

## Article

# Strategic Modeling of Hybrid Smart Micro Energy Communities: A Decision-Oriented Approach

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## Abstract

Hybrid renewable energy systems are increasingly important for enabling sustainable and resilient energy supply in rural smart communities, yet existing tools often lack the ability to integrate environmental variability, multi-technology interactions, and economic-environmental assessment in a unified framework. This study presents Hybrid Smart Micro Energy Community (HySMEC), a novel modeling approach that combines high-resolution meteorological data, technology-specific generation models, detailed demand characterization, and financial analysis to evaluate hybrid configurations of hydropower, solar PV, wind, battery storage, and grid interaction. Hourly simulations capture seasonal dynamics and system behavior under realistic technical efficiencies, investment costs, and emission factors, enabling a transparent assessment of energy flows, self-consumption, and grid dependence. The results show that hybrid systems can achieve competitive economic performance, low Levelized Costs of Energy, and significant CO<sub>2</sub> emission reductions across diverse rural community profiles, even when space or demand constraints are present. The analysis confirms the technical feasibility and environmental benefits of integrating multiple renewable sources with storage, highlighting the importance of self-consumption ratios in improving system profitability. Overall, HySMEC provides a robust and scalable tool to support data-driven design and optimization of distributed energy systems, offering valuable insights for researchers, planners, and decision-makers involved in sustainable rural energy development.



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**Keywords:** strategic modelling; hybrid renewable energy solutions; smart micro energy communities; decision-oriented approach

## 1. Introduction

Regarding optimization and decision-making frameworks, ref. [1] developed smart, integrated, hybrid renewable energy systems for small energy communities and applied them to a real case study to achieve energy self-sufficiency and promote sustainable, decentralized energy generation. Stand-alone (SA) and grid-connected (GC) configurations are compared using an optimized mathematical model and data-driven optimization, complemented by an economic assessment of various renewable combinations (PV, wind, PHS,

BESS, and grid) to identify the optimal solution. Ref. [2] presented a study focused on selecting the optimal configuration of a hybrid renewable energy microgrid (MG) for a village in India. The MG includes solar photovoltaic (PV) modules, a wind turbine generator, a biomass generator, a diesel generator, a battery bank, and an electric vehicle. The optimal model is selected based on technical, economic, environmental, social, and reliability criteria. A novel spoonbill swarm optimization algorithm is proposed to determine the most suitable hybrid MG system, and its performance is compared with particle swarm optimization, a genetic algorithm, and the grasshopper optimization algorithm.

In [3], a modular decision-making framework for impeller optimization is introduced, incorporating design objectives, simulation constraints, and the physical characteristics of turbomachinery. The study in [4] aims to review several types of projects implemented in different micro-communities, specifically small islands and remote villages, considering both real implementations and evaluation-only studies. Documented projects in micro-communities with fewer than 100,000 inhabitants were analyzed, examining indicators related to island characterization, energy demand, and proposed technical solutions, to identify the key factors influencing successful implementation and understanding how these factors differ between islands and remote villages. Finally, ref. [5] proposes a smart hybrid renewable energy system for communities (SHREC), which accounts for both the thermal and electricity markets. A more efficient modeling and optimization method for SHREC is developed, emphasizing the usefulness of day-ahead modeling and optimization for system operation. The approach promotes the integration of renewable energy and energy storage to enhance overall efficiency. The global transition toward decentralized and sustainable energy systems has catalyzed the emergence of Hybrid Smart Micro Energy Communities (HySMECs)—localized networks that integrate diverse energy sources, intelligent control systems, and participatory governance. These communities are increasingly recognized as pivotal nodes in achieving energy resilience, carbon neutrality, and equitable access, particularly in remote or resource-constrained regions. The accelerating shift toward decentralized and low-carbon energy systems has positioned smart micro energy communities (SMECs) as critical building blocks in the pursuit of resilient and sustainable energy futures. These localized networks can integrate diverse energy sources, digital control technologies, and community-driven governance to deliver reliable, efficient, and context-sensitive energy solutions. Their capacity to adapt to dynamic environmental, economic, and social conditions makes them particularly suited for rural, islanded, or disaster-prone regions.

Moreover, other barriers include customers' unwillingness to alter their consumption habits, particularly if they are not involved in the changing process of the energy system [6], the complexity in monitoring and controlling the new energy system, and cost issues due to new technological components [7]. Governance model formalization to empower EC members includes the implementation of RECs [8] as well as the modeling and optimization of RECs using Matlab, developing an algorithm for the operation of cells coupled to RESs [9]. Ref. [10] analyzes energy-sharing directives—energy, environmental, and economic analyses—as well as the comparison of efficient users' systems and conventional single users. Ref. [11] suggests applying the actor-network theory approach. Another study focuses on optimizing RECs to account for economic and environmental factors [12]. A new development of an energy management system (EMS), includes optimization, and sensitivity analysis, and ref. [13] analyzed the energy self-consumption in RECs, developing a mathematical model for multi-criteria decision-making methods. Ref. [14] created an economic assessment with an investigation of the feasibility of a hydrogen power-to-gas system inside a REC. Ref. [15] presents an optimization of the open-loop control problem using a receding-horizon approach and evaluates the performance of algorithms applied to

REC control problems. In [16], a technoeconomic analysis is developed for a real case study involving collective self-consumption and a smart battery management system (BMS), incorporating an optimal BMS strategy based on perfect forecasts. Energy storage system (ESS) technologies are generally categorized into six primary groups: mechanical, thermal, chemical, electrochemical, electrical, and other types such as hybrid energy storage systems [17,18]. Based on their response characteristics, ESSs may also be classified into three main temporal categories. Short-term storage systems, operating over seconds to minutes, are primarily employed to enhance power quality. Medium-term systems, with durations ranging from minutes to hours, help alleviate grid congestion and provide frequency regulation. Long-term systems, spanning hours to days, are used to balance supply and demand over extended periods [19]. A more detailed subclassification of ESS technologies is provided in [20]. A critical component of energy communities (ECs) is the integration of energy storage units, which play a fundamental role in maintaining equilibrium between energy supply and demand, particularly during the operation of distributed generators (DGs). The intermittent nature of most renewable energy sources (RESs) poses a significant challenge to the stability and reliability of power networks. To mitigate these issues, extensive research has examined various strategies, including electrical energy storage (EES), demand-side management, and interconnection with external grids. Among these options, EES has emerged as a particularly promising solution [21]. In the current economic context, batteries are considered a cost-effective option, although they exhibit relatively higher environmental impacts compared to other storage technologies [22]. Energy sharing within renewable energy communities involves the cooperative distribution and utilization of locally generated distributed renewable energy (DRE). In cases of surplus generation, participants redistribute excess energy among themselves, fostering a decentralized and sustainable energy paradigm [23]. This practice transforms individual consumers into prosumers, enabling them to contribute surplus energy to the community. Community-level energy planning offers enhanced opportunities to tailor energy systems to local conditions and specific constraints, thereby improving efficiency and promoting the sustainable use of RESs [24]. Energy sharing mechanisms may include community micro-grids, peer-to-peer energy trading platforms [25–27], and collective energy storage initiatives. These approaches aim to optimize RES utilization, strengthen community engagement, enhance energy resilience, and support self-sufficiency in sustainable energy practices.

