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Development of a Computational Tool for Techno-Economic and Social Impact Assessment in Local Energy Communities: Application to the Mediana de Voltoya Case

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Use of Artificial Intelligence

During the preparation of this thesis, the author used AI tools, including Perplexity, Claude and Gemini, mainly to support coding tasks and the generation and refinement of figures, as well as occasional assistance with academic writing, wording and grammar. These tools were primarily employed to enhance the clarity, implementation, and presentation of the work. All modelling choices, analyses, interpretations, results, and conclusions were con-ceived, verified, and approved independently by the author, who assumes full academic responsibility for the content of this work.

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ABSTRACT:
The deployment of Local Energy Communities (LECs) as instruments of the energy transition requires integrated assessments of financial viability and social impact that remain inaccessible to most local actors. This thesis develops a modular, Python-based computational tool for the techno-economic and social evaluation of LECs in the Spanish regulatory context. The tool comprises two interoperable modules. The financial module computes NPV, IRR, and payback period through a 25-year discounted cash flow model, incorporating photovoltaic degradation, electricity price growth, battery State-of-Health, and risk-differentiated discount rates. The social module produces a Governance Index, Participation Index, composite Social Score, Implementation Feasibility Index, and redistribution metrics quantifying potential support to vulnerable households. Both modules are linked through annual surplus energy, estimated by the financial engine and fed directly into social redistribution calculations.

The framework is validated on the LEC of Mediana de Voltoya, Avila, Spain, across three scenarios: a baseline 10 kWp municipal installation (S1), the same system with 20 kWh battery storage (S2), and a community-scale 3×90 kWp expansion (S3). S1 and S2 fail to achieve viability ($\mathrm{NPV} = -4,796$ and $\mathrm{NPV} = -20,554$ respectively), while S3 yields $\mathrm{NPV} = 273,672$, $\mathrm{IRR} = 11.90\%$, and a 9-year payback, driven by a self-consumption ratio of 0.597 above the identified break-even threshold of 0.41. The Social Score of 0.75 reflects strong institutional governance offset by early-stage participation. Under S3, a 25% solidarity mechanism could support approximately 27 vulnerable households per plant.

Financial viability and social inclusion converge on the same condition: expanding community participation to sustain the required self-consumption ratio. Governance design is therefore a primary engineering variable, not an implementation detail.

Keywords: Local Energy Communities; Collective Self-Consumption; Techno-Economic Assessment; Social Impact; Photovoltaic Viability; Energy Poverty

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Chapter 1

Introduction

This chapter introduces the broader context in which this thesis is situated. It opens with an overview of global energy transition dynamics and the structural drivers behind rising energy demand, before introducing the emergence of Local Energy Communities (LECs) as a participatory governance model for decentralized renewable energy systems.

1.1 Energy Transition Context

Over the last century and a half, global energy demand has grown far more rapidly than the world's population. While the world's population has increased roughly sixfold, global primary energy consumption has experienced a disproportionate twenty-five-fold expansion (Energy Institute [EI], 2025; United Nations [UN], 2024). This difference reveals that the increase in energy consumption cannot be explained solely by population growth, but rather by deeper structural transformations in production systems, the expansion of energy-intensive industrial and service sectors, and the consolidation of global supply chains that rely heavily on fossil fuels. At the same time, accelerated urbanization has concentrated economic activity and infrastructure in cities, increasing the demand for heating, cooling, mobility, and digital services, all of which depend on a continuous and reliable energy supply. It is relevant to note that while primary energy is commonly used for long-term comparisons, its relevance is increasingly questioned in the context of energy transitions, because in these scenarios electrification and efficiency gains can basically reshape how energy demand should be interpreted. In contrast, electricity consumption provides a more direct view of how energy is ultimately used in households, services and industry, and becomes especially relevant in decarbonisation pathways where the electrification of heating, transport and other end-uses plays a central role.

This trajectory indicates that contemporary energy intensity is not merely a byproduct of population scale, but rather the result of systemic structural transformations. Factors such as accelerated urbanization, the mechanization of production systems, and a fundamental technological shift have redefined cultural lifestyles and basic need satisfaction (Smil, 2017). Consequently, addressing the current energy transition requires moving beyond simple demand management to confront the complex socio-technical structures that underpin modern consumption patterns.

In this context of increasing energy consumption and pressure on natural systems, the transition to a system capable of meeting this demand without increasing CO_2 emissions, that is, a decarbonized system, is presented as one of the greatest technological, economic, and social challenges of the 21st century (Herrera & Navarro Rodríguez, 2021). The so-called “energy transition” involves progressively replacing fossil fuels with renewable sources, reconfiguring existing infrastructure, improving efficiency, and electrifying key sectors such as the economy and transportation (International Energy Agency [IEA], 2020). Beyond technical challenges, such as security of supply and balance of payments, this process requires rethinking the organization of the energy system, the role of different actors, and power relations, opening an opportunity to give citizens a central role in energy governance (Sovacool, 2016).

Within this broader transformation, the notion of “community energy” emerges as a model in which groups of people collectively engage in activities such as generation, management and/or consumption of energy, sharing decision-making and benefits at a local scale (Community Energy England [CEE], 2026; Menéndez Sánchez & Fernández Gómez, 2022; Sustainability Directory, 2026). As part of the strategies to move towards a low-carbon electricity system, these initiatives have materialized into what are commonly referred to as energy communities which, despite being named differently depending on the context, share a core objective: to foster citizen participation and democratic governance in the production and use of energy for the benefit of their members (Lawrence Pedroza et al., 2022). These communities aim to generate a combination of environmental benefits, such as renewable energy deployment and emissions reduction; social benefits, including improved energy access, inclusion and local empowerment; and economic benefits, such as reduced energy costs and local value creation, reflecting the three pillars of sustainability.

Building on this broader movement towards decentralized and participatory energy systems, Local Energy Communities (LECs) have emerged as a key governance model to enable citizen participation, local value creation, and the collective management of renewable energy resources. LECs are organizational structures in which citizens, local authorities, and small businesses collaborate to produce, manage, and consume energy at a local scale (Hanke et al., 2026). The concept has gained increasing relevance within European energy policy frameworks, particularly following the Clean Energy for All Europeans Package, which formally recognizes energy communities as actors capable of generating renewable energy, participating in energy markets, and contributing to the decarbonization of the energy system (European Commission [EC], 2019).

Unlike traditional centralized energy models dominated by large utilities, LECs promote decentralized energy production and collective governance structures in which members can actively participate in decision-making processes. These communities typically integrate distributed renewable generation technologies, such as photovoltaic systems, with local consumption, and in some cases incorporate energy storage, demand response mechanisms, or peer-to-peer energy sharing arrangements (Hanke et al., 2026). Beyond their technical role in facilitating renewable energy deployment, LECs are also considered instruments for advancing broader socio-economic objectives, from local economic development, to fostering citizen empowerment and new forms of democratic participation in the energy system, including the integration of households in or at risk of energy poverty (ECODES, 2024).

However, despite their potential, the effective implementation of energy communities faces a number of challenges that affect their long-term viability. Among these, three key areas stand out: managing economic and financial uncertainty, optimizing and technically sizing the systems, and ensuring public accessibility and understanding of these models, in other words, their social cohesion. In this context, there is a growing need for API-based digital tools that can simulate the techno-economic performance and social impact of Local Energy Communities in smart urban environments, providing accessible decision support for both experts and non-experts.

1.2 Challenges for Energy Communities

Building on this general definition, the following subsections examine these three challenges that have been identified across European experiences with Local Energy Communities and are also highly relevant in the Spanish context: economic and financial uncertainty, technical optimization and sizing, and issues of accessibility, understanding, and social barriers.

1.2.1 Economic and Financial Uncertainty

Among the key challenges facing Local Energy Communities (CELs), economic and financial uncertainty stands out as particularly critical, as the viability of these initiatives relies on the stability and predictability of their cash flows (Khorrami et al., 2026). This uncertainty stems primarily from the volatility of wholesale electricity prices, which exhibit significant fluctuations driven by market dynamics, renewable intermittency, and external shocks. Compounding this issue are unstable regulatory frameworks, where sudden policy changes, such as shifts in subsidies, feed-in tariffs, or grid access rules, create prolonged periods of unpredictability, further exacerbating price volatility and deterring investment (Ciarreta et al., 2020).

These factors complicate the estimation of core financial metrics like Net Present Value (NPV), Internal Rate of Return (IRR), and payback period, especially for small-scale projects that struggle to secure external financing. Zatti et al. (2021) highlight the challenges of designing financial models tailored to local contexts, noting that they often fail to capture the dynamic interplay between pricing strategies and market trading structures. Similarly, Khorrami et al. (2026) point to the inflexibility of subsidy schemes in adapting to diverse market conditions and evolving tariffs, while Gianaroli et al. (2024) emphasize the need for robust evaluations of financing instruments like grants, cooperative equity, and loans, as well as market integration to address fragmented adoption across Europe.

1.2.2 Technical Optimization and Sizing

Another crucial challenge for the effective deployment of LECs lies in the optimization and technical sizing of their energy systems. The design of these systems must ensure both economic efficiency and technical reliability while accommodating the heterogeneity of local demand profiles, renewable resource availability, and infrastructure constraints (Gianaroli et al., 2024). Achieving the optimal configuration of generation, storage, and consumption assets requires an integrated approach that simultaneously considers energy flows, investment costs, and operational flexibility across various temporal and spatial scales (Chang et al., 2022).

A key complexity stems from the intermittency of renewable resources such as solar and wind, which introduces variability into generation profiles and complicates load balancing. Improper system sizing, whether under- or over-dimensioning, can lead to inefficiencies, either by increasing curtailment and storage losses or by relying excessively on external grid imports (Zatti et al., 2021). Advanced modelling tools, including mixed-integer optimization, multi-objective algorithms, and machine learning-based forecasting, are increasingly employed to address these issues by enabling data-driven decision-making and adaptive control strategies (Khorrami et al., 2026).

Technical optimization also involves digital platforms capable of coordinating distributed assets in real time. These systems enable demand-response mechanisms, peer-to-peer trading, and predictive maintenance, improving both resilience and user participation (Darii et al., 2025). However, the cost and technical complexity of such solutions can limit adoption, particularly in smaller or rural communities with limited financial and technical capacity.

One of the main operational challenges concerns the definition of energy distribution coefficients. Moving from static to dynamic allocation schemes offers potential efficiency gains, but their technical and administrative implementation remains complex (Llera-Sastresa et al., 2023), and in some national contexts such as Spain these dynamic allocation models are not yet fully recognised or regulated within the existing legal framework. Poorly optimized allocation mechanisms may generate asymmetries among members and discourage participation. Finally, ensuring technically optimized and right-sized energy systems remains a multidisciplinary challenge that intersects engineering, economics, and social dimensions.

Beyond these operational aspects, the deployment of LECs also reflects a broader paradigm shift in the relationship between energy systems and territory. While fossil-fuel based energy infrastructures concentrated most environmental and visual impacts in specific production sites often located far from end-users, renewable-based systems are less energy-dense, non-stock and spatially distributed, bringing generation assets closer to where energy is consumed. This proximity can intensify local debates around land use, landscape impacts and social acceptance, making territorial integration and community engagement critical dimensions of system design and optimisation.

1.2.3 Accessibility, Understanding, and Social Barriers

While community energy initiatives aim to democratize energy governance, participation often requires technical knowledge, financial resources, and institutional capacity that are unevenly distributed across society. In this context, the social gaps produced by the unequal distribution of wealth and the unequal cost of access to energy turn democratization processes into a potential tool for shaping a different energy reality. Yet this democratization of energy faces important challenges, particularly those linked to knowledge gaps and limited energy literacy among citizens, which act as barriers to meaningful participation in community-based initiatives (Calver et al., 2024). According to the Joint Research Centre of the European Commission, insufficient understanding of technical, legal, and financial aspects restricts the ability of households, especially vulnerable ones, to engage with complex tariff models, contract structures, or governance mechanisms potentially reproducing existing social inequalities rather than mitigating them (Koukoufikis et al., 2023).

Empirical evidence shows that LECs often attract individuals with higher income levels and educational backgrounds (Hanke & Guyet, 2023), leading to the underrepresentation of women, youth, and low-income households in community energy projects. This indicates that participation barriers are not only technical but also deeply socio-structural. Factors such as limited community cohesion, mistrust in collective governance, and the absence of participatory decision-making frameworks can discourage even more citizen involvement (Bielig et al., 2022).

From an energy justice perspective, this unequal participation raises concerns regarding the distribution of benefits and decision-making power within community energy initiatives. Without deliberate inclusion strategies, LECs risk reproducing existing social and economic hierarchies rather than mitigating them (ECODES, 2024). Measures such as participatory governance mechanisms, inclusive education programs, and targeted support for underrepresented groups are therefore essential to ensure that the energy transition becomes a genuinely collective and equitable process.

