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Designing Renewable Energy Communities for Incentive Optimisation: Hydropower vs. Photovoltaic Systems

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Abstract. The increasing adoption of distributed renewable energy sources introduces new challenges for local energy management. Renewable Energy Communities (RECs) offer a promising framework by promoting collective energy self-consumption and citizen participation. This study presents a methodology for optimally sizing a REC based on consumers grouped into three typical energy consumption profiles. The objective is to maximise the economic revenue from feed-in tariffs associated with shared renewable energy, using hybrid systems with a total installed capacity of 100 kW in central Italy. Five renewable energy generation scenarios are analysed: i) HYDROpower- (HYDRO) only, ii) Photovoltaic- (PV) only, and iii) three PV-HYDRO hybrid combinations. Each scenario is assessed under two ownership models: i) third party-owned generation and ii) REC-owned generation. Results show that the HYDRO-only configuration delivers the highest economic benefits, namely 71,450 in total revenue, which €33,538 comes from in feed-in tariffs, and over 127 tonnes of CO₂ avoided annually. Consumer savings peak at €184 per household per year under third party ownership, which, while less financially beneficial to the REC itself, can support broader community initiatives. The analysis confirms that integrating HYDRO into RECs enhances energy efficiency, economic performance, environmental impact, and social value.

Acronyms

ARERA Autorità di Regolazione per energia Reti e Ambiente

COE Cost of Energy

EF Emission Factor

EU-CEP European Union Clean Energy Package

GHG Greenhouse Gas



H2EES Hydrogen-based Electrical Energy Storage System

HYDRO Hydropower

NPC Net Present Cost

PV Photovoltaic

RECs Renewable Energy Communities

RESs Renewable Energy Sources

TIP Time-of-Use Incentive Premium

Nomenclature

B_{Cx} Economic benefit assigned to a category Cx

$C1_t, C2_t, C3_t$ Energy consumption of households 1, 2, and 3 at time t , respectively

C_t Total energy consumption of the REC at time t

$C_{public,t}$ Energy consumption from the public sector at time t (for REC-owned plants)

N_1, N_2, N_3 Number of households corresponding to 3 typical energy consumption profiles

$P_{HYDRO,t}$ Hydropower energy production at time t

$P_{PV,t}$ Photovoltaic energy production at time t

Pz_t Hourly zonal market price at time t

TIP_t^{HYDRO} Time-dependent feed-in tariff for shared hydropower energy at time t

TIP_t^{PV} Time-dependent feed-in tariff for shared photovoltaic energy at time t

1 Introduction

The widespread adoption of distributed Renewable Energy Sources (RESs) is essential for achieving both decarbonisation and energy decentralisation goals. First, RESs play a critical role in reducing GreenHouse Gas (GHG) emissions, thereby supporting the decarbonisation of the energy sector. Globally, the energy sector is a leading source of GHG emissions, largely due to its dependence on fossil fuels such as coal, oil, and natural gas. Transitioning to clean energy sources like solar, wind, and hydropower significantly reduces reliance on carbon-intensive fuels, directly lowering CO_2 emissions [1]. Second, RESs contribute to energy decentralisation. Traditional energy systems are typically based on large, centralised power plants that deliver electricity over long transmission lines. This model often results in energy losses, grid congestion, and vulnerability to single points of failure. In contrast, distributed RESs enable local energy generation near the point of use. This decentralised structure enhances grid resilience, minimises infrastructure stress, and empowers communities and individuals to take an active role in the energy system [2]. Finally, the adoption of RESs promotes the integration of innovative technologies, fosters entrepreneurship, and stimulates local economic development. The deployment and maintenance of small-scale renewable systems create job opportunities, support energy literacy, and can help alleviate energy poverty by reducing household electricity expenses [3].