There are main gaps identified in the literature, namely the lack of integrated, transparent, and data-driven modeling frameworks that combine hourly environmental variability, multi-technology interactions, and joint techno-economic–environmental assessment within a single methodology as developed in HySMEC. A central challenge in HySMEC design lies in the optimization of hybrid energy configurations, which typically combine renewable sources (e.g., solar, wind, hydro) with conventional or storage-based systems in an old heritage mill. The heterogeneity of energy profiles, load demands, and environmental conditions necessitates robust frameworks for resource allocation, system sizing, and operational scheduling. Moreover, the integration of smart technologies, including digital twin and IoT, enables monitoring, predictive analytics, and adaptive control, allowing dynamic response to fluctuating supply and demand, enhancing overall system efficiency. Hence, this study presents a comprehensive framework for the design and optimization of hybrid energy systems in smart micro energy communities, emphasizing the role of intelligent configurations and data-driven decision support. By integrating simulation, modeling, and stakeholder-informed criteria, the proposed approach aims to develop reproducible and scalable methodologies for next-generation energy planning.

## 2. Materials and Methods

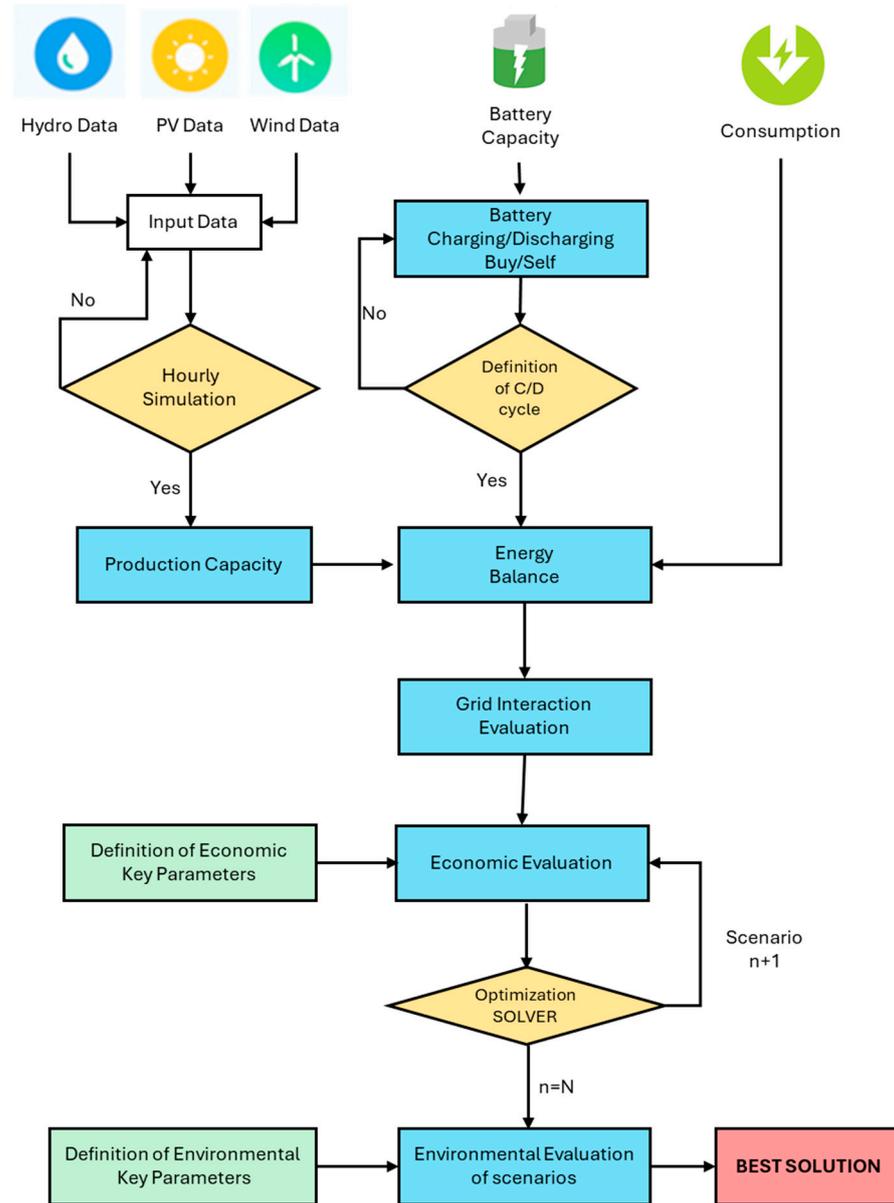
### 2.1. Brief Description

The methodology is developed to evaluate the technical, economic, and environmental feasibility of hybrid renewable energy systems tailored to a specific Hybrid Smart Micro Energy Community (HySMEC). The proposed methodology integrates the collection of technical and environmental data, energy generation modeling, demand estimation, and comprehensive financial analysis. By combining hourly simulations with system optimization techniques, the approach seeks to identify the most appropriate system configurations under varying consumption patterns and operational constraints.

The methodology begins with the acquisition of environmental and meteorological data from open-access sources, such as Open-Meteo, which are used to estimate hydrological flow availability, solar irradiance, and wind speed profiles. These inputs are processed on an hourly basis to simulate the potential energy production of micro-hydropower systems, photovoltaic (PV) arrays, and small wind turbines, applying established performance models and technology-specific assumptions. In parallel, four distinct hourly electricity demand scenarios are developed to represent different consumption profiles of nearby residential, commercial, and institutional buildings. For each scenario, a detailed annual hourly energy balance is calculated by comparing electricity generation and demand. This analysis identifies periods of energy surplus and deficit, which subsequently determine the operational behavior of the battery storage system, including charging, discharging, and interactions with the electricity grid through imports and exports. The methodology illustrated in Figure 1 outlines a structured, multi-criteria framework for evaluating and optimizing hybrid energy systems in small communities. It begins with the collection of input data—typically hourly environmental and demand profiles—which feed into a simulation module that models energy production from hydropower, solar, and wind sources. In parallel, the system simulates battery charging and discharging behavior, including buy/sell interactions with the grid, and defines the control logic for charge/discharge cycles. These simulations converge in an energy balance module that integrates generation, storage, and consumption dynamics. Following this, the methodology evaluates grid interactions and defines key economic parameters such as investment costs, electricity prices, and financial indicators. These feed into an economic evaluation module that calculates metrics like Net Present Value (NPV). The system then enters an optimization phase, where a solver adjusts PV and wind capacities to maximize NPV, while hydropower remains fixed due to regulatory constraints. Environmental parameters—such as emission factors—are defined and used to assess the environmental impact of each scenario. The process concludes by identifying the best solution based on technical feasibility, economic performance, and environmental benefit.