Finally, another important social challenge relates to the difficulty of defining and measuring the social impacts. While these initiatives are often associated with positive outcomes such as increased participation, social cohesion, and empowerment, these effects are difficult to capture through standardized indicators. Social impacts frequently manifest through perceptual, emotional, and community-based dimensions that cannot be easily translated into quantitative or monetary metrics (Epstein & Yuthas, 2014; Vurro & Perrini, 2013). As a result, assessing whether community energy projects effectively contribute to reducing social inequalities or improving collective well-being remains methodologically complex. Consequently, the lack of consistent evaluation frameworks complicates the assessment of whether these initiatives effectively reduce inequalities and improve collective well-being (Bielig et al., 2022).

1.3 Motivation

Despite the growing interest in Local Energy Communities as instruments for advancing the energy transition, their implementation faces a persistent gap between technical complexity and local capacity. Designing and operating community-based energy systems requires integrated techno-economic assessments that consider generation, storage, demand profiles, and market interactions. However, the analytical tools required for such evaluations are often complex and inaccessible to local actors without specialized expertise. At the same time, the digitalization of energy systems offers new opportunities to support data-driven decision-making and system optimization. Nevertheless, without accessible digital tools and simplified analytical frameworks, communities may struggle to translate these technological opportunities into practical solutions.

In the specific context of Spain, where the regulatory framework for energy communities is still evolving and where issues such as economic uncertainty, technical sizing and the need to ensure active community participation beyond purely technical system design. There is a need for tools that translate complex techno-economic and social assessments into accessible outputs for local actors. Developing a digital, API-based simulation tool for LEC can therefore contribute to bridging this gap by providing transparent, scenario-based analyses of financial viability and social impact tailored to the Spanish context.

Chapter 2

State of the Art

This chapter reviews the theoretical and empirical literature underpinning the research questions of this thesis. It is organized into four thematic sections. Section 2.1 examines the European regulatory framework for Local Energy Communities. Section 2.2 presents the key operational concepts, focusing on collective self-consumption and sharing coefficients. Section 2.3 surveys the methods and indicators commonly used for the economic evaluation of renewable energy projects. Section 2.4 addresses the social dimension of LECs, reviewing the literature on social impact assessment.

2.1 Definition and European Legal Context

The conceptualization of Local Energy Communities (LECs) in the European Union is grounded in the “Clean Energy for all Europeans” package, which recognizes collective action as a pillar of the energy transition toward a decentralized system. The definition is primarily articulated through two key directives: Renewable Energy Communities (RECs), introduced by Directive (EU) 2018/2001 (RED II, Article 22) (European Parliament and of the Council [EU Parliament], 2018), and Citizen Energy Communities (CECs), established by Directive (EU) 2019/944 (IEMD, Article 16) (EU Parliament, 2019).

These documents state that Renewable Energy Community is a legal entity based on voluntary and open participation, autonomous in operation, and effectively controlled by members located in the proximity of the renewable energy projects it owns and develops. Its members may include individuals, SMEs, or local authorities, and its primary purpose is not financial profit but the delivery of environmental, social, and economic benefits to members or the local area. A Citizen Energy Community broadens the scope beyond renewable generation, operating across the entire electricity market (including generation, distribution, supply, consumption, aggregation, and energy storage). Membership must be open to all categories of entities, but decision-making powers are reserved for members who dont́ conduct energy activities as their primary commercial occupation, preventing the concentration of control by large market players, promoting non-discriminatory, transparent, and inclusive participation by local actors.

Despite their regulatory differences, EU law defines both of them as non-commercial entities whose primary purpose is to deliver environmental, economic, or social benefits, emphasising active participation and effective control by citizens, local authorities, or smaller businesses (REScoop.eu & ClientEarth, 2020). In this context, their shared goals include: citizen participation in energy production and decision-making; supporting a decentralised energy transition through distributed generation; promoting the democratisation of energy through shared ownership and governance; and contributing to environmental sustainability through renewable energy integration and emissions reduction (Koukoufikis et al., 2023)

Building on these common features, this thesis adopts the term Local Energy Communities (LECs) as an umbrella concept encompassing both Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs). In this broader sense, LECs refer to collaborative initiatives in which local actors (such as households, businesses, civil society organizations, and municipalities) collectively engage in the production, management, or consumption of energy at the local level. These initiatives are typically driven by bottom-up participation and they aim to promote environmental sustainability for local energy autonomy, and more democratic governance of energy systems (Bonfert, 2024). LECs are generally characterized by relatively open and participatory governance structures, although they may differ significantly in their organizational models, business structures, and technological configurations (Bokolo, 2026).

2.2 Operational Concepts

This section introduces the two core operational concepts that underpin the design and assessment of LECs in the Spanish context: collective self-consumption (Section 2.2.1) and sharing coefficients (Section 2.2.2).

2.2.1 Collective Self-Consumption

Collective self-consumption (CSC) refers to the shared use of locally generated renewable electricity among a group of two or more consumers who are typically located in the same building, multi-apartment block, or within a defined geographic proximity. The concept is also articulated in Directive 2018/2001 (RED II, Article 21) (EU Parliament, 2018), which defines “jointly acting renewables self-consumers” as cooperating final customers who generate renewable electricity for their own consumption and are permitted to arrange the sharing of that energy among themselves. It is important to distinguish CSC as an activity (the act of sharing locally produced energy) from the organizational formats of RECs and CECs discussed in section 2.1. While EC are legal entities with governance and membership structures, CSC can occur both within and outside these organizational frameworks.

In the Spanish context, which is the main focus of this thesis, Royal Decree 244/2019 established a specific framework for collective self-consumption by allowing the association of several consumers with a shared generation installation, based on proximity criteria and a simplified surplus compensations mechanism. From a network perspective, two main modalities can be distinguished: behind-the-meter collective self-consumption ("red interior") and grid-based through the public distribution network. In the first case, the sharing is on the internal wiring of a building or condominium, so some of the generation is directly consumed and does not have to go through the distribution network. By contrast, in the second case, all energy is injected into the distribution grid and allocated to each participant via virtual sharing on the electricity bill (EU Parliament, 2019); in this case, the distribution network does not technically "see" the internal allocation, which is implemented through contractual and billing arrangements. More recently, the draft reform of RD 244/2019 proposes extending the maximum distance for proximity criteria from 2 to 5 kilometres and introduces the figure of the "self-consumption manager" to streamline administrative procedures in collective projects (Gallego-Castillo et al., 2021).

2.2.2 Sharing Coefficients

A crucial element in the operation of collective self-consumption schemes and energy communities is the sharing coefficient (also referred to as distribution coefficient or sharing key), which determines the proportion of locally produced energy allocated to each member of the community (Directorate-General for Energy [DG ENER], 2024). In the Spanish context, each participant is identified by a Universal Supply Point Code (CUPS), and the entire installation is registered under a Self-Consumption Code (CAU). The community's generation is divided between all associated CUPS for every billing hour according to a set of coefficients whose hourly sum must equal one, and any surplus not immediately consumed is injected into the grid and later compensated individually on each participant's electricity bill (Instituto para la Diversificación y Ahorro de la Energía [IDAE], 2024). These coefficients are defined by mutual agreement among participants and notified to the Distribution System Operator (DSO), which uses them in the metering and settlement process (IDAE, 2024; Villalonga Palou et al., 2023).

In the literature, usually three main types of sharing coefficients are distinguished. Fixed equal coefficients divide surplus energy equally among all members, whereas fixed proportional coefficients allocate surplus according to a pre-defined criterion, such as each member's contracted power, investment share or annual demand (DG ENER, 2024). Variable (dynamic) coefficients are recalculated at each time interval (e.g. every 15 minutes or hourly) in proportion to real-time or forecast consumption, often using data-driven or optimisation-based approaches (Madrigal et al., 2026; Queiroz et al., 2023). Several studies have shown that time-varying or dynamically optimised coefficients can increase community self-consumption and self-sufficiency, reduce surplus injections and reduce overall energy costs compared to static schemes, even if they also introduce larger variability and uncertainty in the allocation of individual benefit (IDAE, 2024; Llera-Sastresa et al., 2023; Madrigal et al., 2026; Shooshtari et al., 2025)

The choice of how sharing rule is going to be within the community has important implications for both, the economic performance and the perceived fairness of LECs members. Consumption-based or dynamically adapted coefficients tend to improve the results of aggregate indicators such as self-consumption and cost savings, but may favour larger or more flexible consumers, leading to distributional imbalances (Llera-Sastresa et al., 2023). Conversely, simple static or investment-proportionate coefficients are often viewed as more transparent and equitable, even if they can be less efficient in matching generation and demand over time (EC, 2023; Madrigal et al., 2026). Balancing these efficiency–equity trade-offs under existing regulatory constraints makes the design of sharing coefficients a critical modelling choice in the techno-economic assessment of collective self-consumption schemes and Local Energy Communities.

2.3 Economic Evaluation of Energy Projects

While the previous section established the regulatory and governance dimensions of Local Energy Communities (LECs), their effective deployment ultimately depends on proving financial viability to potential members, investors, and policymakers. Energy projects are usually evaluated economically using the discounted cash-flow techniques, which compare investment costs, operating costs, and expected revenues over the project lifetime.

In this framework, capital expenditures (CAPEX) refer to the upfront investment required to acquire and install the energy system, while operating expenditures (OPEX) include recurring costs such as operation, maintenance, insurance, and, where relevant, electricity purchases from the grid (Novak Pintařič & Kravanja, 2017; Wilson et al., 2025). These cost and revenue streams are represented through a cash-flow profile and discounted to present value using a rate that reflects both the time value of money and project risk, forming the basis of standard financial appraisal in energy systems (Gilson Dranka et al., 2020; Short et al., 1995).

Energy projects based on renewable generation are usually assessed over relatively long time horizons, often around 20 to 25 years, in order to reflect the technical lifetime of assets such as photovoltaic systems and wind turbines (Richter et al., 2017). During these periods, economic outcomes are highly sensitive to assumptions about technical degradation, electricity price evolution, tariff structures, and regulatory conditions. Variations in these parameters can significantly affect financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and payback period (Short et al., 1995; Wilson et al., 2025). For this reason, sensitivity analysis is widely recommended in renewable energy project evaluation, especially under volatile market conditions (Akteruzzaman, 2025).

Within this framework, NPV and IRR remain the principal indicators for assessing absolute and relative profitability. NPV measures the difference between the present value of expected cash inflows and outflows, while IRR represents the discount rate at which NPV equals zero (Short et al., 1995). In the context of LECs, these indicators remain applicable but require careful interpretation, as community-based projects often involve heterogeneous participants, longer investment horizons, and objectives that extend beyond profit maximization. As a result, the discount rate applied in such projects may be lower than in purely commercial investments, reflecting social and environmental motivations alongside financial returns (EC, 2020; Hanke et al., 2026). The literature also supports the use of risk-differentiated discount rates across configurations of the same project to reflect the conditions and technology-specific risk fees (IEA, 2024), a principle that will be applied in the methodological design in this work (see Section 5.4).

In addition, the Levelized Cost of Energy (LCOE) is widely used to express the average lifetime cost of electricity generation per unit of output and to compare generation technologies. It also provides an approximate benchmark for economic viability, as it indicates the minimum electricity price at which a project would need to recover its lifetime costs under the assumed operating conditions. Similarly, the Levelized Cost of Storage (LCOS) can be used to assess the cost of stored electricity remains compatible with the price signals of the target market, particularly in systems where storage is expected to enhance self-consumption or reduce grid purchases (Lazard, 2024). However, in collective self-consumption schemes and LECs, generation-based metrics alone are insufficient, as participants typically rely on a combination of locally generated and grid-supplied electricity. For this reason, their economic performance is affected by factors such as self-consumption rates, electricity purchase prices, tariff structures, and the allocation of costs among members. Therefore, the literature increasingly highlights the need for complementary, user-oriented indicators that reflect the actual cost of electricity consumed rather than only generated (Chaudhry et al., 2022; Pagnini et al., 2024).

The Simple Payback Period (SPP) remains a relevant and intuitive indicator, particularly for non-expert participants, as it provides a straightforward estimate of the time required to recover the initial investment. However, because it does not account for the time value of money or after-payback cash flows, it should be interpreted as a complementary screening metric rather than a stand-alone decision criterion (Manso-Burgos et al., 2021; Short et al., 1995).

Nevertheless, relying exclusively on these indicators may provide a narrow perspective of the assessment of community energy projects. Standard cash-flow approaches tend to monetise only direct financial costs and revenues, leaving out wider collective benefits such as local value creation, social cohesion, energy security and environmental co-benefits, which are central to energy communities (EC, 2020; Hanke et al., 2026). Moreover, the economic evaluation of LECs should consider how costs and benefits are distributed among participants, as allocation mechanisms strongly influence perceived fairness and user acceptance (Basilico et al., 2025a; Zelaia Eizaguirre, 2023). For this reason, the financial indicators implemented in digital tools for community energy planning should ideally be complemented by distributional or multi-criteria perspectives when the objective is not only profitability, but also equitable and socially robust decision-making.