However, integrating RESs into existing energy infrastructures poses significant challenges for local energy management, grid stability, and consumer engagement. Variability in energy generation, spatial dispersion of energy sources, and limited storage capacity are among the main technical obstacles [4]. Moreover, the economic and regulatory frameworks often lag, complicating the implementation of community-based energy systems [5]. In this context, Renewable Energy Communities (RECs) have emerged as a promising solution, offering a bottom-up approach to energy transition by promoting collective energy self-consumption and increasing citizens' active participation [6]. RECs are characterised by their potential to simultaneously deliver economic benefits through energy sharing and feed-in tariffs, environmental gains by replacing fossil fuel consumption with clean energy sources, and social value by

enhancing local empowerment and energy democracy [7]. These communities align with the European Union's Clean Energy Package (EU-CEP), which recognises the role of citizens and local actors in the energy transition [8].

While Photovoltaic (PV) systems are the most commonly adopted technology within RECs due to declining costs and ease of installation, the integration of HYDROpower (HYDRO), particularly small-scale and run-of-river installations, presents an underexplored opportunity. Indeed, HYDRO offers greater generation stability and can complement intermittent sources like PV [9]. Li et al. [10] proposed a three-stage decision-making framework for optimally configuring a HYDRO-wind-PV-storage system to support carbon reduction goals. Using scenario generation, multi-objective optimisation, and advanced decision-making methods, the framework was validated on a HYDRO plant. Results showed that the hybrid system effectively reduces power fluctuations. Lima et al [11] evaluated the integration of HYDRO and PV power with a Hydrogen-based Electrical Energy Storage System (H2EES) at Brazil's Serra da Mesa HYDRO plant. By converting excess renewable energy into hydrogen via electrolysis and reconvert it through fuel cells, the system increased total energy output by 11.10%, with H2EES contributing 36.06% of the gain. Substation capacity use improved by 9.71%, demonstrating the approach's potential to enhance renewable energy use and reduce emissions with minimal infrastructure changes. Irshad et al [12] explored optimal capacity planning for a 100% off-grid hybrid renewable energy system to support sustainable development in remote areas. Using a multi-objective genetic algorithm, the ideal configuration of PV, wind, and HYDRO was determined, achieving the lowest Net Present Cost (NPC) and Cost Of Energy (COE) among the examined communities. The optimal setup (PV 88 kW, wind 18 kW, Hydro1 215 kW, Hydro2 197 kW) delivered reliable energy at 0.35 USD/kWh without storage. Results confirmed the feasibility of fully renewable, storage-free systems for resilient rural electrification.

Despite the growing interest in RECs, to the authors' knowledge, there remains a significant gap in the scientific literature regarding the comparative analysis of PV-only, HYDRO-only, and hybrid PV-HYDRO configurations specifically designed for REC applications without the need for energy storage systems, thanks to the complementary operation of the two aforementioned technologies. Moreover, an analysis that incorporates not only renewable energy production but also consumer typologies and real domestic consumption data, sourced from the Italian energy authority "Autorità di Regolazione per energia Reti e Ambiente" (ARERA) [13], further enhances the applicability and scalability of the proposed model, ensuring its alignment with actual user behaviour and demand patterns within RECs. This is especially true in the context of the Italian regulatory framework, which presents unique opportunities and constraints for the deployment and optimisation of such systems.

This paper introduces a novel methodology for optimally sizing RECs based on consumer segmentation into distinct energy profiles, and compares five renewable generation scenarios, such as HYDRO-only, PV-only, and three hybrid configurations combining both technologies, to a total of 100 kW. Furthermore, the analysis distinguishes between two ownership models: a third party-owned renewable energy power plant and a renewable energy plant owned directly by the REC. This dual-layered comparison (technology and ownership) contributes to existing scientific literature by exploring how different configurations affect economic performance, environmental outcomes, and consumer benefits in the specific context of central Italy.

The paper is structured as follows: Section 2 presents the methodology for REC sizing and scenario development. Section 3 describes the case study, including consumer profiles and renewable resource characteristics. Section 4 reports the results for each scenario and ownership model. Section 5 concludes the paper with final remarks and directions for future work.

2 Material & Methods

The methodology adopted for the optimal sizing of the RECs is based on a computational approach implemented in the Python programming language. The main objective is to determine the optimal composition of the REC in terms of the number of residential users with different typical energy consumption profiles to maximise the economic revenue coming from local renewable energy generation and energy sharing within the REC.

The mathematical problem is formulated as a constrained numerical optimisation, where the decision variables are defined as follows:

- N_1, N_2, N_3 are the number of households corresponding to three typical, different energy consumption profiles.

