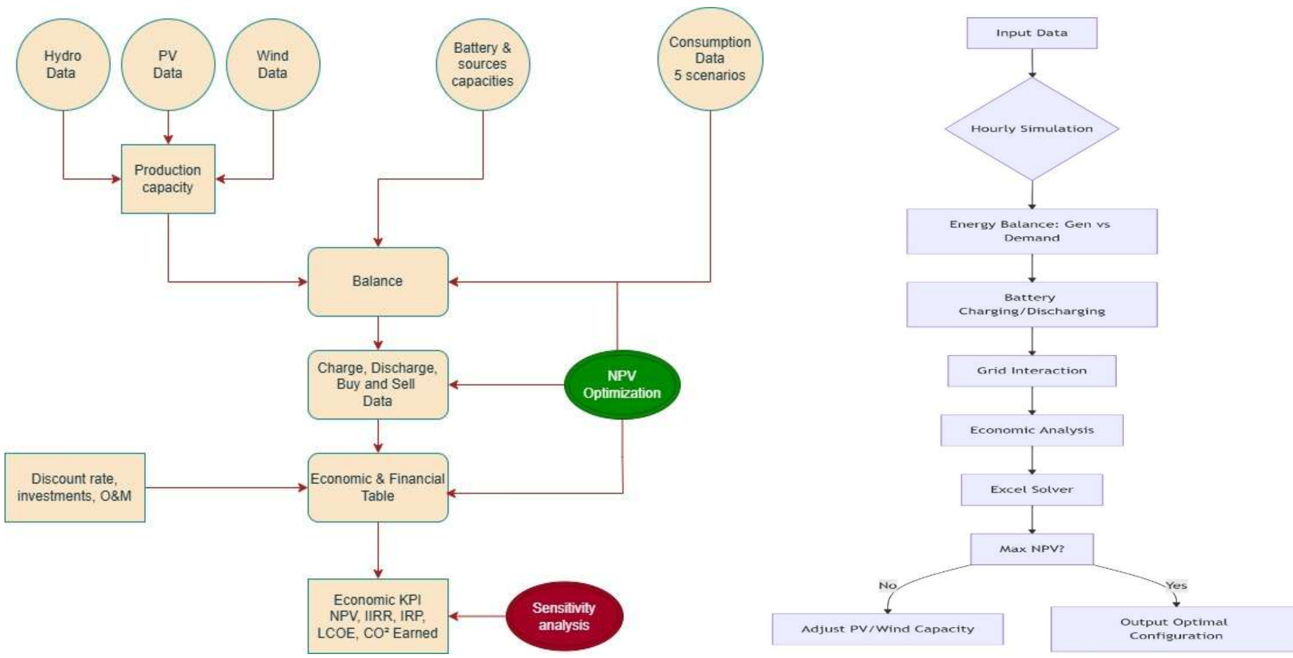
- SoCt: Battery state of charge at time ttt
- Cbat: Battery capacity (kWh)
- ηdischarge: Charge/discharge efficiencies (typically 0.95)
- Echarge,Edischarge: Energy charged/discharged (kWh)

2.2 Techno-Economic Assessment Framework and Environmental Impact

Using this hourly simulation, the model computes the total energy flows and system interactions for each scenario, making the outputs dependent on the installed capacity of each energy source. These results feed into a financial model, which calculates economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and Payback Period, based on variables including electricity prices, capital investments, and technology lifetimes.

The system is then optimized to maximize NPV by adjusting the size of the solar PV and wind components, while hydropower remains fixed due to its low LCOE. After finding the optimal configuration for each scenario, an alternative version is also tested where the rooftop area available for PV is limited to 6 m² per building (excluding the church), introducing spatial constraints that affect the maximum installable PV capacity.

Finally, a sensitivity analysis is performed to evaluate the robustness of the proposed solutions under changing conditions. Key parameters such as the electricity purchase/selling price and the discount rate are varied to assess their influence on the financial viability of each scenario. This methodology ensures a comprehensive evaluation of both technical performance and economic resilience. The full process is summarized in the following diagram **figure 1**:



a) b)

Figure 1. Flow Chart of the methodology used: a) General integration; b) Specific optimization.

2.2.1 Key Financial Metrics (LCOE, NPV, IRR)

Levelized Cost of Energy (LCOE)

$$LCOE = \frac{\sum_{t=0}^{n} \frac{It+Ot+Mt}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Et}{(1+r)^t}} \quad (5)$$

where:

- It: Investment cost in year ttt
- Ot: Operational cost in year ttt
- Mt: Maintenance cost in year ttt
- Et: Energy produced in year ttt
- r: Discount rate
- n: Project lifetime (years)

Net Present Value (NPV)

$$NPV = \sum_{t=0}^{n} \frac{Rt+Ct}{(1+r)^t} \quad (6)$$

where:

- Rt: Revenue in year t
- Ct: Cost in year t

Internal Rate of Return

$$0 = \sum_{t=0}^{n} \frac{Rt+Ct}{(1+IRR)^t} \quad (7)$$

where:

- Rt: Revenue in year t
- Ct: Cost in year t
- IRR: Tasa interna de retorno
- N: Tiempo de vida útil del proyecto (años)

Payback Period: The number of years required for the cumulative net cash flow to become positive, i.e., for the initial investment to be recovered.

In summary, this integrated methodology enables a detailed and quantitative assessment of the technical performance and economic feasibility of hybrid renewable energy systems adapted to the local context of Moinho do Salto. The combination of hourly simulations across varied scenarios and the incorporation of a financial model ensures that the results are relevant and useful for strategic decision-making. As an example, the first energy balance table and the economic-financial analysis are presented to illustrate the operation and viability of the studied configurations. The remaining tables and detailed data are provided in the Appendix. This approach relies on assumptions regarding the availability and quality of meteorological data, equipment efficiency, and energy price stability, which should be taken into account when interpreting the results. Future research could enhance the model by including uncertainty analysis of climatic variables or exploring emerging technologies.
To illustrate the functioning of this methodology, the energy balance and financial results for Scenario 1 are presented in Table 1. This scenario corresponds to a typical residential consumption profile, combined with an initial configuration of hydro, PV, wind, and battery systems. The energy balance (Table X) shows hourly generation and demand patterns, battery operation, and grid exchanges throughout the year. Based on this simulation, the financial model calculates key economic indicators such as NPV, IRR, LCOE, and Payback Period (Table Y), validating the feasibility of the system under current economic assumptions. The full set of results for all scenarios is available in the appendix.

Table 1. Energy balance for Scenario 1

Date+Time	Temperature (°C)	Wind (m/s)	Q (m3/s)	Consumption 1 (kWh)	PV Production (kWh)	Wind Production (kWh)	MicroH Production (kWh)	produccion total	Balance 1(kWh)	Excess 1(kWh)	Deficit 1 (kWh)	SOC 1	Charge 1	Discharge 1	Sell (KWh) 1	Buy (kWh) 1
2018-01-01 00:00	8.40	2.25	20.26	0.91	0.00	0.02	4.94	4.96	4.05	4.05	0.00	2.09	2.20	0.00	0.00	-1.85
2018-01-01 01:00	8.80	2.11	19.97	0.88	0.00	0.02	4.94	4.96	4.08	4.08	0.00	4.18	2.20	0.00	1.88	0.00
2018-01-01 02:00	8.60	2.19	19.77	0.89	0.00	0.02	4.94	4.96	4.07	4.07	0.00	4.18	0.00	0.00	4.07	0.00
2018-01-01 03:00	8.70	2.53	19.09	0.89	0.00	0.03	4.94	4.97	4.08	4.08	0.00	4.18	0.00	0.00	4.08	0.00
2018-01-01 04:00	8.80	2.78	19.09	0.89	0.00	0.04	4.94	4.98	4.09	4.09	0.00	4.18	0.00	0.00	4.09	0.00
2018-01-01 05:00	8.70	2.50	18.41	0.89	0.00	0.03	4.94	4.97	4.08	4.08	0.00	4.18	0.00	0.00	4.08	0.00
2018-01-01 06:00	9.50	2.89	18.41	0.85	0.00	0.04	4.94	4.98	4.13	4.13	0.00	4.18	0.00	0.00	4.13	0.00
2018-01-01 07:00	10.40	3.19	18.03	0.80	0.00	0.06	4.94	5.00	4.20	4.20	0.00	4.18	0.00	0.00	4.20	0.00
2018-01-01 08:00	10.90	3.56	18.03	0.79	0.00	0.08	4.94	5.02	4.23	4.23	0.00	4.18	0.00	0.00	4.23	0.00
2018-01-01 09:00	11.70	3.86	18.31	0.75	0.02	0.10	4.94	5.06	4.31	4.31	0.00	4.18	0.00	0.00	4.31	0.00
2018-01-01 10:00	12.80	4.69	17.65	0.71	0.08	0.18	4.94	5.20	4.49	4.49	0.00	4.18	0.00	0.00	4.49	0.00
2018-01-01 11:00	13.50	5.69	17.65	0.70	0.13	0.31	4.94	5.38	4.68	4.68	0.00	4.18	0.00	0.00	4.68	0.00
2018-01-01 12:00	13.80	6.14	17.87	0.69	0.17	0.39	4.94	5.50	4.81	4.81	0.00	4.18	0.00	0.00	4.81	0.00
2018-01-01 13:00	14.10	7.11	18.73	0.70	0.18	0.61	4.94	5.73	5.03	5.03	0.00	4.18	0.00	0.00	5.03	0.00
2018-01-01 14:00	13.90	5.67	18.73	0.67	0.14	0.31	4.94	5.39	4.72	4.72	0.00	4.18	0.00	0.00	4.72	0.00
2018-01-01 15:00	14.40	5.25	18.36	0.63	0.14	0.25	4.94	5.32	4.69	4.69	0.00	4.18	0.00	0.00	4.69	0.00
2018-01-01 16:00	13.90	4.61	17.78	0.64	0.04	0.17	4.94	5.15	4.51	4.51	0.00	4.18	0.00	0.00	4.51	0.00
2018-01-01 17:00	12.60	3.50	17.50	0.68	0.02	0.07	4.94	5.04	4.36	4.36	0.00	4.18	0.00	0.00	4.36	0.00
2018-01-01 18:00	12.10	2.78	17.23	0.68	0.00	0.04	4.94	4.98	4.30	4.30	0.00	4.18	0.00	0.00	4.30	0.00
2018-01-01 19:00	11.10	2.28	17.23	0.73	0.00	0.02	4.94	4.96	4.23	4.23	0.00	4.18	0.00	0.00	4.23	0.00
2018-01-01 20:00	10.90	2.17	16.59	0.75	0.00	0.02	4.94	4.96	4.21	4.21	0.00	4.18	0.00	0.00	4.21	0.00
2018-01-01 21:00	10.40	2.11	16.32	0.78	0.00	0.02	4.94	4.96	4.18	4.18	0.00	4.18	0.00	0.00	4.18	0.00
2018-01-01 22:00	10.80	2.25	16.32	0.76	0.00	0.02	4.94	4.96	4.20	4.20	0.00	4.18	0.00	0.00	4.20	0.00
2018-01-01 23:00	11.20	2.42	15.71	0.73	0.00	0.02	4.94	4.96	4.23	4.23	0.00	4.18	0.00	0.00	4.23	0.00
2018-01-02 00:00	10.90	2.61	15.71	0.77	0.00	0.03	4.94	4.97	4.20	4.20	0.00	4.18	0.00	0.00	4.20	0.00
2018-01-02 01:00	11.50	2.92	15.71	0.73	0.00	0.04	4.94	4.98	4.25	4.25	0.00	4.18	0.00	0.00	4.25	0.00
2018-01-02 02:00	11.70	3.31	15.71	0.73	0.00	0.06	4.94	5.00	4.27	4.27	0.00	4.18	0.00	0.00	4.27	0.00

Table 2. financial results for Scenario 1

All sources - 1st scenaric

Concept	0	1	2	3	4	5	6	7	8	9	10	11	12
Investment Hydro	- 9,700 €												
Investment Solar	- 1,020 €												
Investment Wind	- 1,568 €												
Batteries	- 2,337 €												- 2,337 €
O&M Hydro		- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar		- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €
O&M Wind		- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €
O&M Batteries		- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €
Electricity Purchase		- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €
Electricity Sales		1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €
Energy Earned		1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €
Total	**- 14,625 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**- 138 €**

Concept	0	1	2	3	4	5	6	7	8	9	10	11	12
Cash Flow Acumulated	- 14,625 €	- 12,426 €	- 10,227 €	- 8,029 €	- 5,830 €	- 3,632 €	- 1,433 €	765 €	2,964 €	5,162 €	7,361 €	9,559 €	11,758 €
K	100%	95%	91%	86%	82%	78%	75%	71%	68%	64%	61%	58%	56%
CashFlow modificated	- 14,625 €	2,094 €	1,994 €	1,899 €	1,809 €	1,723 €	1,641 €	1,562 €	1,488 €	1,417 €	1,350 €	1,285 €	- 77 €
NPV Acumulated	- 14,625 €	- 12,531 €	- 10,537 €	- 8,637 €	- 6,829 €	- 5,106 €	- 3,466 €	- 1,903 €	- 415 €	1,002 €	2,352 €	3,637 €	3,560 €
NPV	15,060 €												
IRP	6.65	years											
IIRR	14.00%												
LCOE	0.036 €												
CO² Emisions (yearly)	-3,583	Kg											

Concept	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment Hydro													
Investment Solar													
Investment Wind													
Batteries													
O&M Hydro	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €	- 15 €
O&M Wind	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €	- 39 €
O&M Batteries	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €	- 35 €
Electricity Purchase	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €	- 217 €
Electricity Sales	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €	1,424 €
Energy Earned	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €	1,372 €
Total	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**	**2,199 €**

Concept	13	14	15	16	17	18	19	20	21	22	23	24	25
Cash Flow Acumulated	13,956 €	16,155 €	18,353 €	20,552 €	22,750 €	24,949 €	27,147 €	29,346 €	31,544 €	33,743 €	35,941 €	38,140 €	40,338 €
K	53%	51%	48%	46%	44%	42%	40%	38%	36%	34%	33%	31%	30%
CashFlow modificated	1,166 €	1,110 €	1,058 €	1,007 €	959 €	914 €	870 €	829 €	789 €	752 €	716 €	682 €	649 €
NPV Acumulated	4,726 €	5,836 €	6,894 €	7,901 €	8,860 €	9,774 €	10,644 €	11,472 €	12,262 €	13,013 €	13,729 €	14,411 €	15,060 €

2.2.2 Input Parameters and Assumptions

The techno-economic model relies on a series of predefined assumptions and input parameters that reflect both technical characteristics and economic conditions relevant to the Moinho do Salto context. The following values were used in all simulations:

Technical Assumptions

- PV surface per kW installed: 4.5 m²/kW
- Average daily PV usage: 6 hours
- Battery charging/discharging efficiency: 95%
- Battery State of Charge (initial): 50%
- Battery SOC minimum threshold: 10%

- Emissions per kWh (PV): 35 g CO_2-eq
- Emissions per kWh (Wind): 10 g CO_2-eq
- Emissions per kWh (Hydro): 10 g CO_2-eq
- Emissions per kWh (Grid): 170 g CO_2-eq

Economic Assumptions

- Discount rate: 5%
- Electricity purchase price: 0.26 €/kWh
- Electricity selling price: 0.06 €/kWh
- Hydro investment (fixed): 9,700 USD
- PV investment cost: 1,650 €/kW
- Wind investment cost: 2,185 €/kW
- Battery investment cost: 560 €/kWh (year 0 and 12)
- O&M cost (Hydro): 3% of investment
- O&M cost (PV): 1.5% of investment
- O&M cost (Wind): 2.5% of investment
- O&M cost (Batteries): 1.5% of investment

These parameters are kept constant across all scenarios unless otherwise noted in the sensitivity analysis. The investment costs reflect average values found in recent literature and market data for Portugal, while emission factors are based on life-cycle assessments. No inflation or escalation of electricity prices was considered, and all values are expressed in constant 2024 euros (except for the hydro investment, which was provided in USD).