2.4 Social Dimension of Local Energy Communities

Energy poverty is an issue of particular relevance in this debate. It is the lack of access by households to adequate energy services at an affordable price, which impacts on thermal comfort, health, and general living conditions; moreover, it is also related not only to income constraints but also to housing conditions, energy prices, and access to essential energy services (Parreño-Rodriguez et al., 2023). LECs aim to tackle this problem due to their local and benefit-oriented nature by improving the equitable access to renewable electricity and by enabling solidarity-based redistribution mechanisms, such as reduced tariffs, priority allocation of benefits, or the transfer of surplus electricity to vulnerable consumers free of charge or at reduced prices (ECODES, 2024).

From a socio-economic perspective, LECs can contribute to local development by keeping value within the community, through mobilising local investment, supporting local employment, and strengthening collective ownership over energy infrastructures. Their governance structures may also reinforce trust, participation, and community cohesion (EC, 2020). Recent research further shows that community management can promote collective well-being when their organisational and economic design includes benefit-sharing mechanisms that assist members with lower self-consumption capacity or households in vulnerable situations (Basilico et al., 2025b). Therefore, the social assessment of LECs should not be limited to aggregate community savings, but should also include indicators that capture the distribution of benefits and their contribution to reducing vulnerability. Relevant indicators may include the percentage of savings achieved by vulnerable households, the reduction in household energy expenditure, the number of supported beneficiaries, the volume of energy transferred under solidarity schemes, and the degree of participation in governance processes (Bielig et al., 2022; ECODES, 2024).

Chapter 3

Objectives and Research Questions

Building on the literature review and the challenges identified for Local Energy Communities (LECs) in terms of economic uncertainty, technical sizing, and social inclusion, this chapter sets out the objectives and guiding research questions of the thesis.

3.1 General and Specific Objectives

The general objective of this thesis is to develop and integrate a techno-economic evaluation module into an API-based digital tool that allows the simulation of the financial viability and social impact of Local Energy Communities in smart urban environments.

The following specific objectives (SO) are derived from the general objective:

SO1. To define and structure the technical and economic parameters (based on the company's reference model) and prepare their input format for data ingestion through the API.

SO2. To develop the financial calculation algorithm (NPV, IRR, and payback), explicitly differentiating between the investor's perspective (return on capital and risk) and the end-user's perspective (net savings and payback periods).

SO3. To implement a sensitivity analysis module that maps the relationship between self-consumption rate, participant demand, and financial viability, enabling the identification of the minimum viable operating conditions for a given PV installation and supporting the assessment of sizing adequacy relative to community demand.

SO4. To design and integrate a social impact indicator module that quantifies the savings generated by the Local Energy Community, including scenarios of energy sharing with vulnerable consumers, and estimating its potential contribution to reducing energy poverty.

SO5. To explore how participation in a Local Energy Community can complement existing support mechanisms for vulnerable consumers (social tariff, grants, or reduced tariffs), analysing their potential combined contribution to the reduction of energy poverty.

3.2 Research Questions

The following research questions (RQ) are formulated in correspondence with the specific objectives defined above. They serve as the analytical backbone for the methodological design (Chapter 4) and the discussion of results (Chapter 6).

RQ1: How does the correct parameterisation of dynamic variables (inflation, degradation, and market prices) influence the precision of financial viability indicators (NPV and IRR) for a Local Energy Community? **(SO1)**

RQ2: Under what conditions of energy prices, investment costs, and public support do Local Energy Communities in Spain achieve a positive NPV and an IRR above the cost of capital? **(SO2)**

RQ3: How does the ownership model of a LEC affect the divergence between investor and end-user perspectives, and to what extent is this divergence governed by financial parameters versus distributional and social choices? **(SO2, SO4)**

RQ4: What is the minimum self-consumption rate required for a photovoltaic collective self-consumption installation to achieve financial viability, and how does this threshold vary with participant demand, electricity prices, and investment horizon? **(SO3)**

RQ5: To what extent do free energy allocations within a LEC contribute to reducing the energy bill and the energy effort rate of vulnerable households? **(SO4)**

RQ6: How are economic and social benefits distributed between vulnerable and non-vulnerable participants within a LEC, and what tensions emerge between redistribution objectives and investment return requirements? **(SO4, SO5)**

RQ7: To what extent does the governance model of a LEC correlate with the share of benefits allocated to vulnerable households? **(SO4, SO5)**

3.3 Scope of the Study

The framework is designed to support project-level techno-economic and social evaluation of Local Energy Communities based on photovoltaic generation, with or without battery storage. It is not a network simulation tool and does not model power flows, voltage profiles, or grid infrastructure constraints. Sub-hourly load dynamics are outside its scope; the model operates on aggregated annual energy balances derived from hourly or representative demand and generation profiles.

On the economic side, the tool evaluates financial performance from the perspective of the LEC as a collective investment unit. It does not model individual member cash flows, nor does it account for taxation at the household level, financing structures involving debt, or the full complexity of Spanish regulatory arrangements beyond the parameters explicitly incorporated into the scenarios.

The social module is bounded by the availability and quality of qualitative evidence. It provides structured, indicator-based approximations of governance quality, community participation, and redistributive impact. It does not measure outcomes such as employment effects, health improvements, or long-term behavioural change, and its results should not be interpreted as precise social impact measurements.

The framework is validated through a single rural case study, Mediana de Voltoya, in Castilla y León, Spain. While the methodology is designed to be replicable, its transferability to urban contexts, multi-site communities, or regulatory environments other than the Spanish one has not been tested and should be approached with caution.

Chapter 4

Methodology

This chapter describes the methodological approach followed to develop an integrated assessment framework for Local Energy Communities. The framework is designed to generate decision-oriented outputs that capture the financial feasibility, risk exposure, and social implications of different community energy configurations. To produce these outputs, the methodology combines technical, economic, and contextual input data, including energy demand and generation profiles, investment and operating costs, market and regulatory parameters, and social indicators related to community participation and local impact.

It is presented in three stages: first, the financial evaluation framework is defined; second, the social impact dimension is incorporated; and third, both components are implemented in Python to be later integrated in an assessment tool. Together, these methodological elements enable the evaluation of Local Energy Community scenarios from both economic and social perspectives.

4.1 Research Design

This study adopts an applied research approach aimed at developing a computational tool to support decision-making in Local Energy Communities (LECs), grounded in a quantitative methodology based on techno-economic modelling. In line with the specific objectives defined in Chapter 3, the main contribution of this work lies in the design and implementation of an integrated assessment framework composed of three core components: (i) a financial calculation engine, (ii) a risk analysis module, and (iii) a social impact assessment module. Together, these components bridge the gap between technical system design and accessible, decision-relevant tools for regional stakeholders.

The framework is applied to the real-world case of the LEC of Mediana de Voltoya (MdV) in order to validate the proposed methodology under realistic conditions, and allows to examine its robustness, applicability, and interpretability in a practical context.

4.2 Procedure

This section explains the conceptual structure of the financial model, as well as the social module, the main assumptions adopted, and the methodological choices that enable the framework to be replicated in other case studies. Later, it will be integrated within the tool, focusing on software implementation.

4.2.1 Development of the Financial Calculation Engine

This module is designed to estimate the economic performance of LECs under different technical and organisational scenarios. Its purpose is to generate a set of decision-oriented financial indicators based on the interaction between electricity demand, renewable generation, investment requirements, operating costs, and market assumptions.

The financial module relies on a set of technical and economic input parameters that characterise each scenario. On the technical side, the most relevant inputs are the electricity demand profile, the photovoltaic (PV) generation profile, the installed PV capacity, and, where applicable, the battery storage capacity. Electricity demand profiles can be constructed from historical consumption records provided by distribution companies, smart metering data, or engineering estimates based on typical load patterns. PV generation profiles are derived from irradiance datasets and system-specific parameters using tools such as PVGIS or equivalent simulation platforms, which produce hourly or sub-hourly production time series.

Economic Assumptions and Scenario Parameters

The main economic inputs include capital expenditure (CAPEX), annual operating expenditure (OPEX), project lifetime, discount rate, electricity price, electricity price growth rate, and photovoltaic degradation rate. In cases where storage is considered, battery-related parameters such as depth of discharge, round-trip efficiency, C-rate, and degradation assumptions are also incorporated. For transparency and replicability, the complete parameter tables used in the model are included in Appendix A.

To start with, some important general parameters need to be defined:

- *Discount rate* is used to reflect the opportunity cost of capital and the perceived investment risk of the LEC. In practice, values in the range of 3% to 8% are commonly adopted in community energy and renewable energy project appraisal, depending on the financing structure and the risk profile of the investment (Grant Thornton, 2019; Steinbach & Staniaszek, 2015). Literature also supports the use of risk-differentiated discount rates across configurations of the same project to reflect technology-specific risk fees (IEA, 2024; Munson, 2024), which is a principle that is applied in the scenario design for Mediana de Voltoya (see Section 5.4).
- *PV degradation* rate is introduced to account for the gradual reduction in electricity

output over time as the photovoltaic system ages. Typical values in the literature and in manufacturer specifications are generally close to 0.3% to 0.8% per year, and the selected value lies within this range (Pascual et al., 2021).

- *Electricity price growth rate*. This parameter is introduced to reflect the fact that the economic value of self-consumed electricity depends on the future cost of grid electricity. Since future price trajectories are uncertain, this parameter is treated as a scenario assumption rather than a point forecast.
- *Self-consumption ratio*. Self-consumption assumptions play a central role in the financial logic of the model, as they determine how much of the generated electricity offsets grid purchases and how much is exported as surplus. In PV-only systems, the self-consumption ratio is derived from the temporal interaction between demand and generation profiles. When battery storage is included, this relationship becomes dynamic, as part of the surplus may be shifted to later periods of demand; accordingly, battery inclusion is modelled as an element that modifies effective electricity utilisation over the project lifetime, rather than as a static capacity add-on. The complete set of adopted input values is provided in Appendix A.2.

Step 1. Investment and Operating Cost Estimation

The first calculation stage concerns the estimation of investment and operating costs. CAPEX includes the cost of the photovoltaic system and, where applicable, the storage system. When explicit project quotations are not available, unit investment costs are estimated as a function of installed capacity using benchmark market values. This allows the model to approximate realistic investment levels for systems of different sizes while maintaining consistency across scenarios.

The central relationship used for this estimation is the unit cost function C(P), where C(P) represents the unit cost associated with an installation of size P. In case it is not given as a direct input, the model interpolates the unit cost based on installed capacity using market data breakpoints:

$$C(P) = C_i + \frac{C_{i+1} - C_i}{P_{i+1} - P_i}(P - P_i) \tag{1}$$

In practice, this function is derived from benchmark cost intervals and used to determine a representative cost per unit of installed capacity. Based on this, installer CAPEX is calculated as:

$$CAPEX_{\text{inst}} = P_{PV} \times C_{PV} + E_{bat} \times C_{bat} \tag{2}$$

where P_{PV} is the installed photovoltaic capacity, C_{PV} is the unit cost of the PV system, E_{bat} is the battery capacity, and C_{bat} is the corresponding unit storage cost.

From this base value, the final investment cost is adjusted conceptually through commercial margins, subsidies, and applicable taxes. These adjustments are project- and context-specific and are therefore described conceptually rather than formalised through additional equations in the main text. Annual operating costs (OPEX) are estimated either from explicit project data or as a percentage of initial CAPEX. Values in the range of 0.5% to 1.5% of CAPEX are commonly referenced in the renewable energy literature; for Spanish projects some articles recommend 1% following a conventional approach in renewable energy project appraisal. Formulas and parameter values are provided in Appendix A.2 and A.3 to facilitate replication.

Step 2. Estimation of Energy-Related Economic Benefits

Once costs have been characterised, the model estimates the yearly economic benefits associated with energy production. These benefits derive from two main sources: savings obtained through self-consumption and revenues associated with surplus electricity exported to the grid. Both components are calculated on a yearly basis and are updated over the project lifetime to reflect changes in system performance and electricity prices.

First, photovoltaic electricity production is adjusted over time using a degradation factor, so that annual output declines gradually as the system ages. Second, the monetary value of self-consumed electricity is updated through an electricity price growth assumption, reflecting the fact that future avoided purchases from the grid may become more valuable over time. On this basis, the total annual savings are given by:

$$\textit{T. Savings}_t = E_{self,t} \times P_{cap_t} + E_{surplus,t} \times P_{sale} \tag{3}$$

where T. Savings is the total annual saving in year t, $E_{self,t}$ is self-consumed electricity, P_{cap_t} is the applicable electricity purchase price, $E_{surplus,t}$ is exported surplus electricity, and P_{sale} is the remuneration or compensation price for exports.

The central equations governing the evolution of production and electricity prices over time are detailed in Appendix A.