The objective function is designed to maximise the total profit of the community, which is composed of:

- Economic revenues coming from the sale of the renewable energy produced based on the hourly zonal market price P_{z_t} .
- The feed-in tariff for the shared renewable energy within the REC, calculated based on the Time-of-Use Incentive Premium (TIP) that varies depending on the energy source type.

The objective function is expressed as:

$$\max_{N_1, N_2, N_3} \sum_t \left(\frac{P_{z_t}}{1000} \cdot (P_{PV,t} + P_{HYDRO,t}) \right) + 0.55 \cdot [\min(P_{PV,t}, C_t) \cdot TIP_t^{PV} + \min(P_{HYDRO,t}, C_t) \cdot TIP_t^{HYDRO}] \quad (1)$$

where:

- $P_{PV,t}$ and $P_{HYDRO,t}$ are the PV and HYDRO energy production at time t , respectively.
- C_t is the total energy consumption of the REC at time t .
- TIP_t^{PV} and TIP_t^{HYDRO} are the time-dependent feed-in tariffs for shared PV and HYDRO energy, respectively.

The total energy consumption is calculated as follows:

$$C_t = \begin{cases} N_1 \cdot C1_t + N_2 \cdot C2_t + N_3 \cdot C3_t & \text{(third party-owned renewable energy plant)} \\ N_1 \cdot C1_t + N_2 \cdot C2_t + N_3 \cdot C3_t + C_{public,t} & \text{(renewable energy plant owned by the REC)} \end{cases} \quad (2)$$

TIP values are defined as decreasing functions of the zonal price P_{z_t} to promote renewable energy self-consumption during low market price hours according to [14]:

$$TIP_t^{PV} = \frac{84 + \max(0, 180 - P_{z_t})}{1000} \quad (3)$$

$$TIP_t^{HYDRO} = \frac{80 + \max(0, 180 - P_{z_t})}{1000} \quad (4)$$

To ensure feasibility and operational consistency, specific constraints are imposed. First, the number of consumers within each energy consumption profile must remain within realistic and balanced limits.

$$1 \leq N_i \leq 1000 \quad \text{for } i = 1, 2, 3 \quad (5)$$

Furthermore, to prevent renewable energy surplus production that cannot be utilised locally, an energy consumption coverage constraint is applied, ensuring that, at each time step, the total energy consumption is at least equal to the total renewable energy production.

$$\min_t (C_t - (P_{PV,t} + P_{HYDRO,t})) \geq 0 \quad (6)$$

This set of constraints ensures that the renewable energy produced is effectively consumed within the REC, thereby safeguarding both its technical efficiency and economic viability. Once the optimal combination is determined for each technological configuration, a comprehensive evaluation of the benefits was conducted:

- **Economic Benefits:** For each user category C_x , the benefit was calculated using the following expression:

$$B_{C_x,t} = \frac{0.55 \cdot (\sum TIP_t^{PV} + \sum TIP_t^{HYDRO}) \cdot \sum C_x}{\sum C_t \cdot N_{C_x}} \quad (7)$$

where:

- B_{C_x} : Economic benefit assigned to a category C_x
- $\sum TIP_t^{PV}$: Total feed-in tariff for PV energy over the considered periods,

- $\sum TIP_t^{HYDRO}$: Total feed-in tariff for HYDRO energy over the considered periods,
- $\sum C_x$: Total consumers' energy consumption in a category C_x ,
- $\sum C_t$: Total energy consumption across all the consumers,
- N_{C_x} : Number of consumers in category C_x ,
- 0.55: Coefficient representing the portion of the feed-in tariff effectively used for consumers' benefit.

This formulation ensures that the allocated benefit reflects both the proportional consumption and the number of consumers per category, adjusted by the effective share of feed-in tariff production.