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 (PB), 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 water availability and low LCOE after finding the optimal configuration for each scenario.



**Figure 1.** Flow chart of the methodology developed for HySMEC model: general integration and resource optimization.

Finally, a comparison between models is performed to evaluate the robustness of the proposed model and 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, where the full process is summarized in Figure 1.

2.2. Parameters Characterization

For Hydropower Generation the power is calculated as follows:

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

where P is the hydraulic power output in W; ρ is the water density, considering 1000 kg/m<sup>3</sup>; g is the gravitational acceleration, considering 9.81 m/s<sup>2</sup>; Q is the flow rate in m<sup>3</sup>/s; H is the net head in mwc; and η is the overall system efficiency, which is dimensionless.

The Solar PV Output is calculated by

$$EPV = G_{\text{tilted}} \cdot PPV \cdot PRE \quad (2)$$

where EPV is the daily energy output in kWh;  $G_{\text{tilted}}$  is the daily global tilted irradiation in kWh/m<sup>2</sup>; PPV is the installed PV capacity in kW; and PRE is the performance ratio, considering typically 0.75.

The wind turbine yield is modeled by

$$P_{\text{wind}} = PW \cdot \frac{1}{2} \cdot \rho_{\text{air}} \cdot A \cdot v^3 \cdot C_p \cdot \eta \quad (3)$$

where  $P_{\text{wind}}$  is the instantaneous wind power output in W;  $\rho_{\text{air}}$  is the air density, considering 1.225 kg/m<sup>3</sup>; PW is the installed capacity in kW; A is the swept area of the turbine in m<sup>2</sup>; v is the wind speed in m/s;  $C_p$  is the power coefficient, considering typically 0.3–0.4; and  $\eta$  is the system efficiency, considering electrical/mechanical losses.

The Battery Storage Dynamics includes the State of Charge (SoC) update defined by

$$\text{SoC}_t = \text{SoC}_{t-1} + \left( \frac{E_{\text{charge}} \cdot \eta_{\text{charge}}}{C_{\text{bat}}} \right) - \left( \frac{E_{\text{discharge}}}{\eta_{\text{discharge}} \cdot C_{\text{bat}}} \right) \quad (4)$$

where  $\text{SoC}_t$  is the battery State of Charge at time t;  $C_{\text{bat}}$  is the battery capacity in kWh;  $\eta_{\text{discharge}}$  is the charge/discharge efficiency, considering typically 0.95; and  $E_{\text{charge}}$  or  $E_{\text{discharge}}$  is the energy charged/discharged in kWh.

Another important key performance indicator is the Levelized Cost of Energy (LCOE):

$$\text{LCOE} = \frac{\sum_{t=0}^n \frac{I_t + O_t + M_t}{(1+r)^t}}{\sum_{t=0}^n \frac{E_t}{(1+r)^t}} \quad (5)$$

where  $I_t$  is investment cost in € in year t;  $O_t$  is the operational cost in € in year t;  $M_t$  is the maintenance cost in € in year t;  $E_t$  is the generated energy in kWh in year t; r is the discount rate (adimensional); and n is the project lifetime in years.

The definition of the objective function uses the Net Present Value (NPV), which is defined by

$$\max (NPV) = \max \sum_{t=0}^n \frac{R_t + C_t}{(1+r)^t} \quad (6)$$

where  $R_t$  is the revenue in € in year t;  $C_t$  is the cost in € in year t.

The estimation of the Internal Rate of Return is defined as follows:

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

where IRR is the Internal Rate of Return.

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

### 2.3. Input Parameters and Assumptions

The HySMEC model, designed as a techno-economic–environmental framework, operates based on predefined assumptions and input parameters that reflect the technical characteristics and economic conditions of the study site.

For all simulations, the photovoltaic (PV) system was defined with a surface requirement of 4.5 m<sup>2</sup> per kW installed and an average effective generation period of 6 h per day. The battery storage subsystem was modeled with a charging/discharging efficiency of 95%,

an initial State of Charge (SOC) of 50%, and a minimum SOC threshold of 10% to avoid deep discharge and prolong system lifetime. Emission factors for electricity generation were set at 35 g CO<sub>2</sub>-eq/kWh for PV, 10 g CO<sub>2</sub>-eq/kWh for wind and hydropower, and 170 g CO<sub>2</sub>-eq/kWh for grid electricity, ensuring a consistent environmental assessment across technologies.

From an economic standpoint, a discount rate of 5% was adopted for the financial evaluation. The choice of a 5% discount rate follows common practice in techno-economic assessments of small-scale renewable energy systems. While discount rates can vary depending on market volatility, country-specific financial conditions, and investor risk profiles, values in the range of 4–7% are widely used in the literature for community-scale renewable energy projects and infrastructure with relatively low financial risk. The selected value of 5% therefore, represents a moderate and widely accepted benchmark, neither overly optimistic nor excessively conservative, and is consistent with typical assumptions adopted in comparable studies. Grid electricity purchase and selling prices were assumed to be 0.26 €/kWh and 0.06 €/kWh, respectively. The capital investment costs considered were 9700 € for hydropower (fixed), 1650 €/kW for PV, 2185 €/kW for wind generation, and 560 €/kWh for battery storage capacity [28]. Operation and maintenance expenses were calculated as a percentage of the initial investment: 3% for hydropower, 1.5% for PV and battery storage, and 2.5% for wind technology. These assumptions ensure consistency, comparability, and robustness in the techno-economic and environmental evaluation of the hybrid energy configurations.

These parameters are kept constant across all scenarios. The investment costs reflect average values found in the recent literature and market data for the region, while emission factors are based on life-cycle assessments.

**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<sub>2</sub> 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 Equation (8):

$$\text{Avoided Emissions} = E_{\text{generated}} \times \text{EF} \quad (8)$$

where  $E_{\text{generated}}$  is the annual energy produced by the hybrid system (kWh), and EF is the emission factor of the local electricity grid (kg CO<sub>2</sub>/kWh).