Within the LEC, these annual benefits may subsequently be distributed among investors, participating users, or social support mechanisms depending on the organisational design of the initiative. Since these allocation rules are case-specific and do not alter the underlying physical generation of value, they are described conceptually in the model as part of the value allocation logic rather than through a large number of additional equations in the main methodology chapter.

Battery Performance Refinements

When battery storage is included, the estimation of economic benefits is refined through a set of operational and degradation assumptions intended to represent storage behaviour in a physically consistent way. Since battery modelling is not the primary focus of this study, the emphasis here is on the conceptual meaning of the parameters and the typical ranges found in the literature and in industry practice; technical implementation details are provided in the appendices.

The key parameters incorporated into the model are the following. State of Health (SoH) represents the gradual decline in usable storage capacity as the battery ages, driven by both calendar ageing and cycle degradation. Depth of Discharge (DoD) defines the portion of nominal capacity that can be safely used; values typically range from 0.80 to 0.95, with values above 0.90 generally warranted only for LFP (Lithium Iron Phosphate) chemistry. The present model adopts a DoD of 0.90, consistent with manufacturer recommendations for LFP cells. Round-Trip Efficiency (RTE) captures storage losses during charge and discharge; the value adopted here (0.88) implies that only 88% of solar energy directed into the battery is ultimately recovered as usable electricity. C-rate constrains charging and discharging power relative to battery capacity. Equivalent Full Cycles (EFC) are used to track cumulative battery use and to identify the point at which battery replacement should be modelled.

In methodological terms, these assumptions matter because they determine how much electricity can actually be stored and recovered, how rapidly the battery can charge and discharge, and how storage performance evolves throughout the project lifetime. A complete list of battery parameters and adopted values is provided in Appendix A.3.2

Step 3. Construction of Project Cash Flows

After costs and benefits have been estimated, the model constructs annual cash flows over the selected project horizon. This step makes it possible to represent the temporal distribution of investment costs, operating costs, replacement costs, and annual economic returns in a consistent way.

In year 0, the model records the initial net investment associated with the selected system configuration. From year 1 onwards, annual cash flows are obtained by combining the income derived from energy-related benefits with recurring OPEX and, where applicable, component replacement or end-of-life costs. In battery scenarios, replacement costs are introduced when the battery reaches the end of its assumed service life. The resulting annual free cash flow can be expressed as:

$$FCF_t = \textit{Income}_t - \textit{Costs}_t - \textit{Taxes}_t \tag{4}$$

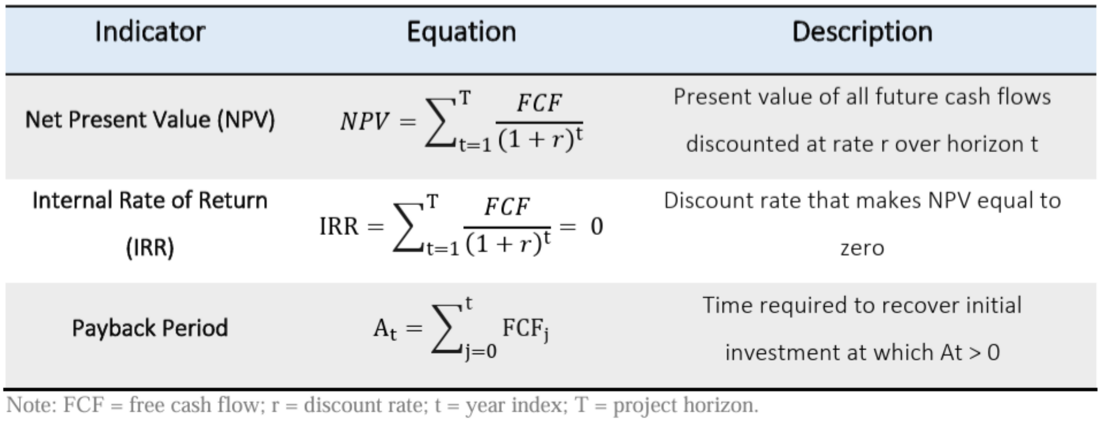
where FCF_t is the free cash flow in a year, Income_t represents the annual economic benefit captured under the selected scenario, Costs_t includes operating and replacement costs, and Taxes_t represents any fiscal charge considered in the analysis.

Step 4. Calculation of Financial Indicators

The final step of the financial module consists of calculating the key performance indicators used to assess project viability and compare scenarios. The three main indicators are Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period, as these are widely used in investment appraisal and are easily interpretable by both researchers and practitioners.

NPV is used to measure the present value of all project cash flows discounted (r) over the analysis horizon (t), and therefore indicates whether the project creates value under the assumed discount rate. IRR identifies the discount rate at which the NPV becomes zero and provides a relative measure of project profitability. Payback Period captures the time required for cumulative cash flows to recover the initial investment. Together, these indicators provide a concise and robust basis for comparing alternative LEC configurations, including scenarios with different self-consumption structures, storage options, and support mechanisms. Their formal definitions are given in Table 4.1.

Table 4.1. Financial Key Performance Indicators.



Indicator	Equation	Description
Net Present Value (NPV)	$NPV = \sum_{t=1}^{T} \frac{FCF}{(1+r)^{t}}$	Present value of all future cash flows discounted at rate r over horizon t
Internal Rate of Return (IRR)	$\mathrm{IRR} = \sum_{t=1}^{T} \frac{FCF}{(1+r)^{t}} = 0$	Discount rate that makes NPV equal to zero
Payback Period	$A_t = \sum_{j=0}^{t} \mathrm{FCF}_j$	Time required to recover initial investment at which At > 0

Note: FCF = free cash flow; r = discount rate; t = year index; T = project horizon.

These indicators constitute the final output of the financial module and support the economic comparison of alternative scenarios. To enhance reproducibility and enable the automated evaluation of multiple cases, the financial calculation procedure was implemented in Python (explained in Section 4.2.3). Next, in Figure 4.1 the conceptual framework and system boundary of the financial assessment module is presented, showing external technical and economic assumptions and the outputs.

4.2.2 Design of the Social Impact Module

This section presents the methodological design of the social impact module integrated into the proposed assessment tool. Whereas the financial module evaluates the economic performance of a LEC, the social module is intended to capture the extent to which the initiative generates socially relevant outcomes at the local level. In line with the theoretical framework presented in Section 2.4, the methodology assumes that the value of an LEC cannot be assessed exclusively through economic efficiency, but must also consider fairness in benefit distribution, the inclusion of diverse social groups, and the capacity to support participatory governance.

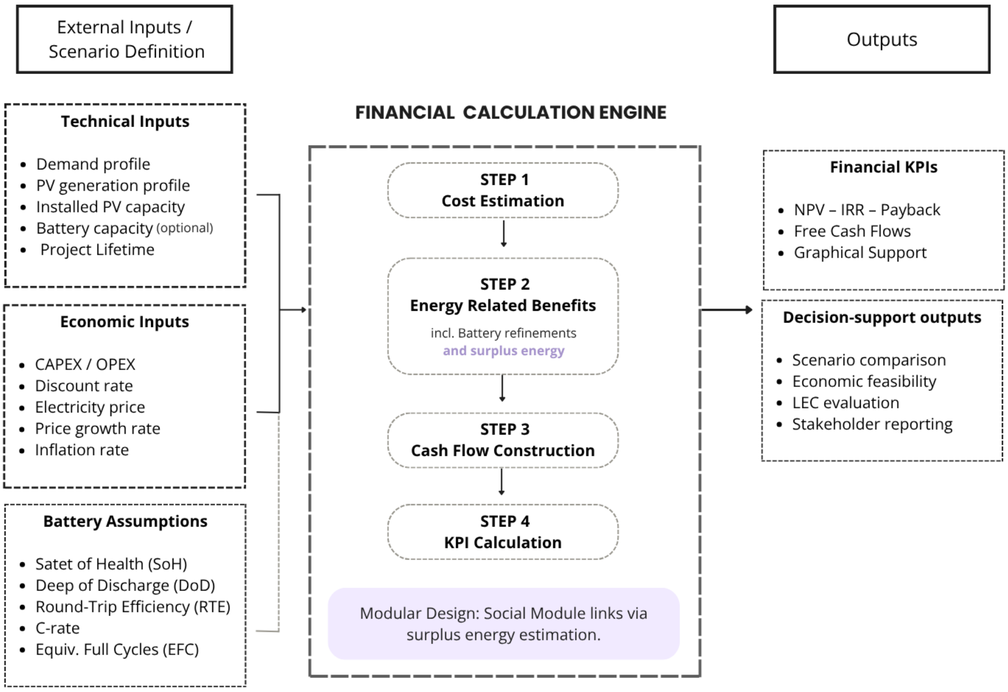


Figure 4.1. Conceptual framework of the financial calculation engine..

Conceptual Framing

For the purposes of this thesis, social impact is defined as the set of positive effects that a LEC generates for its members and the broader community beyond economic returns. These effects are conceptualised through two complementary dimensions: a process dimension, concerned with how the initiative is governed and how community participation is enabled; and an outcomes dimension, concerned with the distribution of energy-related benefits and the potential to reduce energy vulnerability. Additionally, the tool reports the Barriers & Enabling Conditions as a separate contextual layer, capturing how conducive the surrounding economic, social, and administrative environment is to the initiative's development. The relationship between these dimensions and the indicators they generate is illustrated in Figure 4.2 below.

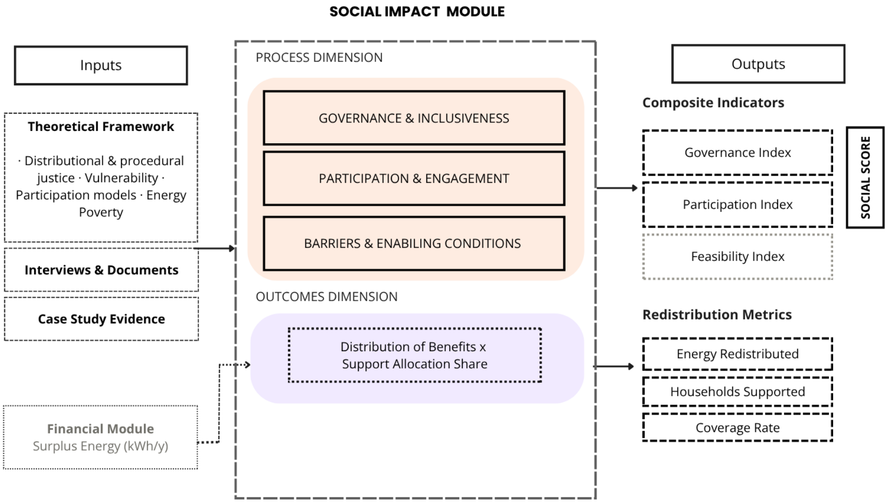


Figure 4.2. Workflow from theoretical framework to social score..

Indicator Selection and Operationalisation

Given the conceptual complexity of social impact and the limited possibility of measuring it through purely quantitative variables, the module adopts an indicator-based approach informed by qualitative evidence. More specifically, key dimensions identified in the literature (especially distributional justice, procedural justice, and the mitigation of energy vulnerability) are translated into a set of operational indicators. The aim is not to provide an exhaustive measurement of all possible social effects, but rather to establish a structured and replicable framework through which social criteria can be adapted to the evidence available in the case study.

It is important to acknowledge that this selection is itself an interpretive act: the choice of which dimensions to measure, and how to weight them, reflects underlying normative assumptions about what constitutes a desirable LEC (see Section 2.4). The framework is oriented towards participatory, horizontally governed models, not because this is the only valid model, but because it aligns with the social justice principles that motivate the research.

To translate the conceptual framework into an empirical assessment, the module operationalises a reduced set of indicators that can be populated with case-specific data. The selection of indicators follows two criteria: (i) each indicator must correspond to a theoretically relevant dimension of social impact, and (ii) it must be possible to compute or categorise each indicator using the data available for the case study.