- **Environmental Benefits:** These benefits were quantified as CO₂ emissions avoided through the use of RESs, such as HYDRO and PV, taking into account the Emission Factors (EFs) of the national electricity grid and the renewable technologies. The calculation was conducted according to the following equation:

$$\text{CO}_2 \text{ avoided} = \sum_t (P_{PV,t} + P_{HYDRO,t}) \cdot \text{EF}_{\text{grid}} - \sum_t P_{PV,t} \cdot \text{EF}_{PV} - \sum_t P_{HYDRO,t} \cdot \text{EF}_{HYDRO} \quad (8)$$

where:

- CO_2 avoided: kg of CO₂ avoided,
- $P_{PV,t}$, $P_{HYDRO,t}$: Energy produced at time t by PV and HYDRO, respectively,
- EF_{grid} , EF_{PV} , EF_{HYDRO} : EFs of the grid, PV, and HYDRO, respectively.
- **Social Benefits:** These benefits were assessed by considering both the number of households directly involved in the selected configuration and the proportion of feed-in tariffs allocated to social purposes (e.g., reduction of energy poverty, investment in local shared services, etc.).

3 Case Study

The previously outlined methodology was applied to a case study in a municipality located in central Italy. The area of interest is home to renewable energy plants, specifically PV and HYDRO plants. Hourly resolution, real energy production data of the renewable plants under investigation were used from the second half of 2023 to the first half of 2024.

For the case study, the methodology was implemented across five distinct technological scenarios. Each scenario featured a unique plant configuration, but all shared the same total installed capacity. In particular, the following scenarios were analysed:

- 100-kW HYDRO, with a yearly production of 380.15 MWh.
- 100-kW PV, with a yearly production of 151.11 MWh.
- 50-kW HYDRO and 50-kW PV, with a yearly production of 265.63 MWh.
- 75-kW HYDRO and 25-kW PV, with a yearly production of 322.89 MWh.
- 25-kW HYDRO and 75-kW PV, with a yearly production of 208.37 MWh.

Figures 1 and 2 illustrate the renewable energy production profiles across different technology scenarios for a representative summer day and winter day, respectively.

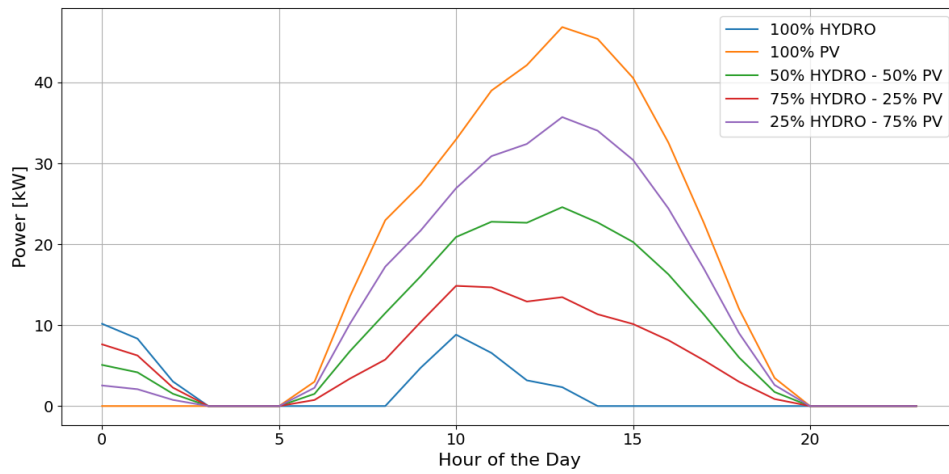


Figure 1: Energy Production Curves - Typical Summer Day (15/07/2023)