#### 2.4. Optimization Procedure and Analyses

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 in the Solver optimizer; a single-objective optimization was carried out using the Nonlinear Generalized Reduced Gradient (GRG) method, which identifies improved solutions by following local gradient patterns and is therefore sensitive to the initial values of the decision variables, often converging to locally optimal solutions. To mitigate this limitation and enhance solution robustness, the multistart option was employed. The multistart strategy combines the computational efficiency of the GRG algorithm with the global search capability of the Evolutionary (genetic algorithm-based) approach implemented in the Solver. By initiating multiple search trajectories from diverse starting points, this hybrid approach significantly increases the likelihood of identifying a

global or near-global optimum. The population size for the evolutionary component was set to 200 individuals to ensure adequate exploration of the solution space, while no initial seed was specified to preserve randomness and avoid bias. The convergence tolerance was maintained at the default value of 0.0001, providing a suitable balance between solution accuracy and computational efficiency. The hybrid renewable energy system is optimized by adjusting the capacities of solar PV and wind components to maximize the Net Present Value (NPV).

An additional constraint is introduced in an alternative scenario by limiting the rooftop area available for PV installation to 6 m<sup>2</sup> per building, 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. To evaluate the robustness of the proposed solutions under varying market and economic conditions, model comparison is performed. Each result assesses its impact on financial indicators such as NPV, IRR, and LCOE, as well as on the optimal system configuration. This analysis helps to support decision-making.

### 3. Case Study

#### 3.1. System Description

The site features an existing hydraulic infrastructure with a usable head of about 2.8 m, which will be utilized for the development of the renewable energy system. The region, in Sousa River, north of Portugal, is characterized by high water availability throughout the year that feeds an old existing mill, 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, as a small community (Figure 2). 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.



**Figure 2.** Smart Energy Community: (a) Top view showing few households, restaurant and church; (b) view of the available water stream surrounding this community; (c) bridge over the water stream; (d) household with old water mills to replace one by a water-wheel turbine; (e) overlaying of the existent old intake channel, which is out of service, to connect to the water-wheel identical to the old water mill.

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. Although access is limited for large vehicles, it is adequate for light machinery and installation work. Local buildings, such as 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. The existing weir is a traditional stone structure located across the stream, with an estimated length of approximately 22 m. It remains in good condition and effectively diverts water to the old mill through a water intake lateral channel. 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 impacts on river dynamics.

As shown in Figure 2d, 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. The existing 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 m, which is crucial for the implementation of a micro-scale hydropower system within the proposed hybrid renewable energy solution.

### 3.2. Energy Balancing

#### 3.2.1. Procedures

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—(i) 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 the system optimization; (ii) Demand: The fixed daily electricity consumption of the household or additional demands; (iii) Excess Energy: When production exceeds demand, the surplus energy is first stored in the battery (if there is capacity). If the battery is full, the remaining excess is sold to the grid; (iv) 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; (v) Battery State of Charge (SoC): The battery charge level is updated daily, constrained by its maximum and minimum operating limits to prevent degradation; (vi) Grid Transactions—Buy: Energy purchased from the grid during deficit periods after battery depletion; Sell: Energy sold to the grid when there is 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 techno-economic assessment.

#### 3.2.2. Demand Scenarios

To assess the technical viability of the proposed renewable energy system, four different consumption scenarios were defined based on the existing infrastructure and potential energy users in the surrounding area (Figure 1).

The electricity demand scenarios were developed based on site-specific conditions, reflecting the existing infrastructure and realistic patterns of energy use in the surrounding

area. Four distinct consumption scenarios were defined to assess the technical viability of the proposed renewable energy system: (i) Scenario 1—1 Household; (ii) Scenario 2—8 Households; (iii) Scenario 3—1 Household + Restaurant + Church; (iv) Scenario 4—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. 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.

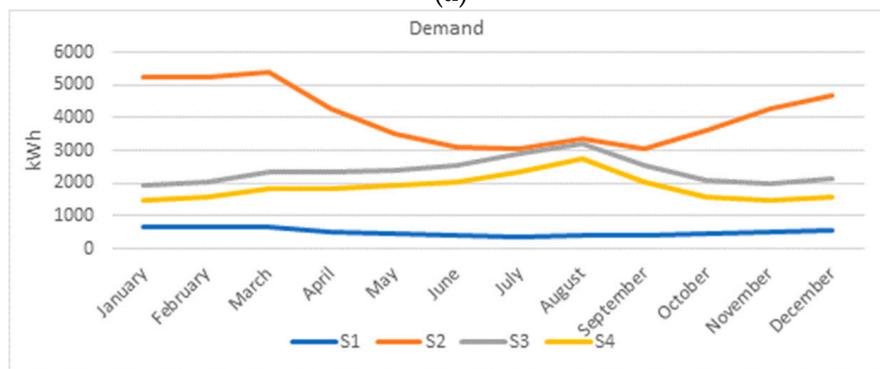
This dual representation enables a better understanding of both temporal usage behavior and cumulative energy needs, helping to identify optimal system sizing and energy balancing strategies under each scenario.

**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 3a, 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 (Figure 3b).

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	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				672	
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	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		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		379	
August	15	16	17	18	17	12	12	12	12	13	13	12	12	14	13	13	14	13	14	14	14	14	13	13	13	13	13	14	12	12	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		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	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	6098	

(a)



(b)

Figure 3. Scenario 1 (a); Evolution of the demand across all scenarios (b).

### Scenario 2—8 Households

With a total annual consumption of 48.8 MWh, this scenario significantly amplifies the residential demand, representing a micro community of eight households. As shown in Figure 3, 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 (Figures 3b and 4).

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	126	108	125	162	213	244	203	185	177	183	190	174	194	195	136	159	179	169	168	126	137	164	175	176	196	184	185	160	166	183	5263	
February	195	217	204	233	226	235	226	225	187	194	154	211	183	153	138	132	152	174	154	153	169	194	201	199	180	178	205	175			5227		
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	5379	
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		4252	
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		3525
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		3123	
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		3031
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		3369
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		3065	
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		3619
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		4266	
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		4662
Total	1642	1600	1551	1635	1675	1669	1681	1682	1606	1643	1625	1683	1634	1603	1529	1486	1520	1554	1508	1506	1503	1539	1592	1607	1575	1587	1643	1679	1502	1521	1004		48,782

Figure 4. Scenario 2.

### 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 3, 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 (Figure 5).

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	90	90	50	53	65	82	116	49	43	48	53	63	81	107	42	47	50	52	66	83	114	45	47	51	1947
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			2014	
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	2352
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		2339
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	2390
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		2520
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	2884
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	3220
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		2566
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	2067
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		1976
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	2137
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

Figure 5. Scenario 3.

### Scenario 4—1 House + Restaurant

The final scenario combines residential and commercial consumption, resulting in a total of 22.4 MWh annually. As shown in Figure 3, 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 (Figure 6).