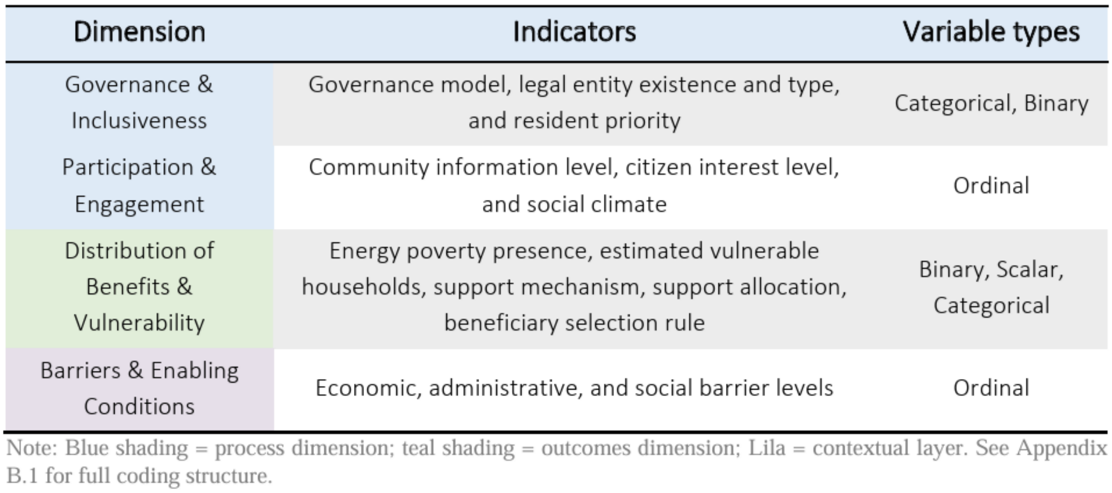
The indicators are grouped into four thematic dimensions:

- *Governance and Inclusiveness:* reflects how decision-making is organised, whether a formal legal entity exists, and whether access conditions are designed to include local residents or other priority groups.
- *Participation and Engagement:* captures the level of local information, citizen interest, and the general level of social support or conflict surrounding the initiative.
- *Distribution of Benefits and Vulnerability:* examines how benefits are allocated, whether vulnerable households are considered, and whether specific support measures address energy poverty.
- *Barriers and Enabling Conditions:* identifies economic, administrative, and social factors that may facilitate or limit participation.

Within this methodology, interview material plays a central role, because several social dimensions of the LEC cannot be inferred from technical or financial data alone. In particular, interviews provide evidence on expected beneficiaries, perceived barriers to participation, governance arrangements, and potential distributional effects. This information is not treated merely as descriptive context, but is systematically codified as input data to characterise the social design of the initiative.

To improve replicability, variables are assigned predefined admissible values. Four variable types are used: binary variables (presence or absence of a feature), categorical variables (institutional or organisational configurations), ordinal variables (reflect intensity or degree, for example the level of community information or social conflict), and scalar variables (quantifiable aspects such as the estimated number of vulnerable households). A summary of the indicator structure is presented in Table 4.2; the full coding structure and admissible values are provided in Appendix B.

Table 4.2. Summary of Social Module Indicators.



Dimension	Indicators	Variable types
Governance & Inclusiveness	Governance model, legal entity existence and type, and resident priority	Categorical, Binary
Participation & Engagement	Community information level, citizen interest level, and social climate	Ordinal
Distribution of Benefits & Vulnerability	Energy poverty presence, estimated vulnerable households, support mechanism, support allocation, beneficiary selection rule	Binary, Scalar, Categorical
Barriers & Enabling Conditions	Economic, administrative, and social barrier levels	Ordinal

Note: Blue shading = process dimension; teal shading = outcomes dimension; Lila = contextual layer. See Appendix B.1 for full coding structure.

Indicators and Impact Metrics

The coded variables are aggregated into three types of outputs: composite indicators summarising governance and participation quality, the Implementation Feasibility Index as a parallel contextual diagnostic, and redistribution metrics quantifying distributional impact.

Composite Indicators

The Governance Index is a weighted composite of three sub-indicators. The governance model receives the highest weight (0.40), reflecting the determining factor of whether it is municipal, intermediate, or mixed. According to the literature, this defines community autonomy and its centrality to procedural justice. The existence of a legal entity follows (0.35) as a threshold indicator of formal accountability and the enforceability of rights. Finally, the citizen-led nature of the entity receives a weight of 0.25, reflecting the substantive distinction between forms controlled by citizens and those controlled by the municipality, without attempting to establish a more precise gradation.

The Participation Index is calculated similarly using three sub-indicators. Citizen interest receives the highest weighting (0.40) as the most direct signal of genuine participation. This is followed by the level of community information (0.35) as a structural condition: meaningful participation cannot occur in an information vacuum. The social climate index weights the level of acceptance/conflict, and, being partially exogenous to the initiative's design and governance decisions, receives the lowest weighting (0.25).

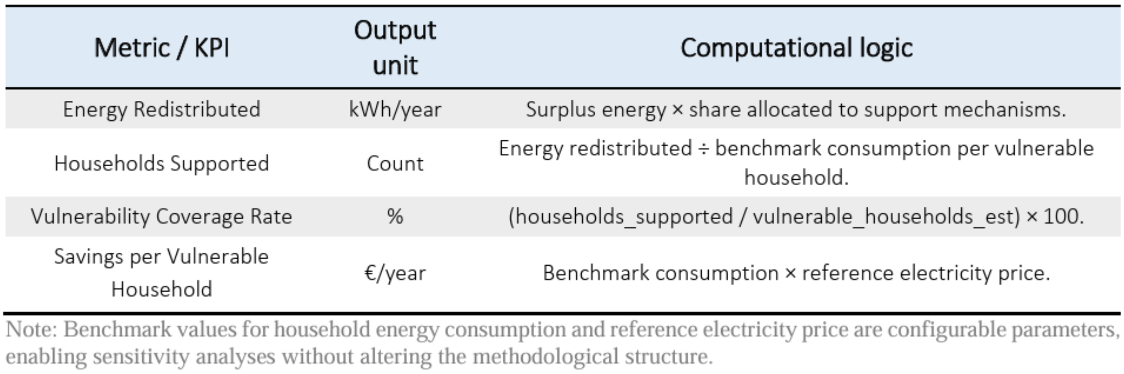
Both indices are combined into a Social Score, which constitutes the overall summary measure of social design. The default equal weighting of 0.50/0.50 reflects the assumption that governance quality and participation are equally important; this can be adjusted for sensitivity analysis. All weightings are documented in Appendix B.2.

The weighting of variables within each index deserves explicit methodological attention. In this framework, weights are assigned according to the theoretical importance attributed to each dimension in the literature (see Section 2.4). It is, however, important to acknowledge that any weighting scheme is subject to subjective judgements. A greater weight assigned to, say, the governance model over the legal entity type reflects a normative priority, meaning that the decision-making process is more important than the formal entity through which decisions are made. Choices are made transparent so that the reader can critically evaluate them and test alternative weighting schemes in a sensitivity analysis. The weight configuration is given in Appendix B.2

Redistribution and Vulnerability Metrics

Complementing the composite indicators, a second set of metrics quantifies the potential redistributive impact of the LEC. These metrics establish a direct link between the financial module outputs and the social assessment: the estimated surplus energy calculated by the financial engine is combined with the social parameters to derive distributional outcomes. The metrics are defined in Table 4.3.

Table 4.3. Social Impact Metrics and Output Indicators.



Metric / KPI	Output unit	Computational logic
Energy Redistributed	kWh/year	Surplus energy × share allocated to support mechanisms.
Households Supported	Count	Energy redistributed ÷ benchmark consumption per vulnerable household.
Vulnerability Coverage Rate	%	(households_supported / vulnerable_households_est) × 100.
Savings per Vulnerable Household	€/year	Benchmark consumption × reference electricity price.

Note: Benchmark values for household energy consumption and reference electricity price are configurable parameters, enabling sensitivity analyses without altering the methodological structure.

The resulting indicators work in close connection with the financial engine: the surplus energy estimated by the financial module feeds directly into the redistribution metrics, while the composite indicators are computed independently from the governance and participation variables. This integration is illustrated in Figure 4.3 (Section 4.2.3).

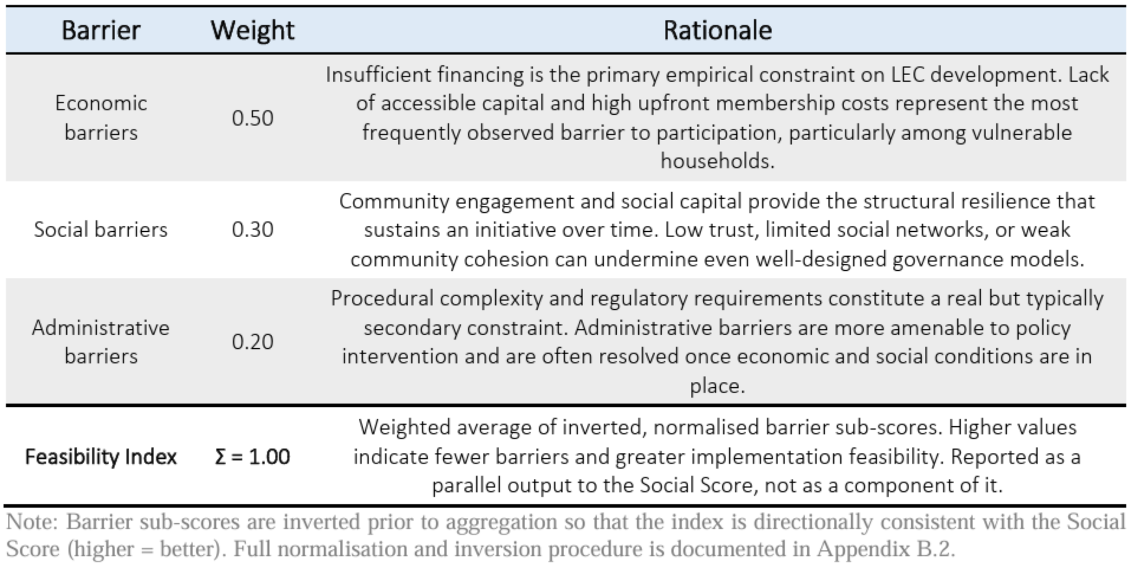
Barriers, Enabling Conditions, and the Implementation Feasibility Index

The Barriers & Enabling Conditions dimension addresses the contextual factors that determine whether the social design of a LEC can be effectively realised in practice. These include economic barriers, social barriers, and administrative barriers that can directly influence the likelihood of successful implementation. If there is, for example, a LEC with a participatory governance model and supportive administrative leadership, it still may not achieve the intended results if economic barriers prevent the participation of vulnerable households, or if a community has funding opportunities but the surrounding social fabric does not allow for the necessary levels of participation. Therefore, identifying and communicating these limitations is fundamental to the evaluation.

In methodological terms, this dimension is operationalised separately through an Implementation Feasibility Index. This distinction is methodologically deliberate: while the Governance and Participation indices measure properties of the initiative's social design, the barrier indicators reflect the contextual conditions in which the initiative is introduced, many of which are external to the control of promoters or participants. Combining these two types of information into a single composite index would conflate the quality of the social design with the surrounding structural constraints, potentially penalising communities for socioeconomic disadvantages beyond their control. The three barrier dimensions and their assigned weights are presented in Table 4.4

Therefore, the Feasibility Index is calculated as a weighted average of inverted and normalised barrier sub-scores, where a higher value reflects fewer contextual barriers and greater implementation feasibility, and is reported alongside the Social Score as a parallel diagnostic indicator rather than as a component of it. This makes it possible to distinguish analytically between two different situations: a community may exhibit a strong social design but face substantial external barriers, or conversely operate under favourable conditions despite a weaker participatory structure. This distinction is important because each configuration suggests different policy and governance implications.

Table 4.4. Implementation Feasibility Index.



Barrier	Weight	Rationale
Economic barriers	0.50	Insufficient financing is the primary empirical constraint on LEC development. Lack of accessible capital and high upfront membership costs represent the most frequently observed barrier to participation, particularly among vulnerable households.
Social barriers	0.30	Community engagement and social capital provide the structural resilience that sustains an initiative over time. Low trust, limited social networks, or weak community cohesion can undermine even well-designed governance models.
Administrative barriers	0.20	Procedural complexity and regulatory requirements constitute a real but typically secondary constraint. Administrative barriers are more amenable to policy intervention and are often resolved once economic and social conditions are in place.
Feasibility Index	**Σ = 1.00**	Weighted average of inverted, normalised barrier sub-scores. Higher values indicate fewer barriers and greater implementation feasibility. Reported as a parallel output to the Social Score, not as a component of it.

Note: Barrier sub-scores are inverted prior to aggregation so that the index is directionally consistent with the Social Score (higher = better). Full normalisation and inversion procedure is documented in Appendix B.2.

4.2.3 Integration into the Python Tool

The Python tool constitutes the central methodological contribution of this thesis. Its purpose is not merely computational convenience, but to provide a structured, transparent, and replicable framework within which the financial and social dimensions of a Local Energy Community can be assessed jointly and consistently. The decision to develop a purpose-built tool, rather than relying on spreadsheet-based calculation or commercial software, responds to three specific requirements of the research design.

First, assessing an LEC involves a non-trivial number of interdependent variables such as technical parameters (generation, degradation, battery state), economic parameters (costs, prices, discount rate), and social indicators (governance, participation, vulnerability) the interactions of which are difficult to trace and audit in a tabular environment. Each calculation step is explicit, sequential, and independently verifiable using a Python-based workflow.

Second, the comparative dimension of the research (evaluating different scenarios for the same case) requires a tool that can be re-run with modified input parameters without altering the underlying model. The tool is designed in a way that all scenario-specific inputs are kept in parameter dictionaries, separated from the logic of the calculation, so that a systematic sensitivity analysis is possible.