2.2.3 Environmental Impact Assessment

Additionally, an environmental impact assessment is incorporated by estimating the emissions reductions associated with the displacement of conventional fossil-fuel based electricity generation. Using emission factors relevant to the regional grid mix, the model quantifies avoided CO_2 and other pollutant emissions for each hybrid system configuration, providing an integrated view of the system's sustainability benefits alongside its techno-economic performance.

The avoided emissions are calculated by multiplying the renewable energy generated by the corresponding emission factor of the regional grid, as expressed by the equation:

$$Avoided\ Emissions = Egenerated \times EF \tag{8}$$

where Egenerated is the annual energy produced by the hybrid system (kWh), and EF is the emission factor of the local electricity grid (kg CO_2/kWh).

2.3 System Optimization Logic

The hybrid renewable energy system is optimized by adjusting the capacities of solar PV and wind components to maximize the Net Present Value (NPV). Hydropower capacity is fixed due to its low Levelized Cost of Energy (LCOE) and stable output. The optimization process uses an iterative approach, where:

- The model simulates hourly energy generation and demand interactions for each configuration.
- Economic metrics are calculated for each scenario.

- The sizes of solar PV and wind components are varied within feasible ranges to find the configuration yielding the highest NPV.
- An additional constraint is introduced in an alternative scenario by limiting the rooftop area available for PV installation to 6 m² per building (except the church), which restricts the maximum PV capacity and influences the optimal design.
- This optimization framework ensures the selection of the most financially viable and technically feasible hybrid system for the local context.

2.4 Sensitivity Analysis

To evaluate the robustness of the proposed solutions under varying market and economic conditions, a sensitivity analysis is performed on key parameters, including:

- Electricity purchase and selling prices, varied by ±20%
- Discount rate, varied between 5% and 7%

Each parameter variation assesses its impact on financial indicators such as NPV, IRR, and LCOE, as well as on the optimal system configuration. This analysis helps identify critical factors affecting project viability and supports risk-informed decision-making.

2.5 Summary of Methodology

This study integrates hourly technical simulations with a detailed financial model to assess hybrid renewable energy systems tailored to Moinho do Salto's local context. The methodology involves:

- Simulating energy flows and system interactions across various scenarios
- Calculating key economic metrics (NPV, IRR, LCOE, Payback Period)
- Optimizing system capacities to maximize economic returns
- Conducting sensitivity analyses to test solution robustness

The comprehensive approach provides a clear understanding of both technical performance and economic feasibility, supporting informed decisions for renewable energy deployment in the region.

3. Case Study: Moinho do Salto System

3.1. Site Characterization

3.1.1 Location and Context

The Moinho do Salto is located on the right bank of the Sousa River, in the parish of Aguiar de Sousa, municipality of Paredes, Porto district, with approximate geographic coordinates of 41.1285° N, -8.4343° W. The geographical context and precise location of the site are illustrated in **Figure 1**, which display detailed maps of the surrounding area and access points.

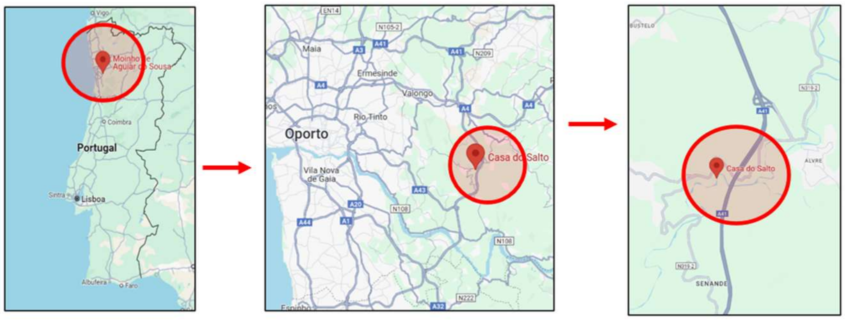


Figure 2. *Geographic location of Moinho do Salto on the Sousa River, municipality of Paredes, Portugal.*

The site features an existing hydraulic infrastructure with a usable head of about 2.8 meters, which will be utilized for the development of the renewable energy system. The region is characterized by high water availability throughout the year, making it suitable for the implementation of a small-scale hydroelectric system integrated with other renewable energy sources. Favorable topographic and environmental conditions allow for an installation that respects and harmonizes with the natural surroundings, minimizing environmental impact. Moreover, the area consists of a small rural community including residences, a restaurant, and a church, all currently fully dependent on the conventional electrical grid. The proximity of these buildings offers an opportunity to supply locally generated renewable energy, contributing to energy self-sufficiency and sustainable development in the region.
Additionally, the location benefits from being part of a region with growing interest in decentralized renewable energy projects, aligning with national and EU goals for energy transition. The historical and cultural value of the site further enhances the project's visibility and potential support from local stakeholders. The site is accessed via a rural path connected to the local road network in Aguiar de Sousa (**Figure 2**). Although access is limited for large transport vehicles, it is adequate for light machinery and installation work. Local buildings—residences, a restaurant, and a church—are currently connected to the public electrical grid. Depending on the final design, the generated power may be used in a self-consumption regime (e.g., UPAC) or injected into the grid, subject to technical and regulatory feasibility.

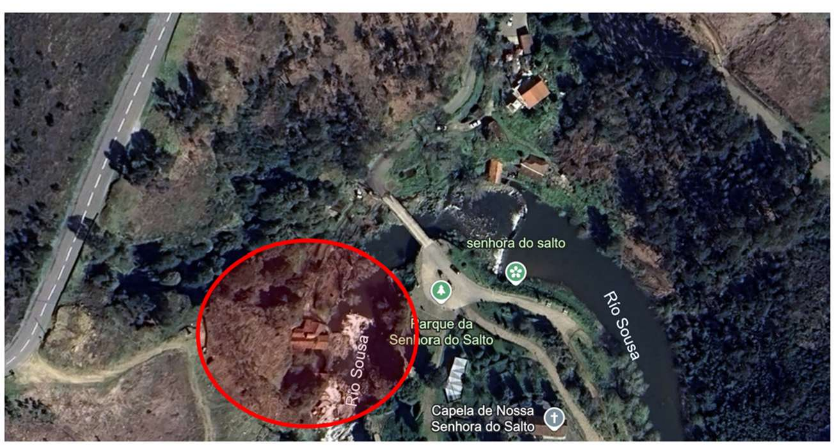


Figure 3. Access road and grid connection layout for local buildings around the Moinho do Salto site.

3.1.2 Existing Infrastructure

Weir and Hydraulic Channel

The existing weir is a traditional stone structure located across the Sousa River, with an estimated length of approximately 22 meters. It remains in good condition and effectively diverts water to the old mill through a side channel. As shown in **Figure 4**, the weir maintains a solid structure and is integrated naturally into the river's landscape. The structure currently supports a gross head of around 2.8 meters, which is crucial for the implementation of a small-scale hydropower system within the hybrid renewable energy solution being proposed

Minor rehabilitation works have already been carried out, including improvements to the intake point and reinforcement of the water diversion system, in order to optimize the turbine's performance. The structural integrity of the weir was preserved, ensuring no negative impact on river dynamics.

As shown in **Figure 5**, the original hydraulic channel leading water from the weir to the mill building remains partially intact and follows the historical path used for mill operation. While some sections may require clearing or stabilization, the existing slope and layout are favorable for reuse in the proposed system.

Figure 4. Existing stone weir at Moinho do Salto used to divert water into the historical mill channel.

A small intake structure may be added or adapted to ensure a steady flow and reduce sedimentation before entering the turbine chamber.

Figure 5. Partially preserved hydraulic channel leading water from the weir to the mill building.

Old Mill Building

The Moinho do Salto is a traditional stone building currently deactivated as a mill (**Figure 6**). Despite its age, the structure is stable and provides adequate space to house the new hydroelectric equipment, including a cross-flow turbine, generator, and control systems. Adaptations will include reinforcing the floor and potentially modifying the outlet canal (tailrace) to accommodate the new discharge path. **Figure 7** shows a schematic view of the mill, illustrating the transition from the historical vertical wooden water wheel to the modern cross-flow turbine system, preserving the mill's visual identity.

Figure 6. Old mill building (Moinho do Salto), proposed site for housing hydroelectric equipment.

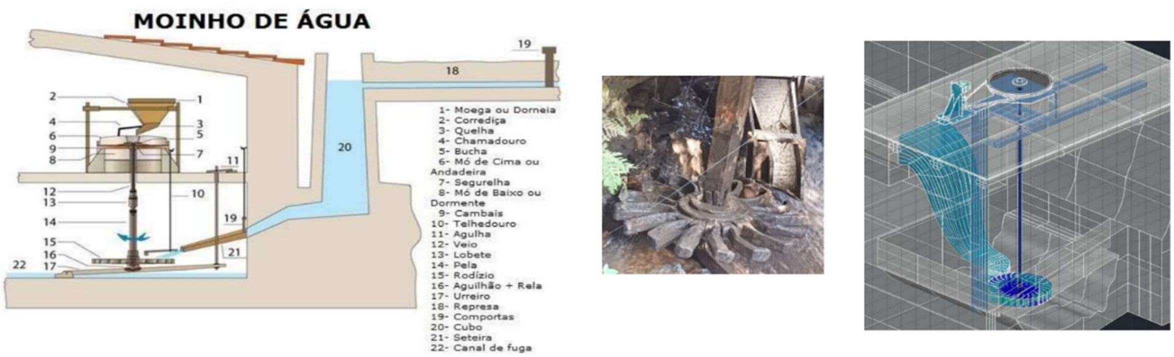


Figure 7. Schematic view of the old Moinho do Salto mill building showing the transition from the historical vertical wooden water wheel to the modern cross-flow turbine system.

3.2 Resource Input Data

This section describes the environmental and climatic data used to characterize the availability of renewable energy resources in Moinho do Salto. The analysis focuses on three main resources: hydropower potential, solar irradiation, and wind speed. All data were obtained from open-access databases with hourly resolution to ensure compatibility with the simulation model.

3.2.1 Hydrological Conditions

The available flow rate at the mill (moinho) was estimated using soil moisture data from multiple soil layers (0–7 cm, 7–28 cm, 28–100 cm, and 100–255 cm), obtained from the Open-Meteo historical weather API for the geographic coordinates of the site. These values were used to estimate the vertical water discharge, referred to as runoff depth (Q_calc), which represents the amount of water contributing to surface flow. By multiplying this value by the surface area of the river basin (556.7 km²), the total river flow rate (in m³/s) was derived.

To determine the flow rate available for hydropower generation at the mill, two key constraints were applied. First, a minimum environmental flow of 0.3 m³/s is always reserved to maintain the ecological balance of the river. Second, when the river flow is below 16 m³/s, this entire amount is diverted upstream to the existing small hydro plant, and only the ecological flow of 0.3 m³/s remains available downstream

for the mill. Therefore, the mill only receives additional water for energy generation when the river flow exceeds 16.3 m³/s. In this case, the flow available for the mill is calculated as the total river flow minus 16 m³/s, respecting the ecological minimum.
Electricity is generated when the available flow at the mill is equal to or greater than 70 % of the turbine's capacity, which in this case is 0.310 m³/s (70 % of 0.4428 m³/s). Therefore, even if the available flow is exactly 0.3 m³/s—corresponding to the ecological flow—the system does produce electricity, albeit at low capacity. If the available flow exceeds the turbine's installed capacity, the output is capped at that maximum. This operational logic ensures that the turbine functions efficiently while respecting technical and ecological constraints.
This methodology ensures a realistic and sustainable assessment of the hydropower potential by balancing energy production with environmental protection and the operational constraints of upstream infrastructure.
Based on the flow duration curve, we observe that 68 days per year exceed the flood threshold of 40 m³/s, indicating periods where the system must shut down or divert excess water to avoid damage. Additionally, there are approximately 9 days per year where the total river flow is below 0.3 m³/s, meaning that even the ecological flow is not fully met and no production occurs. For the remaining days with flow between 0.3 and 16 m³/s, the ecological flow passes through, and if it exceeds 0.31 m³/s, generation is possible. Therefore, under the defined operational rules, the system is fully or partially operational for approximately 287 days per year.
While these figures are based on daily averages, it's important to note that real-time flow can vary throughout the day, potentially allowing for partial operation even on days labeled as non-operational. This highlights the value of high-resolution (hourly or sub-hourly) analysis for improved accuracy.
With an optimized turbine capacity of 0.4428 m³/s, the system is estimated to generate approximately 27 MWh per year under the current hydrological and operational conditions.

Flow Duration Curve and Environmental Flow

It is possible to observe that the operational days occur when the river's flow ranges between 40 and 0.3 m³/s. At the mill site, the flow varies between 24 and 0.3 m³/s, as shown in Figure 15.