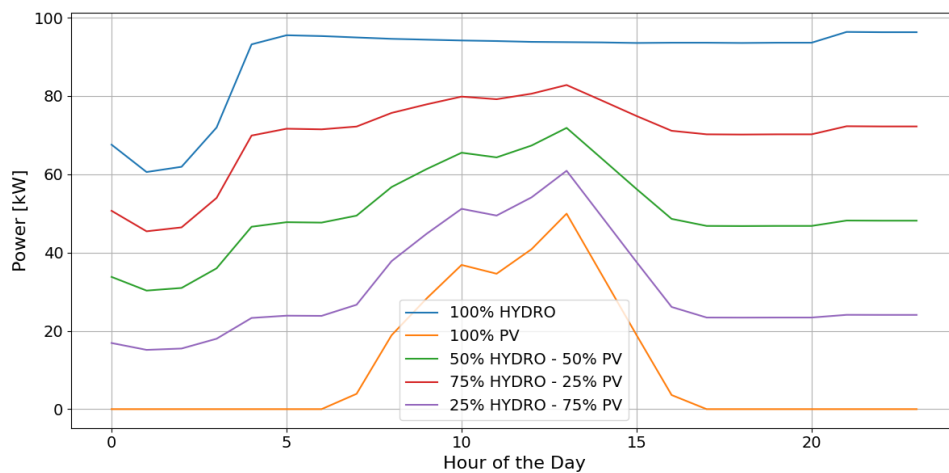


Figure 2: Energy Production Curves - Typical Winter Day (10/02/2024)

The analysis was conducted for two scenarios: one where the renewable energy plant is owned by a third party that does not participate in the REC configuration, and another where the renewable energy plant is owned internally (e.g., a public authority such as a municipality). In both cases, three representative average hourly energy consumption profiles of domestic customers were considered, taken from [13]. Figure 3 shows the weekly consumption patterns.

- C1: $0\text{ kW} < P \leq 1.5\text{ kW}$
- C2: $3\text{ kW} < P \leq 4.5\text{ kW}$
- C3: $P > 6\text{ kW}$

On the other hand, real energy consumption data of a building, whose owner is the municipality, was considered, having a total yearly energy consumption of 61.8 MWh.

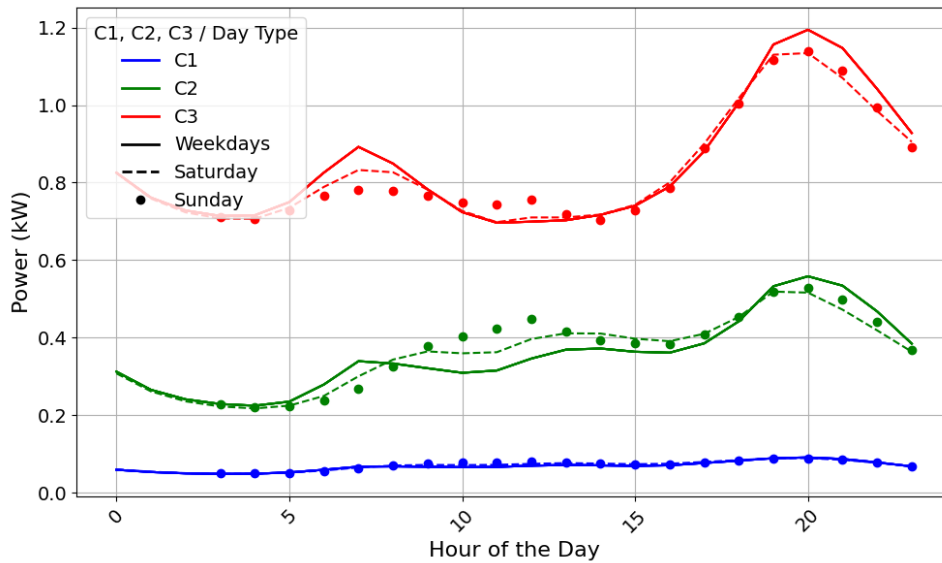


Figure 3: Weekly Energy Consumption Profile

4 Results & Comments

This section presents the results of the study, which is based on the design of a REC and the evaluation of various technological configurations for RESs. The analysis explores different combinations of PV and HYDRO technologies, with a focus on the ecological, environmental, and social benefits they can provide. These configurations were applied to two distinct case studies, as described in Section 3.

4.1 Economic Benefits

This section presents the results of the economic benefits analysis for two distinct case studies: (i) a third-party-owned renewable energy generation plant, and (ii) a REC-owned renewable energy generation plant. The analysis first examines the savings achieved by three consumer categories (C1, C2, and C3), each representing increasing levels of energy consumption. Among all configurations analysed, user C3 consistently achieved the highest savings. This outcome is attributed to the internal REC policy whereby feed-in tariffs from shared renewable energy are distributed proportionally to individual consumption; thus, higher-consuming users receive a larger share of the incentives.