Third, the integration of a social module alongside a financial engine requires a shared data interface. The tool establishes this interface explicitly: the financial module computes the annual surplus energy, which is then passed automatically to the social module as the basis for redistribution metrics. This linkage, while architecturally simple, reflects an important methodological claim: that the social distributive impact of a LEC is inseparable from its financial performance. Finally, the use of Python makes the framework scalable and extensible. The model is designed so that new modules or additional indicators can be added without substantially modifying the overall data structure or the logic of the existing components. This is relevant for future developments of the tool and the integration of new regulatory, environmental, or behavioural dimensions. Also, this strengthens the value of the framework as a reusable methodology for any specific case study.

Architecture and Module Structure

This subsection adopts a more implementation-oriented perspective because the computational workflow itself forms part of the methodological contribution of the thesis and is essential for ensuring transparency, reproducibility, and scenario-based application. The tool is organised into two sequential, interoperable modules. Each module is implemented as a Python source file (.py), which encapsulates all calculation logic, and is executed through a Jupyter notebook that handles input configuration, sequential function calls, and output display. This separation between logic and execution environment ensures that the codebase remains clean and reusable across scenarios. The tool is designed with a view to future deployment through a lightweight user interface, which would allow non-technical users to supply input parameters and obtain results without direct interaction with the code.

The financial module processes technical and economic inputs through five computational stages: input validation and range checks; battery SOH modelling (degradation, effective capacity, and cycle counting); CAPEX and OPEX estimation; annual benefit estimation across three revenue streams (direct self-consumption, battery arbitrage, and surplus export); and cash flow construction leading to NPV, IRR, and discounted payback period. The module outputs a set of financial KPIs and, critically, `potential_surplus_kwh`, the annual surplus energy, that is, the share of generated energy that exceeds the community's own consumption. In this research, that surplus is interpreted not as energy that can be directly donated, but as an estimate of the potential incorporation of vulnerable households into the collective scheme through an appropriate adjustment of sharing coefficients.

The social module transforms qualitative case-study evidence into quantitative outputs through six sequential steps. First, indicator data are loaded from the structured social input parameters, which consolidate governance variables, participation variables, vulnerability parameters, redistribution settings, and barrier levels into a single organised input. In the second and third steps, the Governance Index and Participation Index are each computed as weighted composites of their respective sub-indicators, normalised to the 0–1 interval. In the fourth step, both indices are combined into the Social Score via a configurable weighted average. The fifth step establishes the connection between the social and financial modules: the annual surplus energy available for redistribution is combined with the support allocation parameters to produce the redistribution and vulnerability metrics.

In the sixth step, the barrier variables are normalised, inverted, and aggregated into the Implementation Feasibility Index, which is stored as a parallel diagnostic output alongside the Social Score. All outputs are collected in the `social_results` dictionary, which carries three keys: `scores` (containing the Governance Index, Participation Index, Social Score, and Implementation Feasibility Index), `metrics` (redistribution outcomes), and `barriers` (raw barrier levels per dimension). The full integration between the two modules is illustrated in Figure 4.3.

As shown in the figure, the integration between the two modules is achieved through a single shared variable: the annual surplus energy estimated by the financial module, which the social module receives as input for redistribution metrics. If the financial module has been run in the same session its surplus output is used directly; if not, the analyst can supply the surplus value manually, enabling social-only assessments at early project stages.

Beyond this point of integration, the two modules are completely independent: the composite social indicators and the Implementation Feasibility Index are calculated exclusively from social input variables and are not affected by financial results. This independence ensures that the social assessment reflects the governance and participatory design of the initiative, rather than its financial performance.

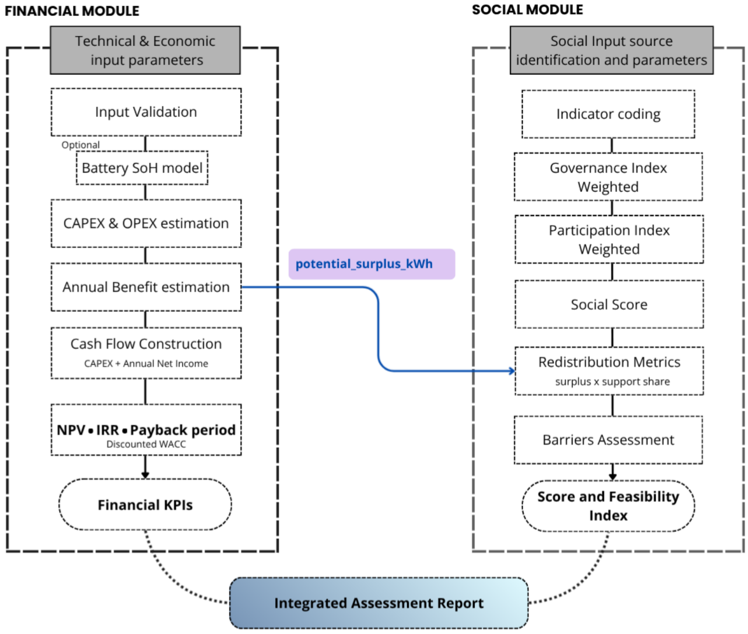


Figure 4.3. Integration between the financial module and the social module.

Design and Limitations

The tool is designed to be modular and adaptable to different Local Energy Community contexts. If social parameters are unavailable, the financial module can be applied independently; conversely, the social module can also be used separately when the objective is to evaluate governance, participation, or redistribution scenarios based on externally defined technical assumptions. This flexibility enhances the framework's replicability and facilitates its application to both rural and urban cases without requiring changes to the overall structure.

At the same time, the framework has clear limitations. It is designed for techno-economic and social evaluation at the project level and does not represent network-level interactions, sub-hour load dynamics, or the full complexity of regulatory arrangements beyond the parameters explicitly incorporated into the scenarios. Furthermore, the social module depends on the availability and quality of qualitative evidence from case studies, meaning that its results should be interpreted as structured approximations rather than precise measurements of social impact. Therefore, the set of indicators should be understood as a first operational approach that could be expanded in future work, for example, by incorporating effects on employment, health outcomes, or dimensions of intergenerational equity as more comprehensive data and more robust assessment tools become available.

Configurable benchmark values, such as the assumed annual energy consumption per vulnerable household and the benchmark electricity price, are explicitly defined as input parameters rather than being integrated into the computational logic. Similarly, the weighting structures used to calculate the Governance Index, the Participation Index, the Social Score, and the Implementation Feasibility Index remain adjustable. This allows for testing alternative regulatory assumptions and conducting sensitivity analyses without modifying the underlying methodological framework.

Together, the financial engine and the social module constitute an integrated assessment framework, and the application of this framework to the Mediana de Voltoya case study is presented in Chapter 5.

Chapter 5

Case Study

This chapter applies the integrated assessment framework developed in Chapter 4 to the case study of Mediana de Voltoya (MdV), a small rural municipality in the province of Avila, Spain. Section 5.1 establishes the context and scope of the analysis; Section 5.2 presents the technical characterization of the system; Section 5.3 defines the parameters for the scenarios; and Sections 5.4 and 5.5 document the parameterization of the financial and social modules.

5.1 Description and Context

The case study selected for the empirical application corresponds to the municipality of Mediana de Voltoya, located in the province of Avila, in the autonomous community of Castilla y Leon (Spain), approximately 10 km from the provincial capital (see Figure 5.1). This small rural municipality registers approximately 117 permanent inhabitants according to official census records, but during the summer months, the local population can reach up to 400 residents, placing seasonal pressure on local infrastructure and public services.

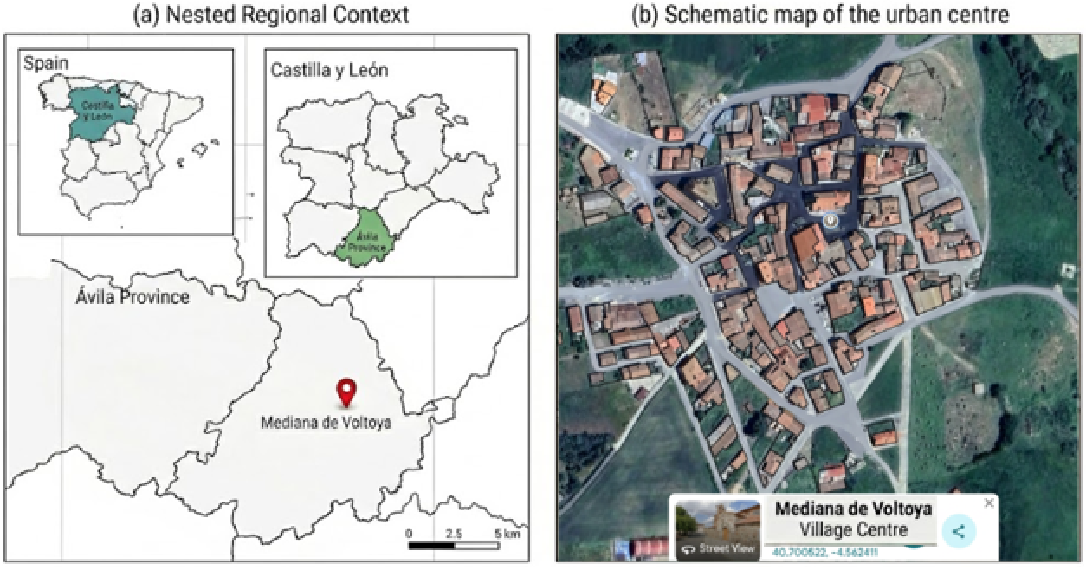


Figure 5.1. Geographical Location of Mediana de Voltoya. (a) Regional Context. (b) Map of the Urban centre.

Climatic conditions in Mediana de Voltoya are typical of the central Spanish plateau, with cold winters, hot summers and high solar resource. Average maximum temperatures reach around 28 °C in July, while January maximums are close to 7 °C and minimums can fall to approximately −1 °C. These conditions, combined with long-term solar irradiation in the area is on the order of 1,600–1,800 kWh/m^2·year, make rooftop photovoltaic installations a technically attractive option and provide a suitable case for the framework to be applied.

The municipal budget is highly limited, and a substantial share of revenue comes from taxes linked to the A-6 highway, which is an exogenous dependence. This, combined with the obligation to maintain infrastructure sized for a floating population several times larger than the permanent one, illustrates the structural economic barriers that small rural municipalities face.

The energy initiative dates back to 2021, when the municipality submitted a technical proposal to a European Union funding call comprising three sub-projects (hybrid wind–PV water pumping, collective self-consumption PV for municipal buildings, and off-grid

PV with battery storage for street lighting). Although the application was unsuccessful, this technical design provides the baseline for the present analysis and is documented in detail in the companion engineering study developed within the R2M Solution framework (Gaubeka Gil, 2026).

This case study is analytically relevant for several reasons: i) Its rural and small-scale character places it within a category of LEC initiatives underrepresented in the existing literature, which has focused predominantly on urban or peri-urban contexts (Caramizaru & Uihlein, 2020); ii) the initiative is entirely municipality-led, making governance and participation dimensions important for the social module assessment; iii) the availability of real metered consumption data for 2024-2025 enables a data-grounded application of the framework.

5.2 Scope of the Study

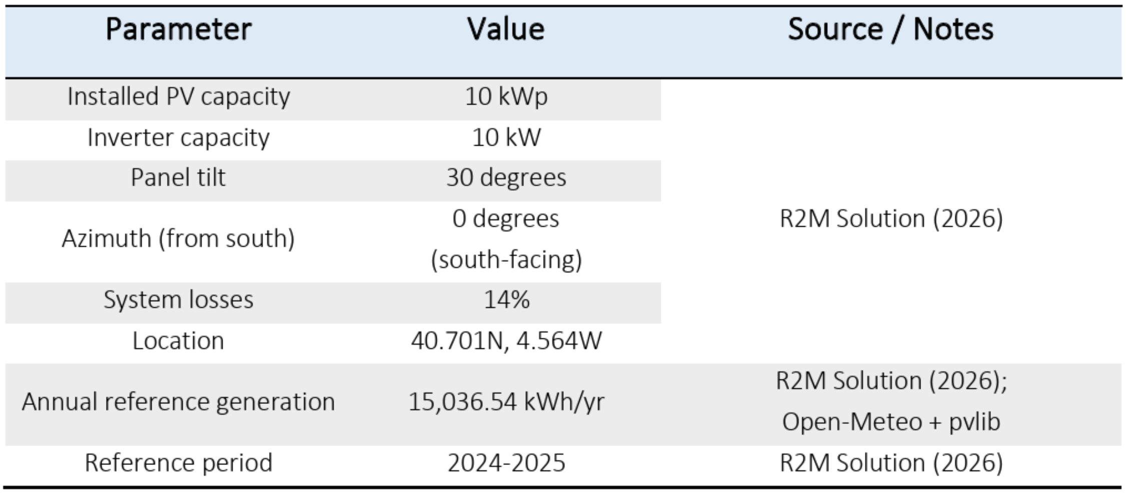
For the purposes of this thesis, this case study is used as a real-world application of the integrated assessment framework developed in Chapter 4, but it is modelled as a prospective community-scale configuration rather than as an operational LEC with final participants, completed governance arrangements, or observed financial outcomes. The case-study boundary covers the technical, economic and social dimensions needed to parameterize the framework, while the detailed construction of demand and generation profiles is taken as given from the companion R2M Solution engineering study.