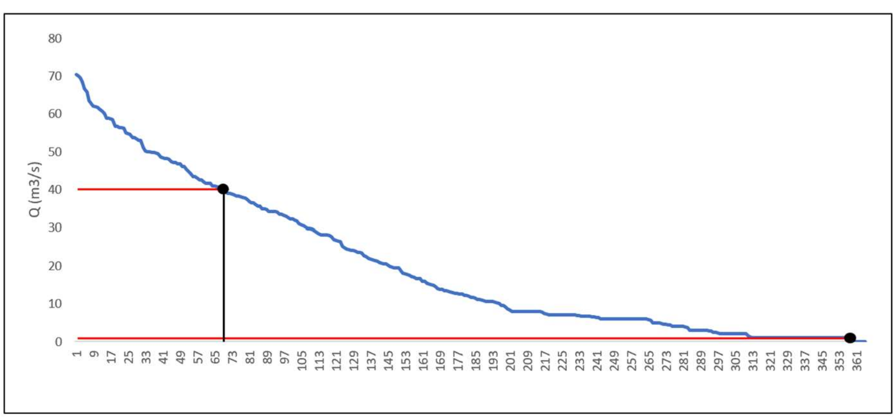


Figure 8. *Flow duration curve of the Sousa River at Moinho do Salto, used to estimate operational days for micro-hydropower.*

Seasonal Variability

The river flow shows significant seasonal variation, with higher values typically observed during the winter and early spring months due to increased rainfall and soil saturation, as shown in Figure 16. Conversely, during the summer months, the flow decreases considerably, often approaching or falling below the minimum ecological flow (0.3 m³/s), limiting the system's ability to operate. Figure 17 presents the average monthly flow, illustrating this seasonal variability more clearly. This variability directly affects the number of operational days throughout the year and highlights the importance of proper sizing and storage solutions to buffer energy production across seasons.

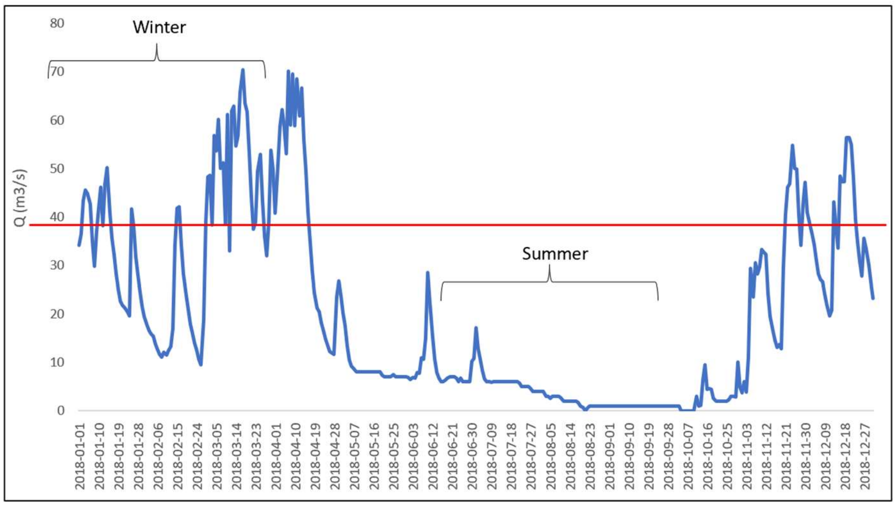


Figure 9. *Seasonal variability of river flow, highlighting periods of hydropower availability and constraint.*

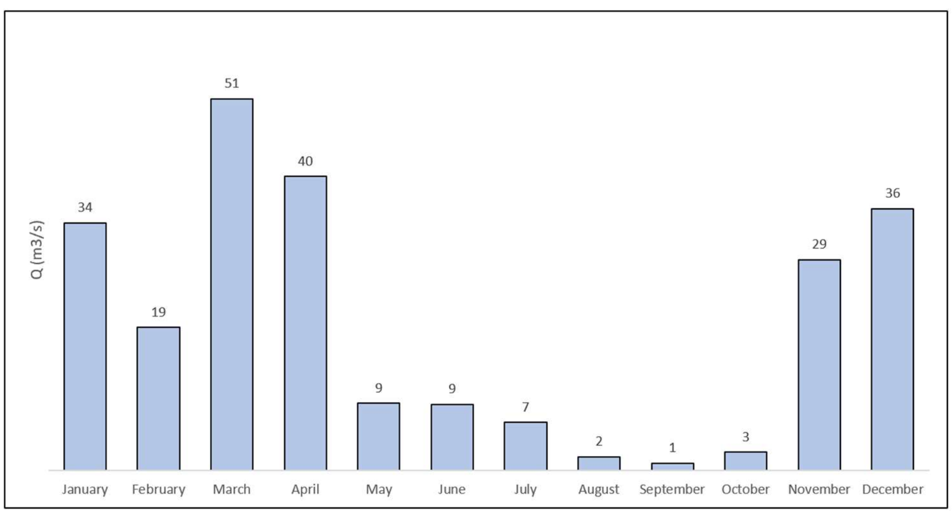


Figure 10. *Charts of seasonal variability of river flow average per month.*

Annual Generation Potential

Based on the flow duration curve and the turbine capacity of 0.4428 m³/s, the estimated annual electricity generation potential is 27 MWh/year (Figure 18). This value considers both the environmental flow constraint and the upstream diversion of up to 16 m³/s. The actual generation occurs only when the

available flow at the mill exceeds 70 % of the turbine's capacity (0.31 m^3/s), and is capped at the installed capacity when exceeded.
The relatively high number of operational days (approximately 268 per year) reflects the site's favorable ecological and infrastructure conditions. However, this still underlines the potential for complementary energy solutions or hybrid systems to improve overall year-round reliability.
Given that the LCOE of the hydro plant at maximum production capacity is €0.025/kWh — well below the selling price of €0.06/kWh — proceeding with this configuration is fully justified and leaves no room for further debate.

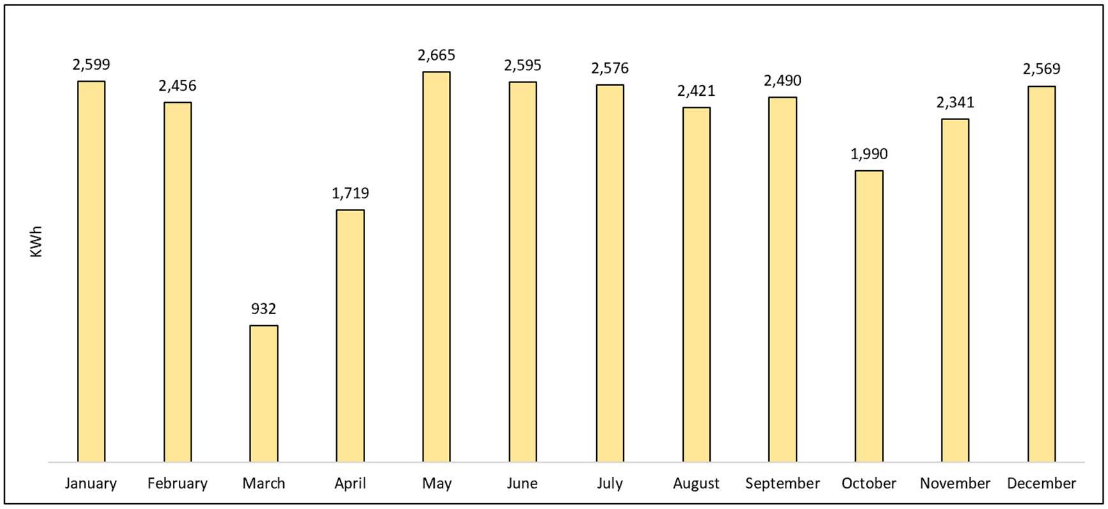


Figure 11. Estimated annual energy production from micro-hydropower under current hydrological and operational constraints.

The hydraulic power output was calculated using the standard formula:

$$P = \rho \times g \times Q \times H \times \eta \quad (9)$$

Using a net head of 2.55 m and an overall system efficiency of 44.6%, the available flow results in an average hydraulic power output of 3.1 kW, with peaks up to 11.5 kW. This corresponds to an estimated annual energy generation of 27 MWh.
This value is realistic for small, low-head micro-hydro systems operating under variable flow conditions and non-ideal installations, such as refurbished historical infrastructure.
For the selected site, a crossflow turbine was identified as the most suitable technology due to its robust performance under low to medium flow conditions, tolerance to debris, and ease of maintenance—critical factors for rural installations. The turbine's nominal capacity of 0.4428 m^3/s was chosen to balance energy production with the site's hydrological limitations and ecological constraints.
The system is designed as a run-of-river installation, meaning no water is stored in a reservoir. Instead, flow is diverted from the river through an intake and directed to the turbine via a penstock, making use of the existing mill infrastructure. This minimizes both capital costs and environmental impact.
While energy production varies with seasonal flow, the selected configuration ensures consistent operation during much of the year. Mechanical components are kept simple to reduce maintenance needs,

and the use of a standardized crossflow turbine allows for easier sourcing of spare parts and future upgrades.
This micro-hydro setup not only leverages existing infrastructure but also allows for modular integration with solar PV or battery storage systems, enabling hybrid configurations that increase energy reliability and self-sufficiency.
Additionally, the modular nature of the technology allows for potential upgrades or hybridization with complementary renewable systems such as solar PV or battery storage, enhancing overall system resilience and self-sufficiency.

Investment Cost Estimation for the Micro-Hydro System

A detailed cost breakdown was prepared to estimate the investment required for the micro-hydro installation. The total estimated cost amounts to €9,700, covering all key components and services necessary for system implementation. This includes the turbine (€2,700), generator (€1,000), civil works and canalization (€1,000), minor adaptations to the existing canal (€500), support structures (€500), as well as the control system and installation (€2,500). Administrative expenses such as permits and paperwork (€500) were also considered, alongside a contingency and miscellaneous allocation (€1,000) to account for unforeseen costs. This estimation reflects a realistic budget for a small-scale micro-hydro project based on similar implementations in rural or semi-rural European contexts. And then an annual Operation and Maintenance (O&M) cost of 3% of the total investment was assumed.
Wind speed data at 10 m height was also sourced from the ERA5 dataset via Open-Meteo, covering a full typical meteorological year with hourly resolution.
Average wind speeds at Moinho do Salto range between 2.5 and 3.2 m/s, with peaks rarely exceeding 5 m/s. These values are below the cut-in speeds of most small-scale wind turbines (typically 3–4 m/s), resulting in limited generation potential.
Given the low wind availability and higher seasonal consistency of solar irradiation, wind power was excluded from the final hybrid system configuration. However, the data remains valuable for broader resource mapping and potential future applications at different elevations or with alternative turbine types (e.g., vertical-axis models optimized for low-speed conditions).

3.2.2 Solar Profile

To estimate the potential electricity production of a solar photovoltaic (PV) system, irradiance data provided by Open-Meteo was used, specifically the global tilted irradiance in W/m², which reflects the solar radiation received by panels installed at an optimal tilt angle. Hourly values were summed over each day to obtain daily irradiation in Wh/m², then converted to kWh/m². This value was multiplied by the installed peak capacity of the system in kWp and by a performance ratio (PR) accounting for system losses. In this case, a PR of 0.75 was assumed to reflect common inefficiencies due to factors like temperature, inverter losses, cable resistance, dust, and non-optimal orientation.
Applying this method to the dataset yielded a total estimated energy production of approximately 1185.69 kWh over the analyzed period for the system considered (Figure 19). For example, on a typical day with 5.34 kWh/m² of irradiation and a 1 kWp system, the estimated daily production is approximately 4.00

kWh. This method provides a realistic estimate of expected energy output based on weather data and system performance.

However, it is important to note that estimating solar production is only one part of designing a solar energy system. Other factors must be considered, such as whether the system will be grid-connected or off-grid.

To estimate the investment cost of the photovoltaic (PV) system, real market prices were considered, resulting in an average value of 1650 €/kW of installed capacity. This includes modules, inverter, mounting structure, cabling, protection systems, labor, and permits. Additionally, an annual Operation and Maintenance (O&M) cost of 1.5% of the total investment was assumed.

These additional elements, along with accurate production estimates, are essential for evaluating the technical and economic feasibility of a solar installation.

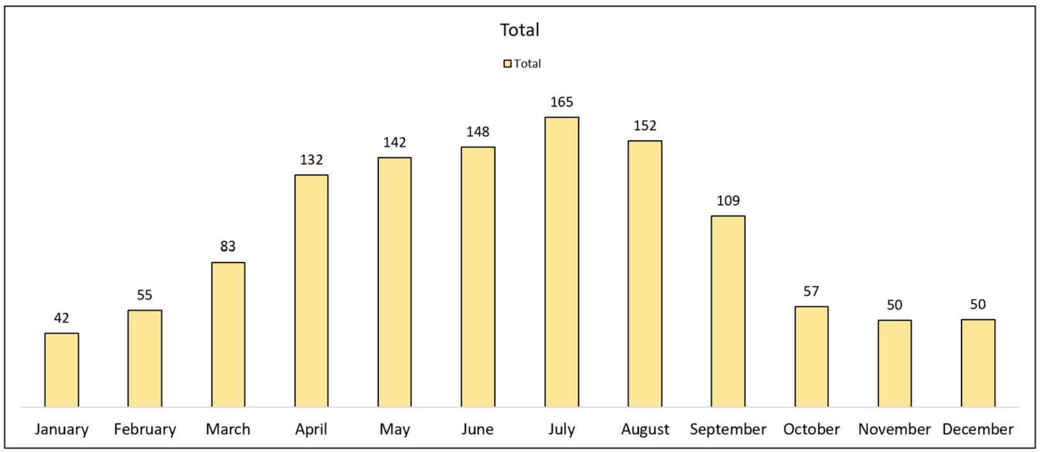


Figure 12. Solar energy production estimation based on irradiance data and 1 kW PV system.

The annual energy yield per kilowatt installed can vary between 1,200 and 1,400 kWh, depending on year-to-year changes in solar radiation. This estimation method was also essential for the techno-economic optimization of the hybrid renewable system, helping to define the optimal balance between solar, hydro, and wind energy contributions.