As shown in Figure 4, the configuration yielding the greatest savings was the third-party-owned plant with 100% HYDRO energy production. In this case, yearly savings were approximately €185 for user C3, €175 for C2, and €90 for C1. This scenario benefited from the more stable and predictable output of HYDRO compared to PV sources, enabling more effective alignment between generation and consumption within the REC. Conversely, mixed generation scenarios (e.g., 75% HYDRO and 25% PV) resulted in lower savings, reinforcing the conclusion that a higher share of HYDRO leads to greater economic benefits due to its consistent production profile.

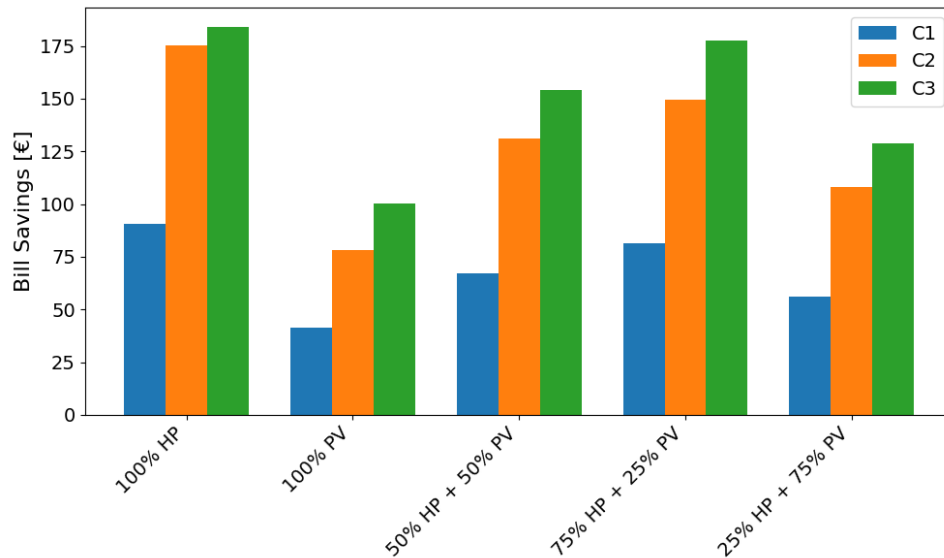


Figure 4: Annual savings in "Third party-owned renewable energy generation plant"

Figure 5 displays the second configuration analysed: the REC-owned renewable energy generation plant, in which the facility is owned by the municipality. In this scenario, a significant reduction in savings was observed for households. This is primarily due to the municipality's substantially higher annual energy consumption, which allowed it to absorb a large portion of the available incentives. Estimated annual savings for households in this configuration were approximately €15.5 for C1, €28.5 for C2, and €29 for C3—figures notably lower than those observed in the third-party ownership scenario. However, the municipality itself experienced substantial economic benefits, with yearly savings reaching approximately €28,000 under the 100% HYDRO configuration.

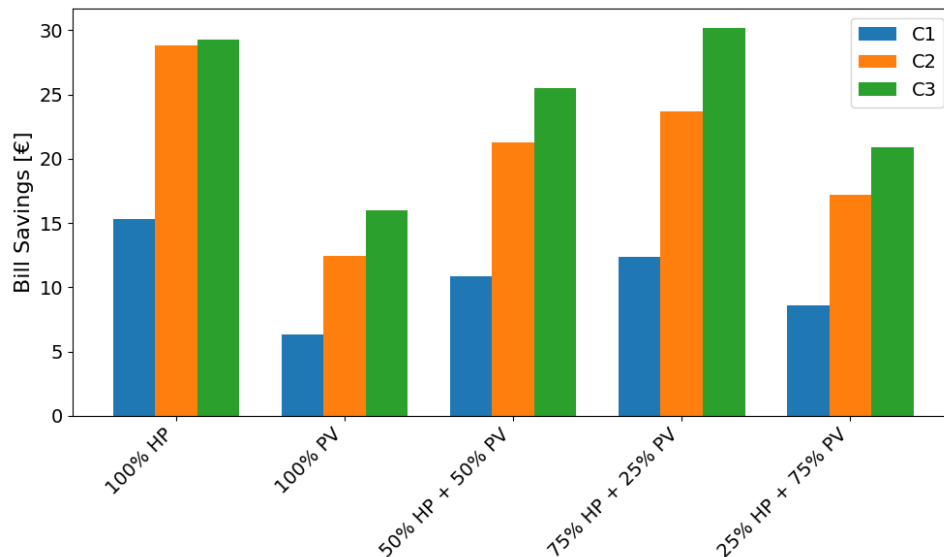


Figure 5: Annual savings in "REC-owned renewable energy generation plant"