Within this setup, technical inputs such as electricity demand, participant characterization and photovoltaic generation estimates are treated as external data drawn from the engineering study and municipal project documentation, and are not reconstructed from raw series. The contribution of the present thesis lies in translating this rural LEC configuration into the financial and social modules through a transparent set of assumptions and three progressive scenarios, as defined in Section 5.3.

5.3 Technical System Characterization

The photovoltaic installation for Scenarios S1 and S2 is located on the rooftop of a municipal building in MdV (Plaza Caidos, 1), with an installed peak power of 10 kWp and an inverter capacity of 10 kW. The system operates under the collective self-consumption modality and supplies four municipal buildings: the Social Bar, Casa Maestra, Municipal Secretary's Office and the Social Centre (Figure 5.2). The technical parameters and the reference generation used as inputs to the financial module are drawn from the R2M Solution engineering study and are summarised in Table 5.1. Annual reference generation was estimated using the Open-Meteo dataset and the pvlib simulation model for the 2024–2025 period.

Table 5.1. PV installation parameters.



Parameter	Value	Source / Notes
Installed PV capacity	10 kWp	R2M Solution (2026)
Inverter capacity	10 kW	
Panel tilt	30 degrees	
Azimuth (from south)	0 degrees (south-facing)	
System losses	14%	
Location	40.701N, 4.564W	
Annual reference generation	15,036.54 kWh/yr	R2M Solution (2026); Open-Meteo + pvlib
Reference period	2024-2025	R2M Solution (2026)

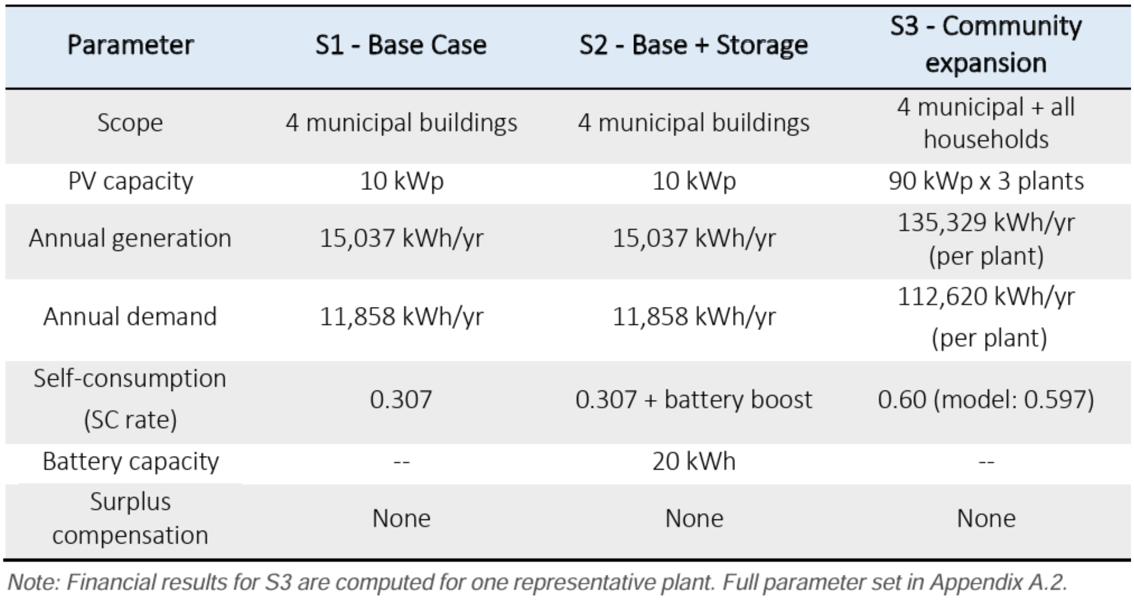
The aggregate annual electricity demand of the four participating buildings amounts to 11,858.15 kWh/year based on metered data for the reference period. These values constitute the demand-side input to the financial module for Scenarios S1 and S2.

Figure 5.2. Satellite view of MdV showing the location of the four participating (S1 and S2) and the residential rooftop areas assessed for S3.
Source: own elaboration based on Google Maps imagery (2024).

5.4 Scenario Definition

Three scenarios are defined to apply the assessment framework progressively. Scenario S1 evaluates the baseline configuration as technically proposed. Scenario S2 assesses the financial impact of integrating battery storage. Scenario S3 extends the community to include all residential participants and all available rooftop generation capacity. In this last scenario, the total capacity was segmented into three 90 kWp sub-plants, because it ensures that the system remains within the operating limits of the CAPEX estimation coding, which is specifically calibrated for small- to medium-scale installations (less than 100 kW). Furthermore, this configuration aligns with local legislation. In Spain, keeping individual generation units below the 100 kW threshold allows the installation to meet the requirements for the simplified surplus compensation mechanism. The differentiating technical parameters are presented in Table 5.2.

Table 5.2. Scenario overview - Parametrization..



Parameter	S1 - Base Case	S2 - Base + Storage	S3 - Community expansion
Scope	4 municipal buildings	4 municipal buildings	4 municipal + all households
PV capacity	10 kWp	10 kWp	90 kWp x 3 plants
Annual generation	15,037 kWh/yr	15,037 kWh/yr	135,329 kWh/yr (per plant)
Annual demand	11,858 kWh/yr	11,858 kWh/yr	112,620 kWh/yr (per plant)
Self-consumption (SC rate)	0.307	0.307 + battery boost	0.60 (model: 0.597)
Battery capacity	--	20 kWh	--
Surplus compensation	None	None	None

Note: Financial results for S3 are computed for one representative plant. Full parameter set in Appendix A.2.

Scenarios S1 and S2 share the same PV system and demand configuration, differing only in battery storage. The base self-consumption rate (SC ratio = 0.307) is derived from the R2M Solution engineering study, representing the fraction of PV generation directly consumed by the four participating buildings under current operating conditions. In Scenario S2, the battery model computes the effective increase in self-consumption endogenously; the battery capture parameter (`bat_direct_capture` = 0.15) was calibrated against the hourly optimisation results of the R2M Solution engineering study, yielding an effective SC ratio of 0.554 versus 0.591 from the hourly model being an acceptable difference for a simplified annual model.

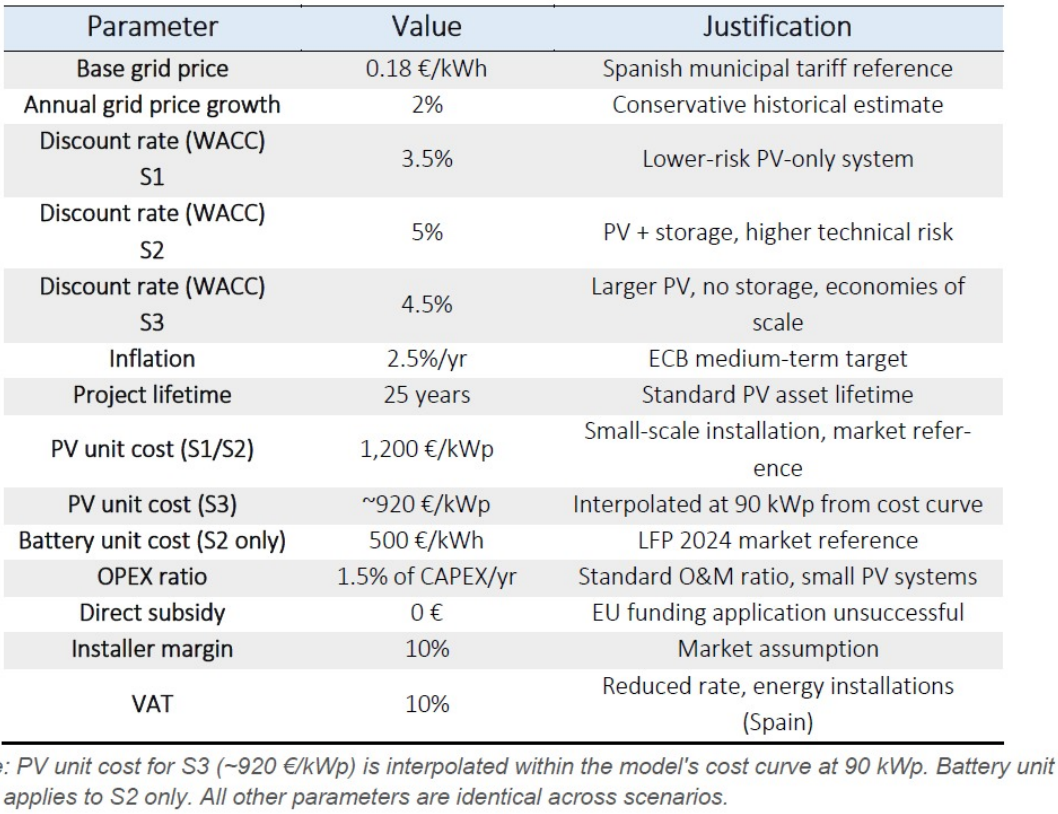
The S3 scenario assumes three distributed installations of 90 kWp each (total 270 kWp), deployed on a mix of municipal and residential rooftops. A preliminary rooftop availability assessment based on standard 600 Wp modules ($\approx$2 m^2 per panel) indicates that the required surface of around 900 to 1,000 m^2 is technically feasible within the municipality, given that solar cadastre analysis (Gaubeka Gil, 2026) identified approximately 2,722 m^2 of usable roof area on different buildings as illustrated in Figure 5.2. The scenario therefore reflects a realistic distributed deployment pattern.

Scenario S3 uses a simulated SC ratio of 0.60, consistent with the technical supervisor's estimate for a plant serving approximately one third of total community demand. The financial model output confirms an effective SC ratio of 0.597 at Year 1, validating the assumption. The SC ratio for S3 is higher than for S1 and S2 because each plant is sized relative to its assigned demand share, achieving better temporal coincidence between generation and consumption.

5.5 Financial Module Parameterization

The financial module developed in Chapter 4 is parameterized using the technical inputs summarized in Table 5.2 and the shared economic parameters detailed in Table 5.3. The full scenario-level input set is provided in Appendix A.2 and A.3. The module computes a 25-year discounted cash flow projection for each scenario, from which NPV, IRR, and payback period are derived. It additionally performs a sensitivity analysis mapping NPV against the self-consumption rate to identify the minimum viable operating threshold. Results are presented in Chapter 6.

Table 5.3. Economic parameters - all scenarios..



Parameter	Value	Justification
Base grid price	0.18 €/kWh	Spanish municipal tariff reference
Annual grid price growth	2%	Conservative historical estimate
Discount rate (WACC) S1	3.5%	Lower-risk PV-only system
Discount rate (WACC) S2	5%	PV + storage, higher technical risk
Discount rate (WACC) S3	4.5%	Larger PV, no storage, economies of scale
Inflation	2.5%/yr	ECB medium-term target
Project lifetime	25 years	Standard PV asset lifetime
PV unit cost (S1/S2)	1,200 €/kWp	Small-scale installation, market reference
PV unit cost (S3)	~920 €/kWp	Interpolated at 90 kWp from cost curve
Battery unit cost (S2 only)	500 €/kWh	LFP 2024 market reference
OPEX ratio	1.5% of CAPEX/yr	Standard O&M ratio, small PV systems
Direct subsidy	0 €	EU funding application unsuccessful
Installer margin	10%	Market assumption
VAT	10%	Reduced rate, energy installations (Spain)

Note: PV unit cost for S3 (~920 €/kWp) is interpolated within the model's cost curve at 90 kWp. Battery unit cost applies to S2 only. All other parameters are identical across scenarios.

The discount rates presented in Table 5.3 are differentiated by scenario to reflect differences in investment risk, in line with risk-adjusted WACC practice in renewable energy finance (IEA, 2024; Munson, 2024). Scenario S1 is a small-scale PV system based on mature and widely deployed technology, and is therefore assigned a lower WACC (3.5%) consistent with the lower perceived uncertainty and capital costs typically seen in community-scale rooftop installations. S2 incorporates battery storage, which adds technical complexity and operational uncertainty, justifying a higher discount rate (5%), consistent with the IEA Cost of Capital Observatory's findings about cost profiles (IEA, 2024). Scenario S3, although larger in scale, doesn't include storage and benefits from economies of scale in procurement and installation; therefore, it is assigned an intermediate WACC (4.5%). This differentiation follows a risk-adjusted cost of capital logic and is reflected in the KPI calculations presented in Chapter 6.