3.2.3 Wind Resource Characteristics

A detailed analysis was conducted to evaluate the inclusion of a wind turbine in the hybrid system, focusing on performance and suitability for a small rural community with moderate wind conditions. As shown in Figure 20, the average wind speed measured at 10 meters above ground level is around 3 m/s, with most wind speeds ranging between 2 and 5 m/s, and higher values occurring only occasionally. This wind profile suggests a low to moderate wind resource, which can still support small-scale wind generation if an appropriate turbine is selected.

Given these conditions, a vertical axis wind turbine (VAWT) was selected as a reference technology, as it performs better at lower wind speeds and is easier to install in rural environments. A turbine with a nominal rated power of approximately 2 kW was used as a baseline to estimate energy output and associated costs. With estimated rotor dimensions of 1.6 m in diameter and 1.92 m in height, the resulting swept area is about 3.07 m². Based on the local wind distribution, this turbine is expected to produce approximately 2.6 kWh per day, which corresponds to a capacity factor of 15%, consistent with similar small-scale installations.

Figure 21 illustrates the monthly average energy production estimated for the reference wind turbine, highlighting seasonal variations in wind availability. These variations are incorporated into the energy modeling to ensure realistic performance projections over the year.

It is important to note that the 2 kW capacity is only a reference used for initial estimations. The final wind capacity is adjusted by the optimization model according to each scenario's energy demands and economic constraints. Therefore, the actual installed wind power may differ.

In terms of investment cost, the components considered include the wind turbine, charge controller, hybrid/off-grid inverter, tower and mounting system, cabling and connectors, protection and safety equipment, installation and labor, permits and paperwork. A monitoring system was considered optional. The estimated capital cost was 2,500 €/kW of installed capacity, and an annual Operation and Maintenance (O&M) cost of 2% was assumed.

Speed	Hs	%	Acumulated %
0	125	1%	1%
1	1340	15%	17%
2	2379	27%	44%
3	1711	20%	63%
4	1364	16%	79%
5	899	10%	89%
6	519	6%	95%
7	248	3%	98%
8	95	1%	99%
9	47	1%	100%
10	22	0%	100%
11	10	0%	100%
12	1	0%	100%
14	1	0%	100%
Total general	8761	100%	100%

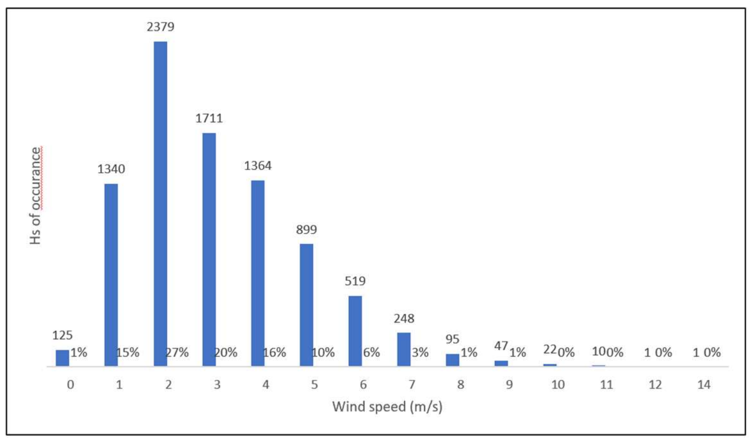


Figure 13. Wind resource analysis showing average wind speeds.

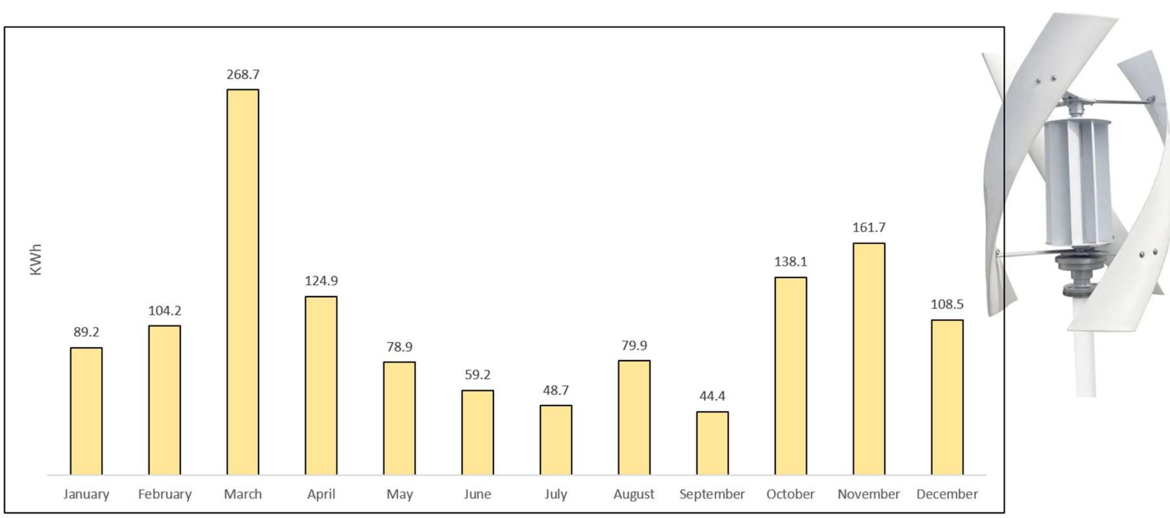


Figure 14. Wind resource analysis showing expected monthly energy production for a small VAWT.

3.2.4 Battery Storage Considerations

Battery storage systems play a crucial role in ensuring energy availability during periods when hydropower generation is not possible, such as during low river flow conditions or planned shutdowns. These systems store surplus energy produced during operational hours and release it when production ceases, significantly improving the reliability and autonomy of the installation.

The system was modeled on an hourly basis, considering an initial State of Charge (SoC) of 50 %, a minimum SoC of 10 % of total capacity, and charge/discharge efficiencies of 95 %. These parameters ensure that the battery operates within realistic technical limits and that efficiency losses are accurately accounted for. The simulation guarantees that SoC never drops below the minimum threshold and avoids oversizing by identifying the precise amount of storage needed to bridge non-generating periods.

Instead of using a fixed battery size across all cases, each hybrid system scenario was assigned a specific storage capacity calculated to ensure 6 hours of energy autonomy, based on the respective energy deficit and load profiles. This duration aligns with typical evening consumption peaks and average hydropower interruption periods observed in the demand profiles. For example, in Scenario 1, a battery of 4.2 kWh was sufficient to meet the demand during hydropower outages. Other scenarios required different capacities depending on the energy mix and generation gaps.

Additionally, operational expenditures (OPEX) were assumed to be 1.5 % of the battery's capital cost per year, in line with maintenance and management costs for similar systems.

A complete replacement of the batteries is assumed at year 12 of the project (typical Li-ion lifespan), with a cost identical to the initial investment (100% of the original CAPEX). This conservative approach does not consider residual value or future technological improvement, maximizing economic rigor in pessimistic scenarios.

3.2.5 Energy Balancing Logic

To evaluate the performance of each configuration, a daily energy balance is calculated over one year. This balance is based on the interaction between energy consumption, renewable production, and the battery system. The main objective is to determine, for each day, whether energy must be purchased from the grid or can be sold to the grid, depending on system behavior.

For each day, the following steps are performed:

Production: Total daily generation from photovoltaic panels and wind turbine. Although the wind turbine was sized around 2 kW as a reference, its actual production varies daily based on wind conditions and system optimization.

Demand: The fixed daily electricity consumption of the household.

Excess Energy: When production exceeds demand, the surplus energy is first stored in the battery (if there's capacity). If the battery is full, the remaining excess is sold to the grid.

Deficit Energy: When demand exceeds production, the system draws energy from the battery. If the battery is depleted, the remaining deficit must be bought from the grid.

Battery State of Charge (SoC): The battery charge level is updated daily, constrained by its maximum and minimum operating limits to prevent degradation.

Grid Transactions:

Buy: Energy purchased from the grid during deficit periods after battery depletion.

Sell: Energy sold to the grid when there's excess production and the battery is already fully charged.

These daily values are accumulated over the year to determine the total amount of energy bought and sold, which are essential inputs for the techno-economic assessment presented in the next section.

3.3 Energy Demand Scenarios

To assess the technical viability of the proposed renewable energy system, five different consumption scenarios were defined based on the existing infrastructure and potential energy users in the surrounding area (**Tables 4 to 8**):

- **Scenario 1** – 1 Household
- **Scenario 2** – 8 Households
- **Scenario 3** – 1 Household + Restaurant + Church
- **Scenario 4** – 1 Household + Church
- **Scenario 5** – 1 Household + Restaurant

The estimations are based on the annual electricity consumption of a real household located next to the mill, occupied by two people, with a total annual consumption of 6 MWh. This value was used as the base for both individual and combined consumption cases.

For the nearby restaurant, an estimated annual consumption of 15 MWh was considered, based on typical usage patterns for small rural restaurants. The church's consumption was assumed to be similar to that of a household (6 MWh/year) but with a constant weekly consumption of 115 KWh per week, reflecting its limited use during the week and higher activity during weekends and religious events.

Each scenario was modeled using realistic daily and seasonal profiles to reflect typical variations in demand throughout the year. These profiles were compiled into tables that display consumption by hour of the day and month of the year (**Table 3**).

To aid in interpretation, two color scales were applied:

One representing unit consumption (e.g., kWh), which highlights usage intensity patterns.

Another based on absolute totals, emphasizing the contribution of each time segment to the overall energy demand.

This dual representation enables a better understanding of both temporal usage behavior and cumulative energy needs, helping to identify optimal system sizing and energy balancing strategies under each scenario.

Table 3. Typical uses

Consumption per day		
Día	**Church**	**Restaurant**
Monday	5%	10%
Tuesday	5%	11%
Wednesday	5%	12%
Thursday	5%	13%
Friday	10%	16%
Saturday	20%	20%
Sunday	50%	18%
Total	**100%**	**100%**

Consumption per Month		
Month	**Restaurant**	**Weekly**
January	5%	188
February	6%	225
March	7%	263
April	8%	300
May	9%	338
June	10%	375
July	12%	450
August	14%	525
September	10%	375
October	7%	263
November	6%	225
December	6%	225

Consumption per hour		
Time	**Church**	**Restaurant**
00:00	0.14%	0.71%
01:00	0.14%	0.71%
02:00	0.14%	0.71%
03:00	0.14%	0.71%
04:00	0.14%	0.71%
05:00	0.14%	0.71%
06:00	0.14%	0.71%
07:00	2.50%	5.00%
08:00	2.50%	5.00%
09:00	13.33%	5.00%
10:00	13.33%	5.00%
11:00	13.33%	5.00%
12:00	5.00%	8.33%
13:00	5.00%	8.33%
14:00	1.67%	8.33%
15:00	1.67%	5.00%
16:00	1.67%	5.00%
17:00	10.00%	3.33%
18:00	10.00%	3.33%
19:00	10.00%	3.33%
20:00	2.25%	6.67%
21:00	2.25%	6.67%
22:00	2.25%	6.67%
23:00	2.25%	5.00%
Total	**100.00%**	**100.00%**

3.3.1 Scenario 1 - 1 Household

This scenario represents the consumption pattern of a single household, with an annual total of approximately 6.1 MWh. The data, shown in Figure 9, reveals a noticeable increase in energy demand during the winter months—particularly December, January, February, and March. This trend is likely associated with the use of electric heating, which raises the household's energy needs during the colder season. The profile is relatively stable during the rest of the year, showing typical residential usage (**Table 4**).

Table 4. Hourly and seasonal electricity consumption profile for a single household (Scenario 1).

1 House Scenario

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total
January	18	16	14	16	20	27	27	25	23	22	23	24	22	24	24	17	20	22	21	21	16	17	20	22	22	25	23	23	20	21	23	658
February	24	27	26	27	28	29	28	28	23	24	19	26	23	19	17	16	19	22	19	19	21	24	25	25	23	22	26	22				653
March	21	24	21	23	22	23	22	18	17	21	24	20	18	20	22	23	22	22	23	25	24	23	20	24	22	21	17	20	23	25	21	672
April	18	18	21	19	19	21	21	21	21	23	23	21	19	18	17	19	15	15	14	12	12	12	13	13	13	15	18	20	22	20		532
May	20	17	14	16	15	13	13	13	15	15	15	20	19	14	15	14	13	12	12	12	14	14	13	12	12	12	13	14	13	13	13	441
June	14	13	14	14	14	12	13	13	14	13	12	12	13	13	12	13	13	15	14	14	13	14	15	13	12	12	12	12	12	12		390
July	12	12	12	12	12	12	12	13	14	13	13	13	12	12	12	12	13	12	12	12	12	13	12	12	13	12	12	12	12	12	12	379
August	15	16	17	18	17	12	12	12	12	13	13	12	12	14	13	13	14	13	14	14	14	13	13	13	13	13	14	12	12	13	14	421
September	15	14	12	12	12	12	13	12	12	13	14	13	13	13	13	13	12	12	13	12	12	13	13	14	13	13	13	12	12	12		383
October	12	14	13	13	13	14	15	14	13	13	12	12	13	16	14	13	14	13	12	12	12	12	14	13	14	14	21	24	22	21	19	452
November	18	13	15	18	20	19	18	20	19	14	17	19	19	17	15	15	14	16	15	17	20	21	20	19	19	20	20	19	19	19		533
December	18	16	15	17	17	15	16	20	17	19	19	18	22	20	17	19	21	21	19	18	17	16	20	22	22	21	18	20	21	23	22	583
Total	205	200	194	204	209	209	210	210	201	205	203	210	204	200	191	186	190	194	188	188	188	192	199	201	197	198	205	210	188	190	126	6,098

3.3.2 Scenario 2 - 8 Households

With a total annual consumption of 48.8 MWh, this scenario significantly amplifies the residential demand, representing a small community of eight households. As shown in Figure 10, the peak consumption shifts to the summer months, especially between June and September. This pattern suggests the influence of seasonal tourism, with the restaurant nearby likely contributing to increased activity during the high season. The data highlights a marked rise in usage during the warmer months, likely due to increased refrigeration, lighting, and air conditioning (**Table 5**).

Table 5. Electricity demand profile for eight households, showing seasonal variation influenced by tourism (Scenario 2).