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	1470
February	54	63	71	67	51	54	55	57	59	60	60	49	48	46	47	52	64	62	42	44	48	54	61	70	63	45	50	49			1553	
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	1851
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		1816
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	1912
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		2025
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	2354
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	2736
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		2026
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	1589
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		1499
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	1591
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

Figure 6. Scenario 4.

### 3.3. Techno-Economic Assessment

#### 3.3.1. Procedures of 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. PV sizing assumed a panel power density of 1 kW per 4.5 m<sup>2</sup>, 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 h 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), and LCOE were calculated. Optimization was performed using the HySMEC model to find the optimal solution.

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

#### 3.3.2. Assumptions and Economic Metrics (LCOE, NPV, IRR, Payback)

This section presents the assumptions for the economic assessment of the four 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, to identify the most financially attractive system layout.

The economic assessment applies a 5% discount rate and relies on a consistent set of cost assumptions across all scenarios. Capital expenditures were based on unit costs of €9700 per kW for hydropower, €1650 per kW for solar PV, €2185 per kW for wind, and €560 per kWh for battery storage. Annual operation and maintenance expenses were calculated as a percentage of the initial investment—3% for hydropower, 1.5% for solar PV and batteries, and 2.5% for wind. Grid electricity purchases were valued at €0.26 per kWh, while exported energy was priced at €0.06 per kWh. Battery replacement costs were incorporated into the cash flow analysis to reflect their shorter lifespan, and residual values of all components were accounted for at the end of the project. Using these assumptions, this study evaluated each scenario through four economic indicators: the Levelized Cost of Energy, which expresses the discounted cost per kilowatt-hour produced; the Net Present Value, which measures overall profitability; the Internal Rate of Return, which identifies the discount rate at which the project breaks even; and the Payback Period, which indicates how long it takes to recover the initial investment. Together, these metrics provide a comprehensive view of the financial performance of the different hybrid system configurations. Cost inputs were based on current market values for solar PV, wind turbines, micro-hydro systems, and battery storage components [28]. 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.

The regional regulatory framework offers substantial advantages for hybrid renewable energy systems, such as subsidies:

- Support to a more sustainable region: Up to 85% coverage of solar/battery costs (€2500 per installation);
- Next Generation EU Funds: 40–60% financing for innovative hydro-solar projects;
- Tax benefits:
- Total of 6% VAT (vs. 23%) on renewable equipment (valid in June 2025);
- Municipal tax deductions for solar installations;
- Administrative simplification:
- Greater than 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. Results and Discussion

### 4.1. Analysis of Scenarios

Each scenario is analyzed, and the behaviors are represented in Figures 7 and 8.

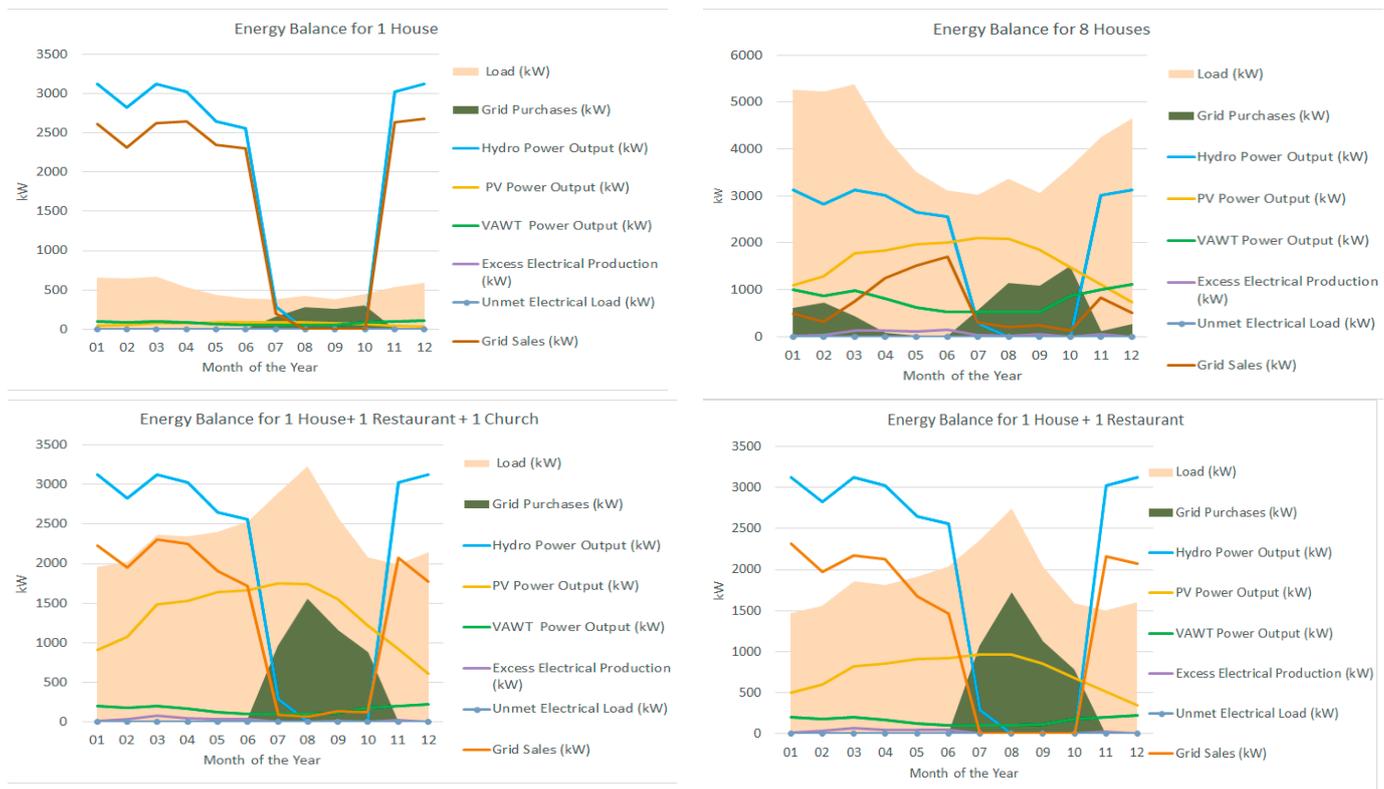


Figure 7. Energy balance across all four scenarios.

#### Scenario 1—Base Case (Single Household) (6100 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 6100 kWh. The optimal configuration includes a fixed hydropower component based on a constant water flow of  $0.44 \text{ m}^3/\text{s}$ , 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 to 266 kWh and discharges 251 kWh, helping to smooth daily fluctuations between generation and consumption.



**Figure 8.** Contribution by energy sources for all scenarios.

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 (Figure 4).