Furthermore, considering the entire REC, it can be noticed that the 100% HYDRO configuration is the most economically profitable solution, providing a total annual revenue of approximately €71,450. On the other hand, the worst configuration from an economic point of view is the 100% PV configuration, which generates an annual revenue of €28,555.

4.2 Environmental Benefits

The environmental benefits of the analysed configurations were quantified in terms of avoided CO_2 emissions resulting from the use of RESs. These avoided emissions represent the amount of CO_2 that would have been released if the equivalent energy had been generated using conventional fossil fuel-based sources. For this study, EFs considered were: 0.345 kg CO_2 /kWh for grid electricity [15], 0.04 kg CO_2 /kWh for PV [16], and 0.01 kg CO_2 /kWh for HYDRO generation [17].

The configuration yielding the highest environmental benefit was the 100% HYDRO scenario, which avoided approximately 127.35 tonnes of CO_2 emissions. In contrast, the 100% PV scenario resulted in the lowest benefit, with 46.09 tonnes of CO_2 avoided. A comprehensive summary of avoided emissions across all configurations is provided in Table 1.

Table 1: Avoided CO_2 Emissions for Different Renewable Energy Configurations

Configuration	Avoided CO_2 [t]
100% HP	127.35
100% PV	46.09
50% HP + 50% PV	86.72
75% HP + 25% PV	107.04
25% HP + 75% PV	66.40

4.3 Social Benefits

From a social perspective, the number of citizens involved varied significantly depending on the configuration. The highest level of participation was observed in the third-party-owned renewable energy generation plant scenario, specifically in the 100% HYDRO configuration, which engaged a total of 194 consumers (C1: 19, C2: 55, C3: 120), representing the greatest outreach among all scenarios analysed.

In contrast, 156 consumers (C1: 18, C2: 50, C3: 88) were involved in the "REC-owned renewable energy generation plant" scenario, the most disadvantageous technological configuration, 100% PV, corresponding to approximately 20% fewer participants than in the most advantageous option.

However, although the total number of participants was lower, the presence of the municipality introduced a strategic social benefit. In particular, the part of the incentives that could be spent on social activities could be reinvested by the municipality in projects aimed at improving community well-being, such as improving the comfort of public housing, supporting energy-poor households, or developing shared green areas.

5 Conclusions

This study examined various technological configurations and ownership models for the optimal design of RECs, focusing on a comparative analysis of PV, HYDRO, and hybrid combinations of both. The objective was to maximise economic returns from shared energy self-consumption and feed-in tariffs, while maintaining a constant total installed capacity of 100-kW within a real-world case study located in central Italy.

The results indicate that the 100% HYDRO configuration delivers the strongest overall performance across economic, environmental, and social dimensions. Specifically, it generates a total annual revenue of approximately €71,450, including €33,538 from feed-in tariffs, and leads to the avoidance of over 127 tonnes of CO_2 emissions per year. Hybrid configurations offered key advantages, notably improved production continuity and better alignment with daily energy demand, enhancing overall REC reliability and efficiency. The analysis also underscored the significant impact of the ownership model on the distribution of benefits. The third-party-owned renewable energy generation plant scenario maximises individual savings, with households benefiting from up to €184 per year. In contrast, the REC-owned renewable energy generation plant model prioritises collective value creation, enabling the reinvestment of revenues into social initiatives and shared infrastructure.

Overall, the integration of complementary technologies, such as HYDRO and PV, combined with targeted consumer segmentation and an incentive-driven approach, emerges as an effective strategy for maximising the benefits of RECs. The proposed model is both scalable and replicable across different territorial contexts, offering a valuable decision-support tool for public authorities, energy planners, and local communities.

Acknowledgments

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