8 houses

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total
January	147	128	108	125	162	213	214	203	185	177	183	190	174	194	195	136	159	179	169	168	126	137	164	175	176	196	184	185	160	166	183	5,263
February	195	217	204	213	226	235	226	225	187	194	154	211	183	153	138	132	152	174	154	153	169	194	201	199	180	178	205	175				5,227
March	171	188	171	181	178	182	179	147	134	166	190	163	141	161	177	184	176	174	185	198	192	184	163	192	180	166	137	161	186	200	168	5,379
April	141	145	164	156	148	164	165	167	167	188	184	168	155	143	140	149	122	120	111	97	99	100	106	100	103	118	141	156	174	160		4,252
May	161	138	115	130	121	103	103	102	124	124	123	157	152	114	117	113	102	99	98	99	109	108	103	95	94	98	102	110	103	102	107	3,525
June	112	106	112	116	109	98	100	107	111	103	97	95	104	106	96	102	107	116	111	109	106	112	118	103	94	94	95	94	96	94		3,123
July	94	94	94	94	95	95	98	106	113	107	102	103	99	95	94	94	103	94	95	96	97	104	97	97	100	95	94	94	95	95	98	3,031
August	118	130	139	144	133	98	94	94	94	105	106	97	94	111	107	101	108	106	110	115	115	107	102	106	104	103	113	98	97	107	113	3,369
September	119	109	98	95	96	100	104	97	98	107	108	105	104	104	103	101	100	97	101	95	98	104	106	109	105	106	105	97	98	98		3,065
October	97	108	107	103	107	113	124	116	108	107	95	94	100	130	109	105	111	104	99	97	94	96	111	103	115	109	164	195	179	165	154	3,619
November	142	105	122	141	161	149	144	160	148	115	133	154	154	133	116	119	115	124	121	140	162	168	164	153	150	158	161	153	149	151		4,266
December	145	131	116	137	138	119	130	157	138	152	150	146	174	157	138	149	167	167	153	140	135	124	157	175	173	165	143	160	164	182	180	4,662
Total	1,642	1,600	1,551	1,635	1,675	1,669	1,681	1,682	1,606	1,643	1,625	1,683	1,634	1,603	1,529	1,486	1,520	1,554	1,508	1,506	1,503	1,539	1,592	1,607	1,575	1,587	1,643	1,679	1,502	1,521	1,004	48,782

3.3.3 Scenario 3 - 1 House + Restaurant + Church

Combining three types of consumers, this scenario reaches a total annual consumption of 28.4 MWh. As shown in Figure 11, the overall consumption pattern follows a similar trend to Scenario 1, with higher energy use in the winter months, again likely due to heating. However, the presence of the restaurant introduces secondary peaks during the summer, driven by seasonal business activity. This dual behavior results in a more balanced yet still winter-heavy consumption curve (**Table 6**).

Table 6. Composite consumption profile combining residential, commercial, and institutional use (Scenario 3).

1 House + Restaurant + Church																																
Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total
January	43	42	42	46	62	87	118	50	50	50	53	65	82	116	49	43	48	53	63	81	107	42	47	50	52	66	83	114	45	47	51	1,947
February	59	75	94	125	56	60	61	63	71	92	117	55	53	52	52	64	87	120	47	50	54	59	73	93	121	51	56	55				2,014
March	61	77	97	127	54	57	60	58	70	96	129	52	52	57	62	77	97	127	55	59	61	63	74	100	127	53	52	57	63	79	97	2,352
April	129	54	59	61	63	80	104	132	57	62	65	66	79	101	129	54	54	57	59	72	95	124	49	51	55	60	77	103	133	56		2,339
May	63	63	64	82	106	131	52	56	62	65	81	110	137	54	58	60	62	78	103	131	53	56	59	61	77	103	131	53	56	59	63	2,390
June	85	111	139	58	61	63	67	85	112	138	55	59	64	68	83	111	138	58	61	64	68	86	113	138	55	59	63	66	84	110		2,520
July	150	63	67	72	76	95	125	152	65	69	73	77	96	125	150	63	68	72	76	95	125	152	63	67	72	76	95	125	150	63	68	2,884
August	83	90	113	146	169	70	75	81	86	109	141	164	70	77	82	87	109	141	166	73	78	82	87	109	141	165	72	76	81	87	110	3,220
September	113	139	55	59	63	67	84	110	137	57	61	64	68	85	111	138	56	59	63	66	84	111	138	57	60	64	68	84	110	137		2,566
October	44	48	51	53	67	90	120	46	48	51	52	65	88	121	46	48	51	53	66	88	117	44	48	50	54	67	96	129	54	55	57	2,067
November	53	61	83	116	48	49	51	55	66	82	115	47	50	49	50	62	82	114	43	48	53	56	68	87	117	48	51	52	54	66		1,976
December	86	114	43	48	50	50	64	88	115	47	49	51	57	67	85	117	49	51	52	53	64	84	118	50	52	53	53	67	89	121	51	2,137
Total	971	937	907	991	875	900	981	976	938	918	990	876	896	972	957	923	903	981	854	880	959	958	936	914	983	864	897	981	918	880	495	28,411

3.3.4 Scenario 4 - 1 House + Church

This more modest scenario totals 12.1 MWh per year. As illustrated in Figure 12, while it also shows slightly higher demand in the winter months, the seasonal variation is less pronounced than in Scenarios 1 and 3. The presence of the church, which is mainly active during weekends and specific events, contributes to a more even distribution of consumption throughout the year. Overall, the winter still represents the peak period, though with a smoother gradient compared to previous cases (**Table 7**).

Table 7. Energy demand profile for a household and church, reflecting weekend-based consumption (Scenario 4).

1 House + Church																																
Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total
January	24	22	19	21	32	50	84	31	29	28	29	35	45	82	30	23	26	28	33	44	73	23	26	28	28	36	46	81	26	26	29	1,135
February	30	39	49	84	34	35	34	34	35	47	77	32	29	25	23	28	42	79	25	25	27	30	37	48	80	28	31	28				1,114
March	27	35	44	80	28	29	28	24	28	44	81	26	23	26	28	35	45	79	29	31	30	29	32	47	80	27	23	26	29	37	44	1,173
April	75	24	26	25	24	32	44	78	27	29	29	27	31	41	75	24	21	21	20	24	35	70	19	18	19	21	29	43	79	26		1,055
May	26	23	20	28	38	70	19	19	21	21	27	43	77	20	20	20	18	24	35	70	19	19	19	18	23	35	70	19	19	18	19	918
June	25	36	71	20	19	18	18	25	37	70	18	18	19	19	23	36	71	20	20	19	19	26	38	70	18	18	18	18	24	35		885
July	69	18	18	18	18	23	35	71	20	19	19	19	24	35	69	18	19	18	18	23	35	71	18	18	18	18	23	35	69	18	18	908
August	20	22	29	41	74	18	18	18	18	25	36	70	18	20	19	18	25	36	71	20	20	19	19	25	36	70	20	18	18	19	26	904
September	38	71	18	18	18	18	24	35	70	19	19	19	19	25	36	70	18	18	18	18	24	36	71	19	19	19	19	24	35	70		924
October	18	19	19	19	25	37	73	20	19	19	18	23	36	74	19	19	20	19	24	35	69	18	20	19	20	25	44	82	28	26	25	930
November	24	25	38	75	26	24	24	26	30	37	74	25	25	22	20	26	37	73	21	23	26	27	32	42	76	25	26	25	24	30		1,011
December	41	74	20	23	23	21	28	43	75	25	25	24	27	31	40	76	27	27	25	23	28	39	77	28	27	26	24	31	44	80	28	1,129
Total	418	407	372	452	359	375	429	423	408	384	451	360	371	419	404	393	368	442	338	355	407	405	406	379	444	348	372	429	395	386	189	12,087

3.3.5 Scenario 5 - 1 House + Restaurant

The final scenario combines residential and commercial consumption, resulting in a total of 22.4 MWh annually. As shown in Figure 13, the data reveals a strong peak in the summer months, reflecting the restaurant's high seasonal activity. This pattern mirrors that observed in Scenario 2, where tourism and warmer weather increase overall demand. While the winter months still contribute to baseline consumption due to the household's heating needs, summer clearly dominates in terms of total energy use (**Table 8**).

Table 8. Demand profile combining household and restaurant usage, showing summer peaks (Scenario 5).

1 House + Restaurant																																
Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total
January	37	37	36	40	50	64	60	44	44	45	47	54	59	58	43	38	42	47	51	58	50	36	41	44	46	55	60	57	39	41	45	1,470
February	54	63	71	67	51	54	55	57	59	69	60	49	48	46	47	52	64	62	42	44	48	54	61	70	63	45	50	49				1,553
March	55	66	74	70	49	52	54	53	59	73	71	47	47	52	56	65	74	69	49	54	56	57	62	77	70	47	46	52	57	67	74	1,851
April	72	48	54	55	58	69	81	75	51	56	59	60	67	78	71	49	48	51	53	60	72	66	43	46	49	54	66	80	76	50		1,816
May	57	58	58	70	83	74	47	50	56	59	69	87	80	48	52	55	57	66	80	73	47	51	53	56	66	80	73	47	50	53	57	1,912
June	74	88	81	52	55	57	61	73	89	80	50	53	58	62	72	88	81	52	55	59	62	74	90	80	49	53	57	61	72	87		2,025
July	93	57	61	66	70	84	102	94	59	63	67	71	84	102	93	57	62	66	70	84	102	94	57	62	67	70	84	102	93	57	62	2,354
August	78	85	101	123	111	65	70	75	80	97	118	107	64	72	76	81	98	118	108	67	72	76	81	97	118	107	67	70	75	82	98	2,736
September	90	81	50	53	57	61	73	87	80	51	55	58	62	73	88	80	50	53	58	61	72	88	81	51	54	58	62	72	87	80		2,026
October	38	42	45	47	55	67	63	41	42	45	46	54	65	64	40	42	45	47	54	65	59	38	43	44	48	56	73	72	49	50	51	1,589
November	47	49	60	58	43	43	45	49	55	59	57	42	44	44	44	51	59	56	38	42	47	50	56	64	59	42	45	46	48	55		1,499
December	63	57	37	42	44	44	52	65	58	41	44	45	51	56	62	59	43	46	46	47	53	61	60	44	46	48	47	56	66	63	45	1,591
Total	758	730	728	744	725	733	763	763	731	740	742	726	729	753	744	716	724	733	704	713	741	745	729	735	736	714	730	763	711	684	432	22,422

3.3.6 Resume

The following table and graph present the energy consumption by scenario and its month-to-month evolution, allowing a clear comparison and analysis of the different demand profiles throughout the year (**Table 9 and Figure 15**).

Table 9. Table of evolution of consumption scenarios during the year.

Etiquetas de fila	S1	S2	S3	S4	S5
January	658	5,263	1,947	1,135	1,470
February	653	5,227	2,014	1,114	1,553
March	672	5,379	2,352	1,173	1,851
April	532	4,252	2,339	1,055	1,816
May	441	3,525	2,390	918	1,912
June	390	3,123	2,520	885	2,025
July	379	3,031	2,884	908	2,354
August	421	3,369	3,220	904	2,736
September	383	3,065	2,566	924	2,026
October	452	3,619	2,067	930	1,589
November	533	4,266	1,976	1,011	1,499
December	583	4,662	2,137	1,129	1,591
Total general	6,098	48,782	28,411	12,087	22,422

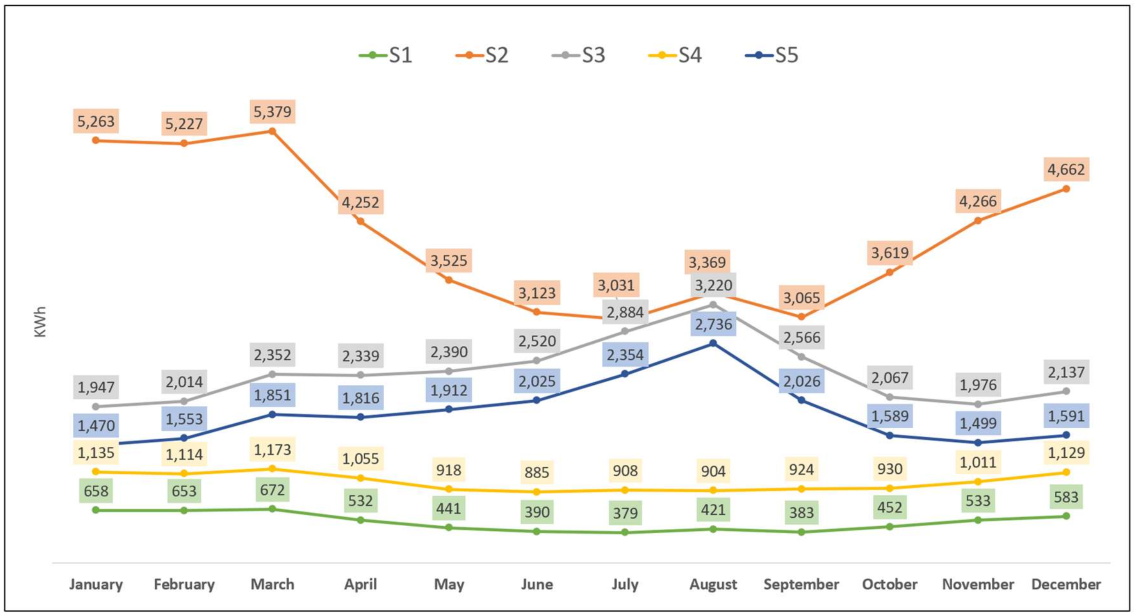


Figure 15. Graph of evolution of consumption scenarios during the year.

4. Techno-Economic Assessment

4.1 System Sizing and Optimization

For the techno-economic assessment, the sizing of each technology was optimized to maximize the Net Present Value (NPV) for each scenario. The micro-hydropower system was fixed in capacity, as its Levelized Cost of Energy (LCOE) is significantly lower than the electricity selling price, making it economically advantageous to operate at full capacity.

Starting from this fixed hydropower baseline, the capacities of the solar photovoltaic (PV) and wind turbine systems were varied to identify the optimal combination maximizing NPV. Two variants were considered for each scenario: one without spatial constraints, and another restricting rooftop area available for PV installation to 6 m² per dwelling (excluding the church but including each house and the restaurant). PV sizing assumed a panel power density of 1 kW per 4.5 m², typical of commercial solar panels.