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 m<sup>2</sup> of PV surface area, averaging 8.12 m<sup>2</sup> per household. Total renewable generation reaches 57,341 kWh, with grid imports at 7041 kWh and exports of 15,130 kWh. Battery cycling involves 4472 kWh charged and 445 kWh discharged. The financial metrics show a NPV of €35,359, a Payback Period of 8.7 years, an IRR of 9%, and a LCOE of €0.09/kWh (Figure 4).

Limiting rooftop PV area to a conservative 6 m<sup>2</sup> per unit (compared to an available 12 m<sup>2</sup>) 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 a 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 2404 kWh and

imports 17,883 kWh from the grid, with battery charges totaling 2679 kWh and discharges of 2638 kWh annually.

Economically, it shows a strong performance with a NPV of €38,860, payback of 7.03 years, IRR of 13%, and a LCOE of €0.07/kWh (Figure 4).

When PV surface is restricted to 6 m<sup>2</sup> 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 4081 kWh, and exports drop to 12,416 kWh, resulting in an NPV of €31,763.

#### Scenario 4—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 1773 kWh, reflecting a high degree of self-sufficiency. Battery activity involves 1458 kWh charged and 1429 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 (Figure 7).

In a restricted PV space of 6 m<sup>2</sup>, 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.

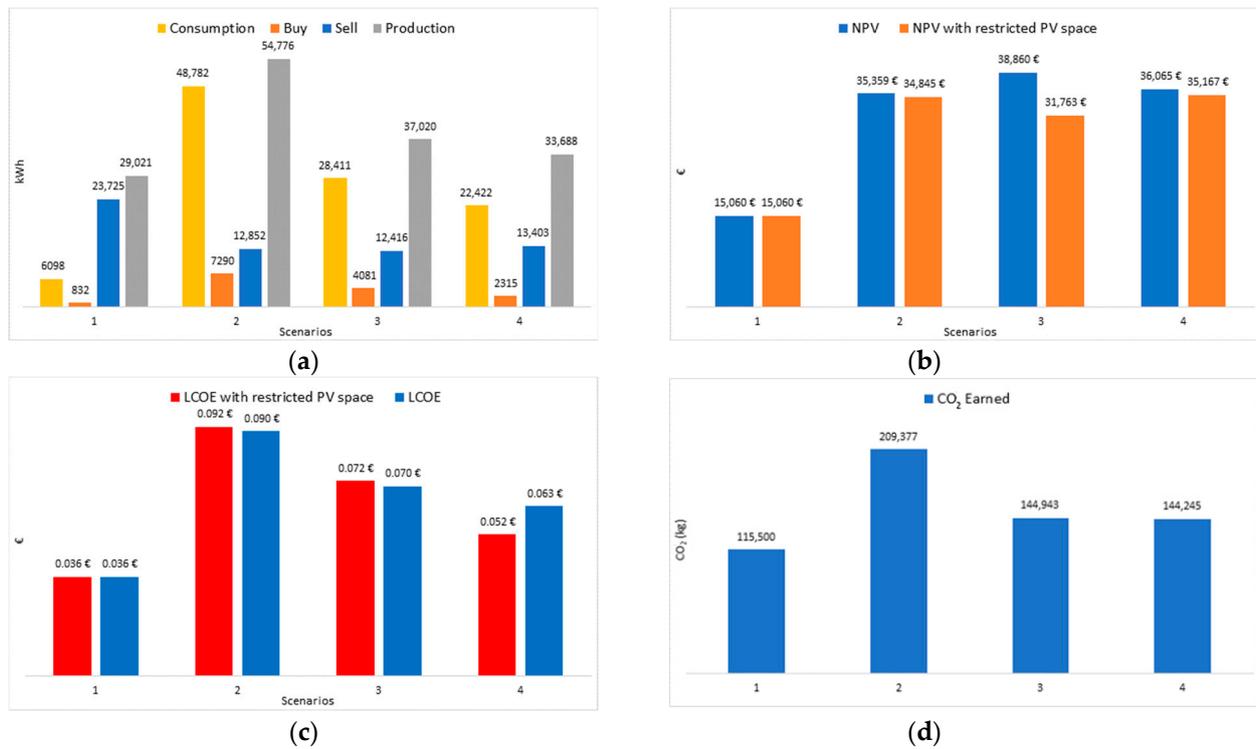
#### 4.2. Comparisons Across Scenarios

The energy performance of each scenario shows the proportions of energy generated, consumed, exported, and purchased (Figure 9a). 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.

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 (Figure 9b). However, when limiting PV surface to 6 m<sup>2</sup> 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.

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 (Figure 9c). Smaller-scale systems (Scenarios 1 and 4) achieve the most competitive LCOE ( $\leq$ €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 Scenario 4 demonstrates 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 9.** Annual energy balance by scenario in kWh (a); comparison of NPV across scenarios without and with PV surface limitation (b); comparison of LCOE with/without restricted PV space (c); and CO<sub>2</sub> earned across scenarios (d).

The implementation of these hybrid renewable energy systems substantially reduces CO<sub>2</sub> emissions compared to conventional grid electricity consumption. Each scenario contributes positively to climate change mitigation (Figure 9d):

Annual CO<sub>2</sub> savings correlate closely with total renewable generation, with larger systems naturally achieving higher absolute reductions.

Scenario 3 achieves a high emission reduction 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.

#### 4.3. Summary of KPI and Discussion

Table 1 consolidates the key technical and financial indicators across all four scenarios, enabling a clear comparison of performance under optimal conditions. Scenarios 3 and 4 stand out in terms of total energy production and Net Present Value, while Scenario 1 demonstrates good 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 1.** Results of the HySMEC.

Scenarios	1	2	3	4
Surface per house (m <sup>2</sup> )	2.78	8.12	17.00	14.99
PV Surface (4.5 m <sup>2</sup> /KW)	2.78	64.96	34.00	29.97
P PV (KW)	0.62	14.44	12.03	6.66
P Wind (KW)	0.72	9.87	1.98	1.71
Q Micro-H (m <sup>3</sup> /s)	0.44	0.44	0.44	0.44
Flood flow in River (m <sup>3</sup> /s)	24	24	24	24
Production (kWh)	29,021	57,342	44,182	37,466
Consumption (kWh)	6098	48,782	28,411	22,422
Buy (kWh)	832	7041	2404	1773
Sell (kWh)	23,725	15,130	17,883	16,654
Balance (kWh)	22,924	8559	15,771	15,044
Charge (kWh)	266	4472	2679	1458
Discharge (kWh)	251	4423	2638	1429
Losses of Ch,Dis (kWh)	26	445	266	144
Check (P-C+B-S) (kWh)	30	470	291	163
NPV (€)	15,060	35,359	38,860	36,065
PB (Years)	6.6	8.7	7.0	6.3
IRR	14%	9%	13%	15%
LCOE (€/kW)	0.036	0.090	0.070	0.063
CO <sub>2</sub> produced (kg)	−89,584	−9364	−45,843	−48,952
CO <sub>2</sub> Earned (kg)	115,500	216,689	166,591	144,245

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. 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 a slightly higher upfront investment.