The assessment included modeling the energy balance for each scenario, incorporating data from the different energy resources and sizing a battery storage system designed to provide an average of 6 hours of autonomy. Economic analyses were conducted over a 25-year project lifetime, considering all relevant cash inflows and outflows, including realistic market electricity prices, investment costs, and maintenance expenses.

Economic indicators such as NPV, Internal Rate of Return (IRR), Investment IRR (IIRR), and LCOE were calculated. Optimization was performed using Excel Solver to find the optimal system sizes. Subsequently, the process was repeated incorporating the PV rooftop area restriction, followed by a sensitivity analysis to assess the impact of key parameters.

This approach allowed evaluation of the trade-offs between system size, installation limitations, and economic performance, providing insight into the most feasible configurations under real-world spatial constraints.

4.2 Economic Metrics (LCOE, NPV, IRR, Payback)

This section presents the results of the economic assessment for the five hybrid renewable energy system configurations evaluated. Each scenario involves different combinations of solar PV and wind generation capacities, along with a fixed micro-hydro baseline, in order to identify the most financially attractive system layout.

- **Cost Assumptions and Economic Inputs**

The economic evaluation was conducted over a 25-year project lifetime using a 5% discount rate. Capital expenditures were estimated based on the following unit costs:

- **Hydropower**: €9,700 per kW of installed capacity
- **Solar PV**: €1,650 per kW
- **Wind**: €2,185 per kW
- **Battery storage**: €560 per kWh (yar 0 and 12 considerin 100% degradation)

Operation and maintenance (O&M) costs were estimated annually as a percentage of the initial investment:

- **Hydropower**: 3%
- **Solar PV and Battery**: 1.5%
- **Wind**: 2.5%

Electricity purchase from the grid was priced at €0.26 per kWh, while energy sold back to the grid was valued at €0.06 per kWh. Battery replacement costs were included in the cash flow projections, assuming a typical lifespan shorter than the overall project. Residual values of components at the end of the project life were also considered.

These cost assumptions were consistently applied across all scenarios to ensure comparability and to evaluate the financial performance of different hybrid configurations under realistic market conditions.

The following economic performance indicators were calculated for each scenario:

• Levelized Cost of Energy (LCOE):

LCOE represents the average cost per kilowatt-hour (kWh) of electricity generated over the lifetime of the system. It is obtained by dividing the total discounted costs (including investment and operation & maintenance) by the total energy produced. A lower LCOE indicates a more cost-efficient system.

• **Net Present Value (NPV)**

NPV measures the overall profitability of the project by summing all future cash flows (savings and revenues minus costs), discounted to their present value. A positive NPV indicates that the project adds value over time, while a negative NPV suggests it is not economically viable.

• Internal Rate of Return (IRR)

IRR is the discount rate at which the NPV becomes zero. It reflects the effective yield of the investment over time. If the IRR exceeds the chosen discount rate, the project is considered financially attractive.

• Payback Period

This indicator reflects the time needed to recover the initial capital investment from net positive cash flows. Shorter payback periods are generally preferred, especially in decentralized rural electrification projects where capital recovery is a key factor.

The economic analysis was carried out assuming a project lifetime of 25 years and a discount rate of 5%. Cost inputs were based on current market values for solar PV, wind turbines, micro-hydro systems, and battery storage components. Revenue streams were estimated from both the reduction in electricity purchases from the grid and potential energy exports. The cash flow analysis considered all capital expenditures, operation and maintenance costs, equipment replacement (such as battery systems), and residual values at the end of the project lifespan. These assumptions provide a solid basis for comparing scenarios and identifying the configuration that offers the optimal balance between investment cost, energy performance, and financial return.

Scenario 1 – Base Case (Single Household) (6,100 KWh per year)

In the first scenario, the system was designed to meet the energy needs of a single household with an annual consumption of approximately 6,100 kWh. The optimal configuration includes a fixed hydropower component based on a constant water flow of 0.44 m³/s, complemented by 0.62 kW of solar PV and 0.72 kW of wind capacity. A 4 kWh battery system was sized to provide autonomy during approximately six hours of typical consumption.

The combined renewable generation across the three sources yields a total annual production of approximately 29 MWh. The system purchases 832 kWh from the grid to cover shortfalls and exports 23,725 kWh, generating revenue from surplus energy. Over the course of the year, the battery is charged with 266 kWh and discharges 251 kWh, helping to smooth daily fluctuations between generation and consumption.

From a financial perspective, this configuration results in a Net Present Value (NPV) of €15,060, an Internal Rate of Return (IRR) of 14%, a Payback Period (PBP) of 6.65 years, and a Levelized Cost of Energy (LCOE) of €0.04/kWh, indicating strong economic viability for a single household deployment under these conditions.

Additionally, this scenario served as the reference case for analyzing the individual performance of each energy source. A system relying solely on hydropower demonstrated a slightly shorter payback period of 6.06 years, a higher IRR of 15.53%, and a NPV of €14,675, but its LCOE was slightly higher at €0.044/kWh compared to the hybrid configuration. On the other hand, if solar PV or wind power were used

independently, their respective LCOEs would be significantly higher—€0.22/kWh for solar and €0.28/kWh for wind—making them less competitive than even purchasing electricity from the grid.
However, when these sources are combined in a hybrid system that shares a common battery, the overall system benefits from cost synergies, reduced intermittency, and greater grid independence. This integration allows the hybrid system to achieve a lower LCOE than grid electricity, highlighting the value of combining generation sources in a coordinated design.

Scenario 2 – 8 Households (48,782 KWh per year)

Scaling up to eight households with a combined annual demand of 48,782 kWh, the optimal capacities are 14.44 kW solar PV and 9.87 kW wind, while hydropower remains fixed. This requires approximately 65 m² of PV surface area, averaging 8.12 m² per household.

Total renewable generation reaches 57,341 kWh, with grid imports at 7,041 kWh and exports of 15,130 kWh. Battery cycling involves 4,472 kWh charged and 445 kWh discharged. The financial metrics show an NPV of €35,359, a payback period of 8.7 years, an IRR of 9%, and an LCOE of €0.09/kWh. Limiting rooftop PV area to a conservative 6 m² per unit (compared to an available 12 m²) results in a slight decrease in NPV to €34,856 and a shift in generation mix to 10.67 kW solar and 11.33 kW wind capacity.

Scenario 3 – 1 House + Restaurant + Church (28,411 KWh per year)

This scenario includes a household, a restaurant, and a church, with combined annual consumption of 28,411 kWh. The optimized system incorporates 12.03 kW solar PV and 1.98 kW wind, producing about 44,182 kWh per year. The system exports 2,404 kWh and imports 17,883 kWh from the grid, with battery charges totaling 2,679 kWh and discharges of 2,638 kWh annually.
Economically, it shows a strong performance with an NPV of €38,860, payback of 7.03 years, IRR of 13%, and an LCOE of €0.07/kWh.
When PV surface is restricted to 6 m² for the house and restaurant only (excluding the church), capacities adjust to 2.67 kW solar and 4.98 kW wind, reducing annual production to roughly 37 MWh. Grid imports increase to 4,081 kWh, and exports drop to 12,416 kWh, resulting in an NPV of €31,763 and a payback period of 6.86 years.

Scenario 4 – 1 House + Church (12,087 KWh per year)

In this scenario, the system is designed to supply electricity to a combined load from a single household and a church, totaling 12,087 kWh of annual consumption. The optimal configuration includes 3.37 kW of solar PV and 0.96 kW of wind capacity, while hydropower remains fixed as in previous cases. This hybrid system achieves a total annual renewable generation of 32,590 kWh.
Thanks to this generation, the system exports 21,908 kWh to the grid, generating additional revenue, and only needs to import 1,523 kWh to cover shortfalls. The battery is charged with 1,088 kWh and discharges 1,065 kWh throughout the year, supporting the system during times of low renewable production and helping to balance the load.
From an economic standpoint, the configuration results in a Net Present Value (NPV) of €20,183, a Payback Period (PBP) of 6.92 years, an Internal Rate of Return (IRR) of 13%, and a Levelized Cost of Energy (LCOE) of €0.05/kWh, demonstrating strong financial viability under the assumed conditions.
When rooftop space is limited—restricting solar PV surface area to 6 m²—the system must adjust its configuration. In this case, the solar PV capacity is reduced to 1.33 kW, and wind capacity is increased to

1.43 kW to compensate. While total production decreases slightly, the NPV remains high at €19,911, and the LCOE stays nearly identical, confirming the robustness of the hybrid design even under spatial constraints.

Scenario 5 – 1 House + Restaurant (22,422 KWh per year)

This scenario considers a combined load from a household and a restaurant, resulting in an annual energy demand of 22,422 kWh. The optimal hybrid system configuration includes 6.66 kW of solar PV and 1.71 kW of wind capacity, with hydropower remaining constant as in previous scenarios. Under these conditions, the system generates a total of 37,466 kWh per year.

The renewable system exports 16,654 kWh to the grid, and imports only 1,773 kWh, reflecting a high degree of self-sufficiency. Battery activity involves 1,458 kWh charged and 1,429 kWh discharged, supporting energy balancing and reducing grid reliance.

Financially, the system performs well, achieving a Net Present Value (NPV) of €36,065, a Payback Period (PBP) of 6.3 years, an Internal Rate of Return (IRR) of 13%, and a Levelized Cost of Energy (LCOE) of €0.06/kWh, indicating solid economic potential for this type of mixed residential-commercial application.

When limiting rooftop PV area to 6 m^2, the configuration adjusts to 2.67 kW of PV and 2.43 kW of wind, shifting the generation mix. Despite the reduction in solar capacity, the system remains financially attractive, with a slightly lower NPV of €35,167, while maintaining comparable performance metrics.

Portugal's regulatory framework offers substantial advantages for hybrid renewable energy systems:

Subsidies:

- Programa de Apoio a Edifícios Mais Sustentáveis: Up to 85% coverage of solar/battery costs (€2,500 cap per installation)
- Next Generation EU Funds: 40-60% financing for innovative hydro-solar projects

Tax benefits:

- 6% VAT (vs. 23%) on renewable equipment (valid until June 2025)
- Municipal tax deductions (IBI/ICIO) for solar installations

Administrative simplification:

- <3 month licensing for projects <1 MW
- Environmental assessment exemption for retrofits

These instruments significantly reduce upfront investment and shorten payback periods, transforming marginally viable configurations into highly profitable projects across all scenarios.

4.3 Sensitivity Analysis

4.3.1 Electricity Price Variations

To assess the robustness of the proposed hybrid energy systems under market fluctuations, a sensitivity analysis was conducted focusing on variations in electricity purchase and selling prices. Since electricity prices significantly influence key financial metrics such as Net Present Value (NPV) and Payback Period, the analysis tested price changes of ±20%. This evaluation was performed using the reference scenario (Scenario 1: single household), which represents a well-balanced configuration in terms of technical feasibility and economic performance.

Results indicated that decreasing electricity prices by 20% reduced the NPV from €15,060 to €7,790. Conversely, increasing electricity prices by 20% raised the NPV to approximately €22,000.

4.3.2 Discount Rate Variation

Additionally, the sensitivity of the system to changes in the discount rate was analyzed by increasing it from 5% to 7%. This change led to a decrease in the NPV from €15,060 to €9,958, demonstrating the significant effect that discount rate variations can have on the financial viability of the system.

5. Results and Analysis

5.1 Energy Production and Grid Interaction

This chart (**Figure 16**) summarizes the energy performance of each scenario, showing the proportions of energy generated, consumed, exported, and purchased. All systems demonstrate a strong energy surplus, exporting significantly more electricity than they import from the grid. This highlights the effectiveness of the hybrid configurations in achieving energy autonomy and contributing renewable excess to the network.

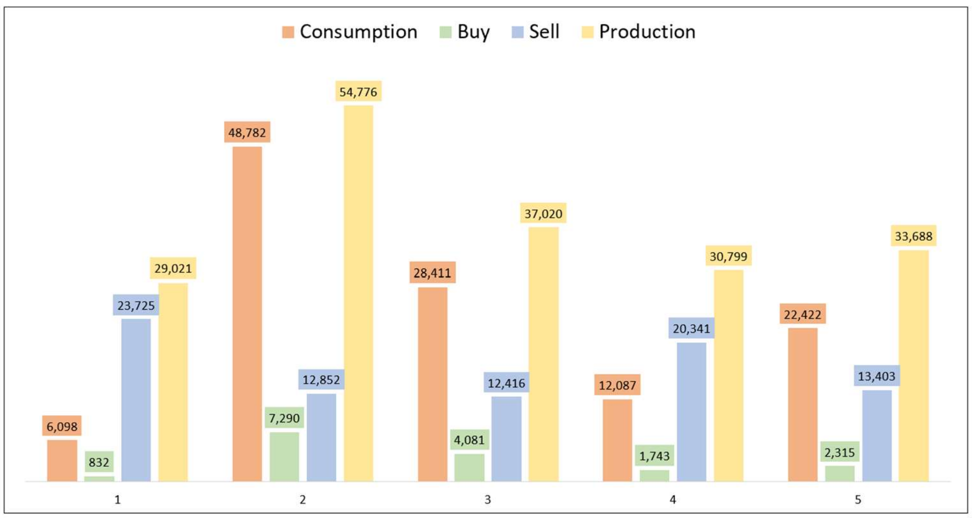


Figure 16. Annual energy balance by scenario: total production, grid exports, purchases, and consumption.

5.2 Financial Comparison Between Scenarios

From a financial standpoint, Scenario 3 (1 household + restaurant + church) offers the highest Net Present Value (€38,860) under optimal conditions, making it the most attractive project configuration when no PV surface restrictions are applied.

However, when limiting PV surface to 6 m² per rooftop (excluding the church in Scenario 3), the situation shifts: Scenario 2 (8 households) becomes the most beneficial, with a strong NPV of €34,856. This shift is largely due to the higher level of collective self-consumption, which enhances the financial returns of shared systems under spatial constraints.

In essence, the more on-site consumption is required, the greater the economic impact of the hybrid renewable system—highlighting the importance of the self-consumption ratio in determining the optimal deployment strategy (**Figure 17**).

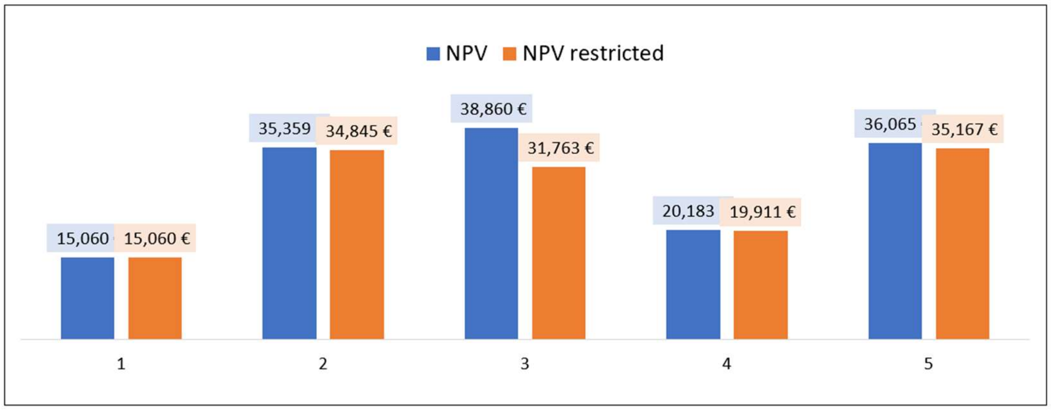


Figure 17. Comparison of Net Present Value (NPV) across scenarios, with and without PV surface limitations.

5.3 LCOE Comparison

The Levelized Cost of Energy (LCOE) assessment reveals significant differences between scenarios, ranging from €0.04/kWh (Scenario 1) to €0.09/kWh (Scenario 2) in unconstrained configurations. Smaller-scale systems (Scenarios 1, 4, and 5) achieve the most competitive LCOE (≤€0.06/kWh), driven by the high contribution of low-cost hydropower (€0.025/kWh) relative to their limited demand. In contrast, collective-demand scenarios (2 and 3) show higher LCOE (€0.07–0.09/kWh) due to greater solar/wind investments, yet remain 65–85% cheaper than grid electricity (€0.26/kWh). PV area restrictions increase LCOE by up to 25% in Scenario 1, while Scenarios 4 and 5 demonstrate resilience by maintaining LCOE through optimal wind compensation. This cost hierarchy confirms hydropower as the economic backbone of the hybrid system, with solar/wind integration proving most advantageous in communities with complementary demand profiles and available space (**Figure 18**).

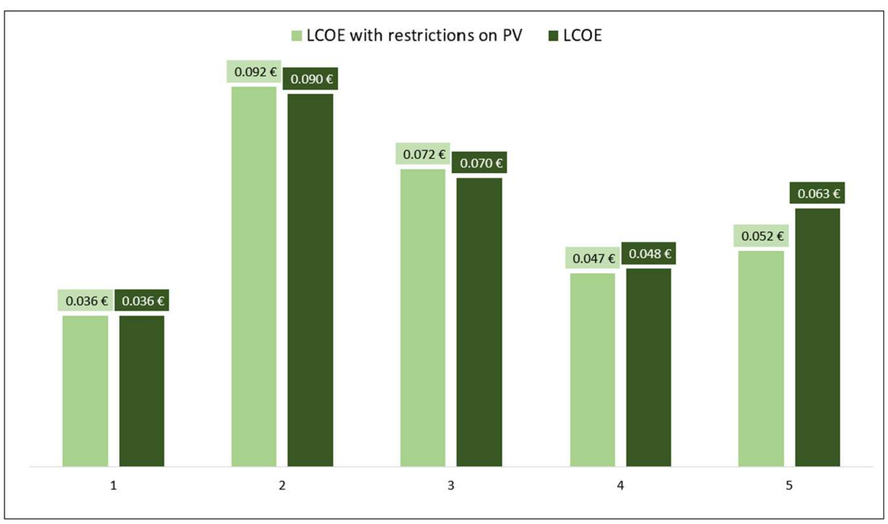


Figure 18. Comparison of Levelized Cost of Energy (LCOE).

5.4 Environmental Performance (CO_2 Savings)

The implementation of these hybrid renewable energy systems substantially reduces CO_2 emissions compared to conventional grid electricity consumption. By displacing fossil-fuel-based generation, each scenario contributes positively to climate change mitigation:

- Annual CO_2 savings correlate closely with total renewable generation, with larger systems naturally achieving higher absolute reductions.
- Scenario 2 achieves the highest emission earnings due to its larger total energy output, while Scenario 1 shows a strong reduction relative to its scale.
- Limiting PV surface area marginally reduces emission savings but still maintains a significant environmental benefit.
- Reduced reliance on grid electricity also decreases transmission losses and grid strain, enhancing overall system sustainability.

These environmental advantages complement the economic benefits, making the proposed hybrid configurations viable solutions for both energy security and ecological responsibility (**Figure 19**).

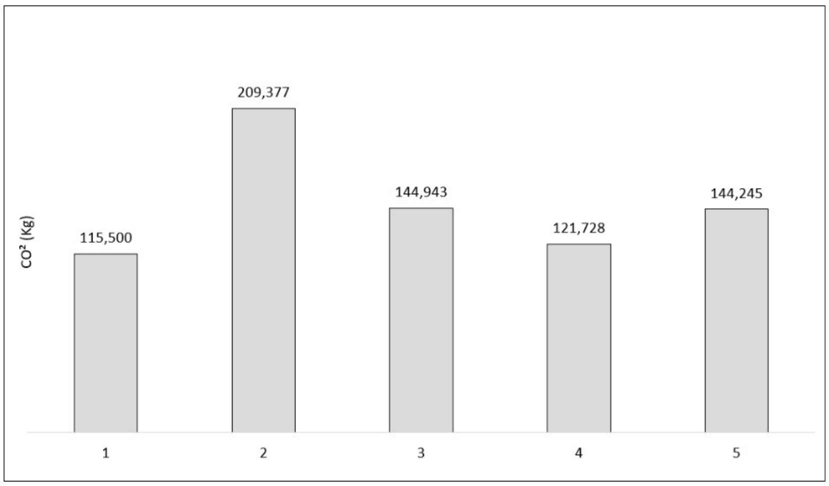


Figure 19. Comparison of CO2 emissions earned per scenario.

5.5 Summary of Key Indicators

The table below consolidates the key technical and financial indicators across all five scenarios, enabling a clear comparison of performance under both optimal and space-constrained conditions. Scenarios 3 and 5 stand out in terms of total energy production and Net Present Value, while Scenario 1 demonstrates exceptional cost-efficiency with the lowest Levelized Cost of Energy. When PV installation is limited, Scenario 2 proves to be the most resilient, maintaining strong returns due to shared demand and high self-consumption. This comparison underscores the importance of tailoring system design to local energy needs, space availability, and consumption profiles to maximize the impact of hybrid renewable systems (**Table 20**).

Table 10. Table comparing all the results of the scenarios with PV restrictions.

Scenarios	1	2	3	4	5
Surface per house	2.78	6.00	6.00	6.00	6.00
PV Surface (4.5 m²/KW)	2.78	48.00	12.00	6.00	12.00
P PV (KW)	0.62	10.67	2.67	1.33	2.67
P Wind (KW)	0.72	11.33	4.98	1.43	2.43
Q Micro-H (m³/s)	0.44	0.44	0.44	0.44	0.44
Flood flow (Mohino) (m³/s)	24	24	24	24	24
Production	29,021	54,776	37,020	30,799	33,688
Consumption	6,098	48,782	28,411	12,087	22,422
Buy	832	7,290	4,081	1,743	2,315
Sell	23,725	12,852	12,416	20,341	13,403
Balance	22,924	5,994	8,609	18,712	11,266
Charge	266	4,100	2,509	1,038	1,609
Discharge	251	4,054	2,472	1,016	1,578
Losses of Ch,Dis	26	408	249	103	159
Check (P-C+B-S)	30	432	274	113	178
NPV	15,060 €	34,845 €	31,763 €	19,911 €	35,167 €
IRP	6.65	8.60	6.86	6.57	5.81
IIRR	14%	10%	13%	14%	0%
LCOE	0.036 €	0.092 €	0.072 €	0.047 €	0.052 €
CO² produced (TOTAL)	-89,584	-2,052	-24,195	-70,358	-48,952
CO² Earned (TOTAL)	115,500	209,377	144,943	121,728	144,245

6. Discussion

Each hybrid system configuration presents unique advantages and challenges that influence its suitability depending on the specific application and constraints:

- **Scenario 1 (Single Household):** Offers high economic viability with the lowest LCOE (€0.04/kWh) and a short payback period. Its compact size and relatively low complexity make it ideal for individual homes. However, its smaller scale limits the benefits of economies of scale and shared infrastructure.
- **Scenario 2 (8 Households):** Benefits from shared resources and economies of scale, improving financial metrics when PV area is limited per unit. This scenario leverages collective self-consumption, which enhances grid independence and reduces peak loads. The main limitation is the need for coordination among multiple households and slightly higher upfront investment.
- **Scenario 3 (House + Restaurant + Church):** The most attractive financially without PV restrictions, due to diverse demand profiles and load complementarities. It maximizes renewable utilization and export potential. Its complexity, involving multiple building types and usage patterns, requires sophisticated management and control systems.
- **Scenario 4 (House + Church):** Balances moderate consumption with optimized renewable capacity, offering good financial returns and environmental benefits. However, its mid-size scale may not fully exploit the advantages of either very small or large systems.
- **Scenario 5 (House + Restaurant):** Delivers high total energy production and competitive financial performance. The higher wind capacity helps diversify generation but may increase system complexity and maintenance needs.

Overall, the hybrid approach enables cost synergies and improved reliability, but system design must carefully consider local demand profiles, spatial constraints, and stakeholder coordination to optimize performance.

7. Conclusions and Recommendations

7.1 Feasibility Summary

The analysis demonstrates that hybrid renewable energy systems combining hydropower, solar PV, and wind generation are technically and economically viable across a range of use cases, from single households to small community clusters. Financial indicators such as positive Net Present Values, reasonable Payback Periods, and competitive Levelized Costs of Energy underline the robustness of these solutions. Furthermore, the systems show resilience to market fluctuations, maintaining positive returns even under conservative assumptions in sensitivity analysis.

It is important to highlight that the economic potential of PV and wind components strongly depends on the level of on-site self-consumption. Higher self-consumption ratios increase the value of generated energy, improving financial returns and enabling larger system sizes, especially under spatial constraints like rooftop area limits. Thus, system design should carefully consider consumption patterns to maximize benefits.

The integration of diverse energy sources within a hybrid system provides enhanced reliability and energy autonomy, while also contributing significantly to CO_2 emission reductions.

Overall, these findings support the deployment of hybrid renewable systems as sustainable, cost-effective alternatives to conventional grid electricity, with strong potential for scalability and adaptability.

In addition to their technical and economic strengths, hybrid renewable systems such as the one proposed for Moinho do Salto also deliver valuable social and cultural benefits. By enabling energy self-sufficiency in a rural community, the project reduces vulnerability to energy insecurity, empowers local stakeholders, and fosters a stronger sense of autonomy.

Furthermore, the rehabilitation of the historical mill site not only preserves local heritage but also creates opportunities for community engagement, education, and sustainable tourism. These intangible benefits reinforce the overall impact of the system, positioning it as a catalyst for both environmental and social sustainability.

7.2 Optimal Scenario Selection

Scenario 3 (1 Household + Restaurant + Church) is identified as the optimal configuration, delivering the highest NPV (€38,860) and significant CO_2 reductions. This design maximizes profitability through high self-consumption ratios and diverse demand profiles, minimizing grid dependence. Crucially, the system's financial performance is amplified by rising electricity prices, as higher tariffs increase savings from self-generated energy and boost revenue from surplus sales. If rooftop space is constrained (≤6 m^2/building), Scenario 2 (8 Households) becomes preferable due to its resilience under spatial limits and collective self-consumption synergies. Both scenarios prove that greater self-consumption and elevated energy prices directly enhance NPV, ensuring robust returns under Portugal's evolving energy market.

7.3 Future Work Suggestions

To advance the implementation of these hybrid systems, the following steps are recommended:

Conduct pilot installations for selected scenarios to validate modeled performance and identify real-world operational challenges.

- Develop detailed design guidelines incorporating local demand profiles, spatial constraints, and stakeholder needs to optimize system sizing and component selection.
- Explore advanced control strategies and energy management systems to maximize self-consumption and grid interaction benefits.
- Investigate financing mechanisms and incentives to improve upfront investment feasibility for end-users.
- Expand environmental impact assessments to include lifecycle analysis and social acceptance factors.
- Consider integration with energy storage innovations and demand response programs to enhance flexibility and resilience.

By following these steps, stakeholders can ensure effective deployment and long-term success of hybrid renewable energy solutions tailored to diverse community needs.

7.4 Final Reflections

This project highlights how tailored hybrid systems can serve as more than just energy solutions — they can act as vehicles for rural revitalization, environmental stewardship, and energy democracy. By combining robust technical design with social engagement and cultural preservation, the proposed system for Moinho do Salto exemplifies a holistic model for sustainable development. As energy transitions accelerate across Europe and the world, small-scale, community-based hybrid systems like this one will play a pivotal role in decentralizing energy production, empowering local actors, and creating resilient, low-carbon futures. Embracing such models is not only a technical choice — it is a strategic, ethical, and generational decision.

List of Figures

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References

Castro, R. (2023). Renewable electricity production through hydro, solar PV, and wind: technical principles, economic assessment, and system integration challenges. *Electricity Production from Renewables*, pp. 1–26, 105–121, 125–173, 181–229, 239–266, 321–343.

Aneke, M., & Wang, M. (2016). Energy storage technologies and real life applications ‑ A state of the art review. Applied Energy, Volume 179, pages 350-377.

Zakeri, B., & Syri, S. (2015). *Electrical energy storage systems: A comparative life cycle cost analysis.* Renewable and Sustainable Energy Reviews, *42*, 569–596.

Ekren, O., & Ekren, B. Y. (2010).
Size optimization of a PV/wind hybrid energy conversion system with battery storage using response surface methodology.
Renewable Energy, *35*(6), 128–132.
https://doi.org/10.1016/j.renene.2010.01.003

Luna-Rubio, R., Trejo-Perea, M., Vargas-Vázquez, D., & Ríos-Moreno, G. J. (2012).
Optimal sizing of renewable hybrids energy systems: A review of methodologies.
Solar Energy, *86*(4), 1077–1088.
https://doi.org/10.1016/j.solener.2011.10.016

Shaahid, S. M., & Elhadidy, M. A. (2008).
Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development.
Renewable and Sustainable Energy Reviews, *13*(3), 625–633.
https://doi.org/10.1016/j.rser.2007.11.001

Ghimire, P. C. et al. (2022). Hybrid renewable energy systems for rural communities: A review. **Renewable Energy, 189**, 1063-1080.