**Scenario 3 (House + Restaurant + Church):** The most attractive financially, 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 + Restaurant):** Delivers high total energy production and competitive financial performance.

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.

#### 4.4. Model Validation

A comparison is made between HySMEC, a research model, and HOMER—a well-known commercial model. HySMEC (**Hybrid Smart Micro Energy Communities**) is a research-oriented modeling framework developed to support advanced analysis of hybrid energy systems in smart micro energy communities within an EU project, particularly emphasizing environmental performance, system dynamics, and integration flexibility. It allows for customized input structures and detailed tracking of emissions, energy flows, and component interactions, making it well-suited for academic and technical investigations. In contrast, HOMER is a commercially available optimization tool widely used in industry and research for designing and simulating microgrids and hybrid energy systems. The adapted HOMER inputs in this study leverage its robust economic modeling capabilities, user-friendly interface, and extensive component libraries. HOMER offers several advantages, including streamlined techno-economic analysis, reliable financial metrics (e.g., NPV, IRR, LCOE), and proven applicability across diverse geographic and operational contexts. Together, the integration of HySMEC and HOMER-adapted inputs enables a comprehensive evaluation of hybrid configurations, combining the methodological rigor of research modeling with the practical strengths of commercial simulation.

Across all four scenarios, energy consumption, production, and supply values reveal small differences between HOMER-adapted and HySMEC outputs. Scenario 1, characterized by minimal consumption (6099 kWh/year), shows that HySMEC estimates slightly higher total production (29,000 kWh/year) and energy supplied (29,832 kWh/year) compared to HOMER (25,505 and 26,508 kWh/year, respectively), suggesting a more generous energy yield. Scenario 2, with the highest consumption (48,776 kWh/year), exhibits a consistent trend. Scenario 3 presents moderate consumption (28,513 kWh/year) but a divergence in energy supply estimates, with HySMEC forecasting 62,065 kWh/year of production and HOMER-adapted 46,428 kWh/year. Scenario 4, with consumption of 22,468 kWh/year, shows close agreement between models in terms of energy supplied (39,239 kWh/year for HySMEC and 39,272 kWh/year for HOMER), indicating minor differences in system efficiency or loss modeling (Table 2).

**Table 2.** Comparison of energy balance between HySMEC and HOMER for each scenario.

Scenario	Consumption (kWh/yr)	Total Production (kWh/yr)		Total Energy Supplied (kWh/yr)	
		HOMER Adapted	HySMEC	HOMER Adapted	HySMEC
Scenario 1	6,099	25,505	29,000	26,508	29,832
Scenario 2	48,776	52,492	57,341	59,094	64,382
Scenario 3	28,513	41,729	44,182	46,428	62,065
Scenario 4	22,468	34,537	37,466	39,272	39,239

Based on a comprehensive evaluation of technical, economic, and environmental indicators (Table 3), Scenario 3 under HySMEC modeling stands out as the most balanced and advantageous configuration. Technically, it operates with moderate renewable capacity (12.03 kW solar PV and 1.98 kW wind), achieving substantial energy production and supply. Economically, it offers a strong Internal Rate of Return (13%), a competitive Levelized Cost of Energy (€0.07/kWh), and a favorable Net Present Value (€38,860), with a Payback Period of just over 7 years. Emissions were quantified based on the emission factors provided in the HySMEC framework, with parameter adaptation in HOMER for compatibility of input data. The analysis encompassed both earned and total generated emissions. Environmentally, Scenario 3 demonstrates robust performance, earning 145 tons

of CO<sub>2</sub> credits while maintaining a net negative total CO<sub>2</sub> production (−24 tons), indicating meaningful carbon mitigation. This scenario effectively integrates technical feasibility, financial viability, and environmental sustainability, making it the most promising option among the evaluated configurations.

**Table 3.** Comparison and verification of both models (HOMER adapted and HySMEC) for techno-economic–environmental conditions across all scenarios.

Tech/ Economic/ Environ	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	HOMER Adapted	HySMEC	HOMER Adapted	HySMEC	HOMER Adapted	HySMEC	HOMER Adapted	HySMEC
Solar PV Capacity (kW)	0.62	0.62	14.44	14.44	12.03	12.03	6.66	6.66
Wind Turbine Capacity (kW)	1	0.72	10	9.87	2	1.98	2	1.71
Grid Purchase (kWh/yr)	1003	832	6602	7041	4699	17,883	4709	1773
Grid Sell (kWh/yr)	20,352	23,725	8274	15,130	16,609	2404	15,969	16,654
Battery Charge (kWh/yr)	86.6	266	6493	4472	2573	2679	885	1458
Battery Disch. (kWh/yr)	80.3	251	9181	445	2435	2638	833	1429
NPV (€)	6103	15,060	89,080	35,359	45,947	38,860	35,045	36,065
LCOE (€/kWh)	0.019	0.036	0.180	0.09	0.106	0.07	0.095	0.063
IRR (%)	−1	14	6	9	9	13	9	13
Payback Period (yr)	-	6.65	10.5	8.7	8.75	7.03	8.9	6.3
CO <sub>2</sub> earned (ton)	108	115	223	209	177	145	147	144
CO <sub>2</sub> total produced (ton)	−75	−90	101	−2	−30	−24	−34	−49

Tables 2 and 3 correspond to the robustness assessment described in the methodology. Hybrid HySMEC configurations clearly outperform single-technology systems, achieving competitive LCOE values (0.036–0.09 €/kWh), self-consumption levels above 70%, and CO<sub>2</sub> reductions exceeding 60%. Their strong economic performance—positive NPVs, IRRs above 8–10%, and Payback Periods under 9 years—shows that community-scale hybrid systems are financially viable even under spatial or demand constraints. The substantial reduction in grid imports (40–80%) further supports policies aimed at strengthening rural resilience and reducing grid congestion.

However, the scalability of these solutions depends on regional environmental agency regulations, which restrict hydropower expansion, land availability for PV and wind, and interventions in heritage water infrastructures. These regulatory limits shape the feasible technology mix and must be incorporated into regional energy-community planning.

The results also reinforce the relevance of self-consumption frameworks, highlighting the potential of collective self-consumption, shared storage, and cooperative ownership models—especially when supported by targeted incentives and streamlined licensing. Finally, the significant emission reductions align HySMEC-type projects with regional decarbonization goals and EU directives promoting distributed renewable generation.