Kaundinya, D. P. et al. (2020). Economic viability of hybrid hydro-PV systems in Portugal. **Energy Policy, 144**, 111680.

Esteves, T. et al. (2023). Renewable energy in heritage mills: Technical constraints and opportunities. **Energy Conversion and Management, 278**, 116734.

Quotations:

- https://54energy.net/products/1kw-2kw-3kw-3-blades-free-energy-vertical-axis-wind-turbine-generator-12v-24v-48v-for-homeuse-low-rpm-windmill
- https://www.ebay.com/itm/375390130973?chn=ps&norover=1&mkevt=1&mkrid=711-167022-160074-

6&mkcid=2&itemid=375390130973&targetid=549379980172&device=c&mktype=pla&googleloc=1011742&poi=&campaignid=22246408200&mkgroupid=178836614287&rlsatarget=pla-549379980172&abcId=&merchantid=5442712991&gad_source=1&gad_campaignid=22246408200&gbraid=0AAAAAD_QDh9xLnaTVDtoihyjZlTtH_d8L&gclid=CjwKCAjw3f_BBhAPEiwAaA3K5Jrrx1BqvG8u5TVnGLT7-YHOxnmFYwhoKbHDAHI97wJNvto9qun9LhoCWQoQAvD_BwE

- http://ehoreka.pt/p/cozinha/turbina-de-1212-polegadas-dtm-1212-6m34-clima-hosteleria
- chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.repic.ch/wp-content/uploads/2020/07/Civil-works-for-micro-hydro-power-units.pdf
- https://www.redawn.eu/case-study/using-hydropower-supply-family-home-portugal
- https://ecofener.com/baterias-de-litio-para-sistemas-solares/1783-bateria-solar-de-litio-byd-b-box-premium-lvs-80-de-48v-y-8kwh.html?utm_source=chatgpt.com
- https://www.shelly.com/collections/all-products
- https://www.dgeg.gov.pt/
- https://www.bobvila.com/articles/home-wind-turbine-cost/?utm_source=chatgpt.com
- https://swimhome.es/es/cuadro-electrico-con-proteccion-fotovoltaica/cuadro-proteccion-ccca-4kw-4019.html?utm_source=chatgpt.com
- https://eur.vevor.com/solar-power-parts-accessories-c_13424/vevor-100ft-solar-panel-extension-wire-female-male-connectors-10awg-set-of-2-p_010528023930
- https://pt.aliexpress.com/item/1005005605327786.html?pdp_npi=4%40dis%21EUR%21295.31%21257.54%21%21%21%21%21%40%2112000033723668702%21ppc%21%21%21&utm_source=chatgpt.com
- https://www.amazon.es/dp/B08M923DZL?shipTo=PT&source=ps-sl-shoppingads-lpcontext&ref_=fplfs&language=pt_PT&utm_source=chatgpt.com&th=1
- https://www.worten.pt/produtos/controlador-do-sistema-hibrido-eolico-voltagem-de-48v-2000w-de-energia-eolica-12v-24v-auto-1500w-vento-800w-solar-oem-mrkean-6152329756718?utm_source=chatgpt.com
- https://54energy.net/products/1kw-2kw-3kw-3-blades-free-energy-vertical-axis-wind-turbine-generator-12v-24v-48v-for-homeuse-low-rpm-windmill
- https://adajusa.com/es/cuadros-de-mando-y-proteccion-ya-cableados/17066-cuadro-de-proteccion-eco-ac-1pnx16a-toscano-8445340170662.html?utm_source=chatgpt.com
- https://eur.vevor.com/solar-power-parts-accessories-c_13424/vevor-30ft-solar-panel-extension-wire-with-female-male-connectors-10awg-1-pair-p_010438829710?lang=pt&currency=eur&adp=gmc&country=PT&utm_source=chatgpt.com
- https://eur.vevor.com/solar-power-parts-accessories-c_13424/vevor-50-inch-solar-panel-mount-brackets-0-90-adjustable-tilt-mount-brackets-

p_010987571953?lang=pt&currency=eur&adp=gmc&country=PT&utm_source=chatgpt.co m

- https://www.kuantokusta.pt/p/11444136/growatt-inversor-monofasico-growatt-mic-1000tl-x?utm_source=chatgpt.com
- https://store.solarcellzusa.com/Canadian-Solar-BiHiKu-CS3W-455MB-AG-PALLET-27-455Watt-144-1-2-Cells-Bifacial-Clear-Monocrystalline-3
- chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.erse.pt/media/qjkdc24l/boletim-eletricidade-eurostat_2024s1.pdf?utm_source=chatgpt.com
- https://www.meoenergia.pt/energia-solar/venda-excedente?utm_source=chatgpt.com
- chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://iea-etsap.org/E-TechDS/PDF/E06-hydropower-GS-gct_ADfina_gs.pdf?utm_source=chatgpt.com

Appendix

Table A1. Financial/Economic analysis Scenario 2 (without restrictions)

												All sources - 2nd scenario	
Concept	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Investment Hydro	- 9,700 €												
Investment Solar (1 kW)	- 23,820 €												
Investment Wind (2 kW)	- 21,574 €												
Batteries	- 18,695 €												- 18,695 €
O&M Hydro		- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar		- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €
O&M Wind		- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €
O&M Batteries		- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €
Electricity Purchase		- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €
Electricity Sales		908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €
Energy Earned		10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €
Total	**- 73,789 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**- 10,212 €**
Cash Flow Acumulated	- 73,789 €	- 65,306 €	- 56,823 €	- 48,340 €	- 39,857 €	- 31,374 €	- 22,891 €	- 14,408 €	- 5,926 €	2,557 €	11,040 €	19,523 €	28,006 €
K	100%	95%	91%	86%	82%	78%	75%	71%	68%	64%	61%	58%	56%
CashFlow modificated	- 73,789 €	8,079 €	7,694 €	7,328 €	6,979 €	6,647 €	6,330 €	6,029 €	5,742 €	5,468 €	5,208 €	4,960 €	- 5,687 €
MPV Acumulated	- 73,789 €	- 65,710 €	- 58,016 €	- 50,688 €	- 43,709 €	- 37,062 €	- 30,732 €	- 24,704 €	- 18,962 €	- 13,494 €	- 8,286 €	- 3,326 €	- 9,013 €
NPV	35,359 €												
IRP	8.70	years											
IIRR	9.50%												
LCOE	0.090 €												
CO² Emisions (yearly)	-375	Kg											

Concept	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Investment Hydro													
Investment Solar (1 kW)													
Investment Wind (2 kW)													
Batteries													
O&M Hydro	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €	- 357 €
O&M Wind	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €	- 539 €
O&M Batteries	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €	- 280 €
Electricity Purchase	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €	- 1,835 €
Electricity Sales	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €	908 €
Energy Earned	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €	10,878 €
Total	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**	**8,483 €**
Cash Flow Acumulated	36,489 €	44,972 €	53,455 €	61,938 €	70,421 €	78,904 €	87,386 €	95,869 €	104,352 €	112,835 €	121,318 €	129,801 €	138,284 €
K	53%	51%	48%	46%	44%	42%	40%	38%	36%	34%	33%	31%	30%
CashFlow modificated	4,499 €	4,284 €	4,080 €	3,886 €	3,701 €	3,525 €	3,357 €	3,197 €	3,045 €	2,900 €	2,762 €	2,630 €	2,505 €
MPV Acumulated	- 4,514 €	- 230 €	3,851 €	7,737 €	11,438 €	14,963 €	18,320 €	21,517 €	24,562 €	27,462 €	30,223 €	32,854 €	35,359 €

Table A2. Financial/Economic analysis Scenario 3 (without restrictions)

All sources - 3rd scenario

Concept	0	1	2	3	4	5	6	7	8	9	10	11	12
Investment Hydro	- 9,700 €												
Investment Solar (1 kW)	- 19,845 €												
Investment Wind (2 kW)	- 4,333 €												
Batteries	- 10,888 €												- 10,888 €
O&M Hydro		- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar		- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €
O&M Wind		- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €
O&M Batteries		- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €
Electricity Purchase		- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €
Electricity Sales		1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €
Energy Earned		6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €
Total	**- 44,766 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**- 4,524 €**

	0	1	2	3	4	5	6	7	8	9	10	11	12
Cash Flow Acumulated	- 44,766 €	- 38,403 €	- 32,039 €	- 25,675 €	- 19,312 €	- 12,948 €	- 6,584 €	- 220 €	6,143 €	12,507 €	18,871 €	25,234 €	31,598 €
K	100%	95%	91%	86%	82%	78%	75%	71%	68%	64%	61%	58%	56%
CashFlow modificated	- 44,766 €	6,061 €	5,772 €	5,497 €	5,235 €	4,986 €	4,749 €	4,523 €	4,307 €	4,102 €	3,907 €	3,721 €	- 2,519 €
MPV Acumulated	- 44,766 €	- 38,706 €	- 32,934 €	- 27,436 €	- 22,201 €	- 17,215 €	- 12,466 €	- 7,944 €	- 3,636 €	466 €	4,372 €	8,093 €	5,574 €
NPV	38,860 €												
IRP	7.03	years											
IIRR	12.78%												
LCOE	0.070 €												
CO² Emisions (yearly)	-1,834	Kg											

Concept	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment Hydro													
Investment Solar (1 kW)													
Investment Wind (2 kW)													
Batteries													
O&M Hydro	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €	- 298 €
O&M Wind	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €	- 108 €
O&M Batteries	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €	- 163 €
Electricity Purchase	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €	- 626 €
Electricity Sales	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €	1,073 €
Energy Earned	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €	6,777 €
Total	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**	**6,364 €**

	13	14	15	16	17	18	19	20	21	22	23	24	25
Cash Flow Acumulated	37,962 €	44,326 €	50,689 €	57,053 €	63,417 €	69,780 €	76,144 €	82,508 €	88,871 €	95,235 €	101,599 €	107,963 €	114,326 €
K	53%	51%	48%	46%	44%	42%	40%	38%	36%	34%	33%	31%	30%
CashFlow modificated	3,375 €	3,214 €	3,061 €	2,915 €	2,776 €	2,644 €	2,518 €	2,398 €	2,284 €	2,175 €	2,072 €	1,973 €	1,879 €
MPV Acumulated	8,949 €	12,163 €	15,224 €	18,139 €	20,916 €	23,560 €	26,078 €	28,477 €	30,761 €	32,936 €	35,008 €	36,981 €	38,860 €

Table A3. Financial/Economic analysis Scenario 4 (without restrictions)

All sources - 4th scenario

Concept	0	1	2	3	4	5	6	7	8	9	10	11	12
Investment Hydro	- 9,700 €												
Investment Solar (1 kW)	- 5,556 €												
Investment Wind (2 kW)	- 2,093 €												
Batteries	- 4,632 €												- 4,632 €
O&M Hydro		- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar		- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €
O&M Wind		- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €
O&M Batteries		- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €
Electricity Purchase		- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €
Electricity Sales		1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €
Energy Earned		2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €
Total	**- 21,981 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**- 1,458 €**

	0	1	2	3	4	5	6	7	8	9	10	11	12
Cash Flow Acumulated	- 21,981 €	- 18,807 €	- 15,632 €	- 12,457 €	- 9,283 €	- 6,108 €	- 2,933 €	241 €	3,416 €	6,591 €	9,765 €	12,940 €	16,115 €
K	100%	95%	91%	86%	82%	78%	75%	71%	68%	64%	61%	58%	56%
CashFlow modificated	- 21,981 €	3,023 €	2,880 €	2,742 €	2,612 €	2,487 €	2,369 €	2,256 €	2,149 €	2,046 €	1,949 €	1,856 €	- 812 €
MPV Acumulated	- 21,981 €	- 18,958 €	- 16,078 €	- 13,336 €	- 10,724 €	- 8,237 €	- 5,868 €	- 3,611 €	- 1,463 €	584 €	2,533 €	4,389 €	3,577 €
NPV	20,183 €												
IRP	6.92	years											
IIRR	13%												
LCOE	0.048 €												
CO² Emisions (yearly)	-3,040	Kg											

Concept	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment Hydro													
Investment Solar (1 kW)													
Investment Wind (2 kW)													
Batteries													
O&M Hydro	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €	- 83 €
O&M Wind	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €	- 52 €
O&M Batteries	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €	- 69 €
Electricity Purchase	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €	- 397 €
Electricity Sales	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €	1,314 €
Energy Earned	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €	2,753 €
Total	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**	**3,175 €**

	13	14	15	16	17	18	19	20	21	22	23	24	25
Cash Flow Acumulated	19,289 €	22,464 €	25,639 €	28,813 €	31,988 €	35,163 €	38,337 €	41,512 €	44,687 €	47,861 €	51,036 €	54,211 €	57,385 €
K	53%	51%	48%	46%	44%	42%	40%	38%	36%	34%	33%	31%	30%
CashFlow modificated	1,684 €	1,603 €	1,527 €	1,454 €	1,385 €	1,319 €	1,256 €	1,196 €	1,140 €	1,085 €	1,034 €	984 €	937 €
MPV Acumulated	5,261 €	6,864 €	8,391 €	9,846 €	11,231 €	12,550 €	13,806 €	15,003 €	16,142 €	17,227 €	18,261 €	19,245 €	20,183 €

Table A4. Financial/Economic analysis Scenario 5 (without restrictions)

All sources - 5th scenario

Concept	0	1	2	3	4	5	6	7	8	9	10	11	12
Investment Hydro	- 9,700 €												
Investment Solar (1 kW)	- 10,990 €												
Investment Wind (2 kW)	- 3,728 €												
Batteries	- 8,593 €												- 8,593 €
O&M Hydro		- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
O&M Solar		- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €
O&M Wind		- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €
O&M Batteries		- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €
Electricity Purchase		- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €
Electricity Sales		999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €
Energy Earned		5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €
Total	**- 33,010 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**- 3,352 €**

13	14	15	16	17	18	19	20	21	22	23	24	25
- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €	- 291 €
- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €	- 165 €
- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €	- 93 €
- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €	- 129 €
- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €	- 462 €
999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €	999 €
5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €	5,381 €
5,241 €	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**	**5,241 €**