## 5. Conclusions

HySMEC (Hybrid Smart Micro Energy Communities) is a research-oriented modeling framework designed to evaluate and optimize hybrid renewable energy systems for smart micro energy communities. It emphasizes environmental performance, dynamic system behavior, and flexible integration of hydro, solar PV, wind, batteries, and grid interaction. The model supports customized inputs and tracks emissions, energy flows, and component interactions, enabling rigorous academic and technical investigations. This study integrates

environmental data collection, energy generation modeling, demand estimation, and financial analysis to identify technical and economically viable configurations. Hourly data from Open-Meteo informs simulations for hydro, PV, and wind generation, while four demand scenarios are modeled: Scenario 1 (1 household, 6.1 MWh/year), Scenario 2 (8 households, 48.8 MWh/year), Scenario 3 (house + restaurant + church, 28.4 MWh/year), and Scenario 4 (house + restaurant, 22.4 MWh/year). Hourly energy balances guide battery charging, discharging, and grid interactions, capturing seasonal variations such as winter heating and summer tourism peaks.

Optimization is performed by varying PV and wind capacities to maximize Net Present Value (NPV), while hydropower remains fixed due to its low Levelized Cost of Energy (LCOE). A constrained variant limits PV installation to 6 m<sup>2</sup> per building, excluding the church. Technical assumptions include a PV surface requirement of 4.5 m<sup>2</sup>/kW, battery efficiency of 95%, and initial State of Charge at 50%. Emission factors are set at 35 g CO<sub>2</sub>/kWh for PV, 10 g for wind and hydro, and 170 g for grid electricity. Economic inputs include a 5% discount rate, electricity purchase price of €0.26/kWh, and sale price of €0.06/kWh. Investment costs are €9700/kW for hydro, €1650/kW for PV, €2185/kW for wind, and €560/kWh for batteries, with operation and maintenance costs ranging from 1.5% to 3% of the investment.

Scenario 3 emerges as the optimal configuration, delivering the highest NPV (€38,860), strong IRR (13%), a Payback Period of 7.03 years, and a competitive LCOE (€0.07/kWh). It achieves significant CO<sub>2</sub> mitigation, earning 145 tons and producing −24 tons, indicating net carbon negativity. This scenario benefits from high self-consumption and diverse demand profiles, minimizing grid dependence and enhancing profitability, especially under rising electricity prices. If rooftop space is constrained, Scenario 2 becomes preferable due to its resilience and collective self-consumption synergies, yielding a NPV of €35,359, IRR of 9%, and LCOE of €0.09/kWh. Scenario 1 offers the lowest LCOE (€0.04/kWh) and highest IRR (14%) with minimal capacity and strong environmental performance (−90 tons CO<sub>2</sub> produced). Scenario 4 demonstrates high self-sufficiency and low grid imports, with a NPV of €36,065 and LCOE of €0.063/kWh.

Overall, the analysis confirms that hybrid systems combining hydropower, solar PV, and wind are technically viable and economically robust across varied use cases. Financial returns remain positive under conservative market assumptions, and higher self-consumption ratios significantly improve profitability and system sizing. Beyond technical and economic strengths, the proposed system delivers social and cultural benefits by enabling energy autonomy, reducing vulnerability to energy insecurity, and fostering community empowerment. Inherent rehabilitation of historical mill sites supports heritage preservation, education, and sustainable tourism. These findings position HySMEC-based hybrid systems as scalable, sustainable, and adaptable solutions for rural communities. The HySMEC framework addresses the lack of transparent, data-driven, and integrative modeling tools that combine hourly environmental variability, multi-technology interactions, and joint techno-economic–environmental assessment within a single framework tailored for small energy communities. To further substantiate the scientific novelty, this research includes a benchmark comparison with an established modeling tool (HOMER), which serves to validate the proposed approach and demonstrate its consistency with existing methodologies while highlighting its added value in terms of transparency, adaptability, and community-specific applicability.

There are main gaps that HySMEC addresses. Existing tools, such as digital twins, focus on large or urban systems and require data infrastructures unavailable in rural areas, whereas HySMEC offers a lightweight, hourly, data-driven framework suitable for small communities. Current multi-objective optimization studies emphasize algorithmic

performance rather than transparent, reproducible decision support, so HySMEC provides an interpretable NPV-based optimization with scenario-driven sensitivity analyses for planners. Additionally, most models overlook regulatory constraints; HySMEC explicitly incorporates regional environmental agency limits on hydropower, land use for PV and wind, and heritage-related restrictions. HySMEC's data-driven structure provides a scalable and reproducible tool for planners, researchers, and local authorities seeking to evaluate distributed energy solutions in smart micro energy communities under diverse conditions. Further research can include potential extensions such as integrating more detailed demand-side management strategies, incorporating real-time control or digital-twin applications, exploring additional storage technologies, and applying the framework to different community typologies or climatic contexts.

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## Abbreviations

The following abbreviations are used in this manuscript:

### Acronyms

EF	Emission Factor
EU	European Union
IRR	Internal Rate of Return
IIRR	Investment Internal Rate of Return
LCOE	Levelized Cost of Energy
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PB	Payback Period
PR	Performance Ratio
PV	Photovoltaic
SoC	State of Charge
UPAC	Production Units for Self-Consumption
VAWT	Vertical Axis Wind Turbine

### List of variables

A	Swept area of the turbine (m <sup>2</sup> )
C <sub>bat</sub>	Battery capacity (kWh)
C <sub>p</sub>	Power coefficient (typically ~0.3–0.4)
C <sub>t</sub>	Cost in year t
C <sub>t</sub>	Cost in year t

Echarge/Edischarge	Energy charged/discharged (kWh)
Egenerated	is the annual energy produced by the hybrid system (kWh)
EPV	Daily energy output (kWh)
Et	Energy produced in year t
g	Gravitational acceleration (9.81 m/s <sup>2</sup> )
Gtilted	Daily global tilted irradiation (kWh/m <sup>2</sup> )
H	Net head (m)
IRR	Internal rate of return
I	Investment cost per year
M	Maintenance cost per year
n	Project lifetime (years)
N	lifespan of the project (years)
O	Operational cost per year
P	Hydraulic power output (W)
PPV	Installed PV capacity (kW)
PR	Performance ratio (typically 0.75)
PW	Installed W capacity (kW)
Pwind	Instantaneous wind power output (W)
Q	Flow rate (m <sup>3</sup> /s)
r	Discount rate
Rt	Revenue in year t
SoCt	Battery state of charge at time t
v	Wind speed (m/s)
η	Overall system efficiency (dimensionless)
η	System efficiency (electrical/mechanical losses)
ηdischarge	Charge/discharge efficiencies

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