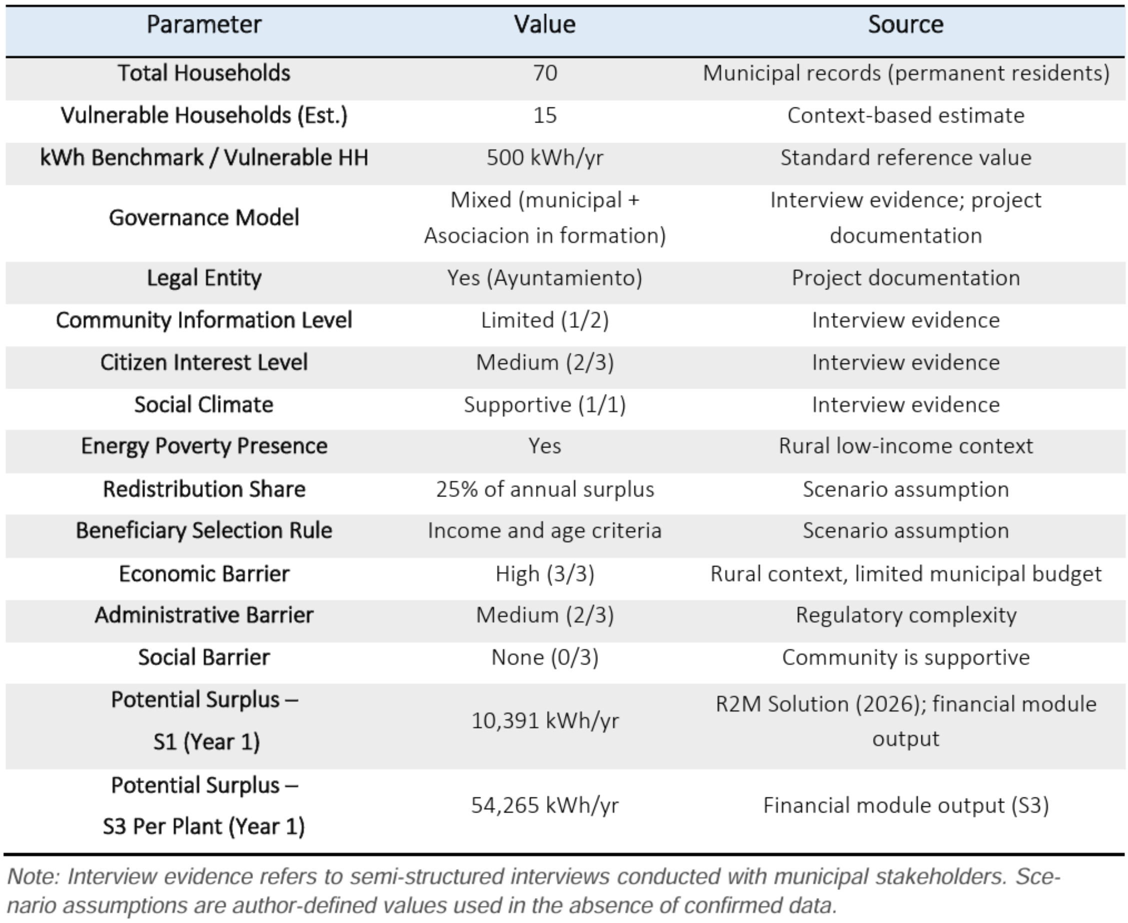
5.6 Social Module Parameterization

The social module is parameterized using data drawn from three sources: semi-structured interview evidence collected during fieldwork; project documentation from the municipal technical proposal; and contextual assumptions justified by the rural demographic and socioeconomic profile of the municipality. All parameters set are presented in Table 5.4.

The governance dimension reflects the municipality's current status as the lead promoting entity, combined with an anticipated transition to a formal association structure. At the time of analysis, the municipality is in the process of formalizing an association to govern the energy community; the governance parameterization reflects this anticipated configuration. Participation indicators are derived from interview evidence and reflect limited but supportive community engagement at the pre-implementation stage. Vulnerability and redistribution parameters are based on contextual estimates, as no formal energy poverty register exists for the municipality at this scale.

The potential surplus figures used as redistribution inputs are the Year 1 outputs of the financial module: 10,391 kWh/yr for S1 and 54,265 kWh/yr per plant for S3 (producing a total of 162,795 kWh/yr when all three plants are considered), which is in line with the energy balance findings from the study supervised by R2M Solution. This approximately fifteen-fold increase in overall collective re-distribution, is the primary social argument for pursuing community-wide expansion.

Table 5.4. Social module input parameters - Mediana de Voltoya.



Parameter	Value	Source
Total Households	70	Municipal records (permanent residents)
Vulnerable Households (Est.)	15	Context-based estimate
kWh Benchmark / Vulnerable HH	500 kWh/yr	Standard reference value
Governance Model	Mixed (municipal + Asociacion in formation)	Interview evidence; project documentation
Legal Entity	Yes (Ayuntamiento)	Project documentation
Community Information Level	Limited (1/2)	Interview evidence
Citizen Interest Level	Medium (2/3)	Interview evidence
Social Climate	Supportive (1/1)	Interview evidence
Energy Poverty Presence	Yes	Rural low-income context
Redistribution Share	25% of annual surplus	Scenario assumption
Beneficiary Selection Rule	Income and age criteria	Scenario assumption
Economic Barrier	High (3/3)	Rural context, limited municipal budget
Administrative Barrier	Medium (2/3)	Regulatory complexity
Social Barrier	None (0/3)	Community is supportive
Potential Surplus – S1 (Year 1)	10,391 kWh/yr	R2M Solution (2026); financial module output
Potential Surplus – S3 Per Plant (Year 1)	54,265 kWh/yr	Financial module output (S3)

Note: Interview evidence refers to semi-structured interviews conducted with municipal stakeholders. Scenario assumptions are author-defined values used in the absence of confirmed data.

Chapter 6

Results and Discussion

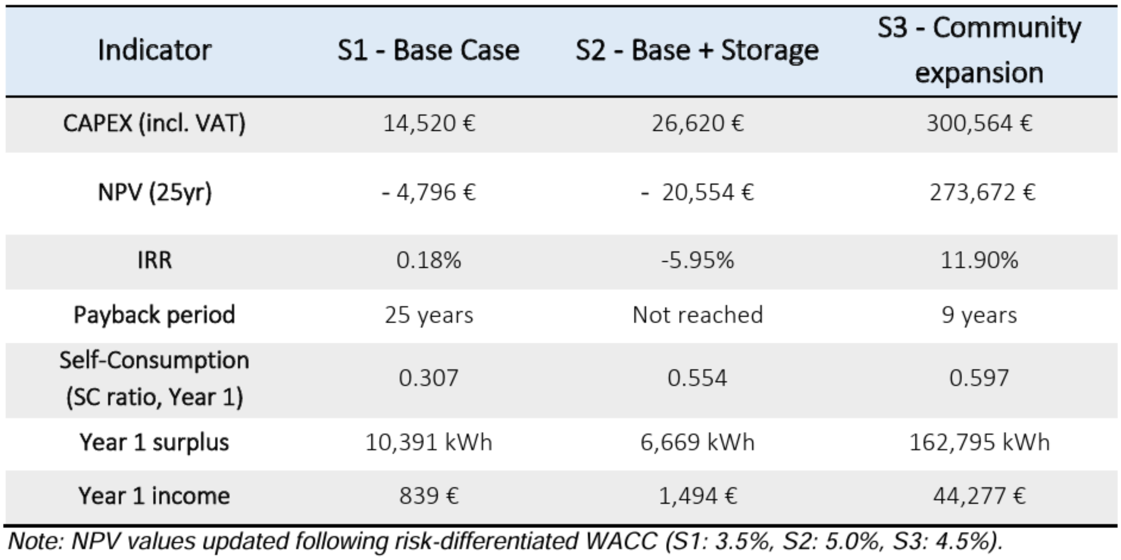
This chapter presents and interprets the outputs of the financial and social modules applied to the Mediana de Voltoya case study. The analysis is organised into three sections: financial module results (Section 6.1), social module results (Section 6.2), and an integrated discussion that connects both modules and addresses the research questions (Section 6.3). Limitations of the analysis are noted where relevant.

6.1 Financial Module Results

6.1.1 Scenario comparison

Table 6.1 and Figure 6.1 present the principal financial KPIs for the three scenarios evaluated. Scenario S3 values reflect the total community investment, sized to remain below the Spanish producer registration threshold while maximizing the use of available rooftop and parcel surface within the municipality (three plants of 90 kWp each). A risk-differentiated discount rate is applied: 3.5% for S1 (small-scale PV-only), 5.0% for S2 (PV with battery storage), and 4.5% for S3 (larger-scale PV-only), reflecting the incremental financial risk associated with each configuration.

Table 6.1. Financial KPI summary for S1, S2, and S3..



Indicator	S1 - Base Case	S2 - Base + Storage	S3 - Community expansion
CAPEX (incl. VAT)	14,520 €	26,620 €	300,564 €
NPV (25yr)	- 4,796 €	- 20,554 €	273,672 €
IRR	0.18%	-5.95%	11.90%
Payback period	25 years	Not reached	9 years
Self-Consumption (SC ratio, Year 1)	0.307	0.554	0.597
Year 1 surplus	10,391 kWh	6,669 kWh	162,795 kWh
Year 1 income	839 €	1,494 €	44,277 €

Note: NPV values updated following risk-differentiated WACC (S1: 3.5%, S2: 5.0%, S3: 4.5%).

Scenario S1 shows a negative NPV of -4,796 at a 3.5% discount rate, despite reaching undiscounted payback at Year 25. The system generates approximately 839 /year in avoided grid costs from direct photovoltaic consumption, but this income is insufficient to reach the 14,520 investment at any meaningful discount rate. The logic constraint is explicit in the energy split: at SC ratio = 0.307, approximately 69% of generation (10,391 kWh/year) is exported to the grid without compensation under the "*sin compensación de excedentes*" (collective self-consumption without surplus compensation) modality. While this eliminates the need to manage energy sales, agent contracts, market settlements, or producer registration, it represents a total loss of financial value.

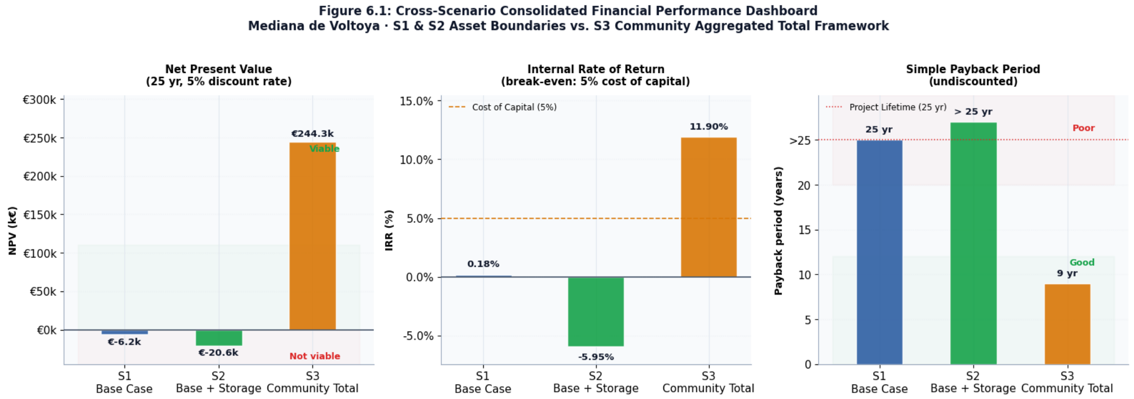


Figure 6.1. KPI comparison S1 / S2 / S3.

Scenario S2 performs worse than S1 despite a higher effective SC ratio (0.554) achieved through the 20 kWh battery installation. The NPV deteriorates to -20,554 because the additional capital cost of the battery (12,100) is not justified by the incremental annual income of 655 /year generated at the prevailing self-consumption rate. This counterintuitive result is examined further in Section 6.1.3 which shows that the storage system captures more energy but does not create enough additional value per kWh to justify its cost under current price and regulatory conditions.

By contrast, Scenario S3 is the only configuration that delivers clearly positive returns. With a selfconsumption rate of 0.597, each 90 kWp plant generates around 14,759 /year in income, yielding an internal rate of return of 11.90% and a simple payback period of 9 years. At the community scale, the total investment of 300,564 across three plants results in a discounted NPV of 273,672 at a 4.5% discount rate, which implies a net gain of approximately 0.91 per euro invested over the project lifetime. This improvement is driven mainly by a better match between generation and demand (higher self-consumption ratio reduces uncompensated exports), combined with economies of scale in CAPEX and the absence of battery replacement costs.

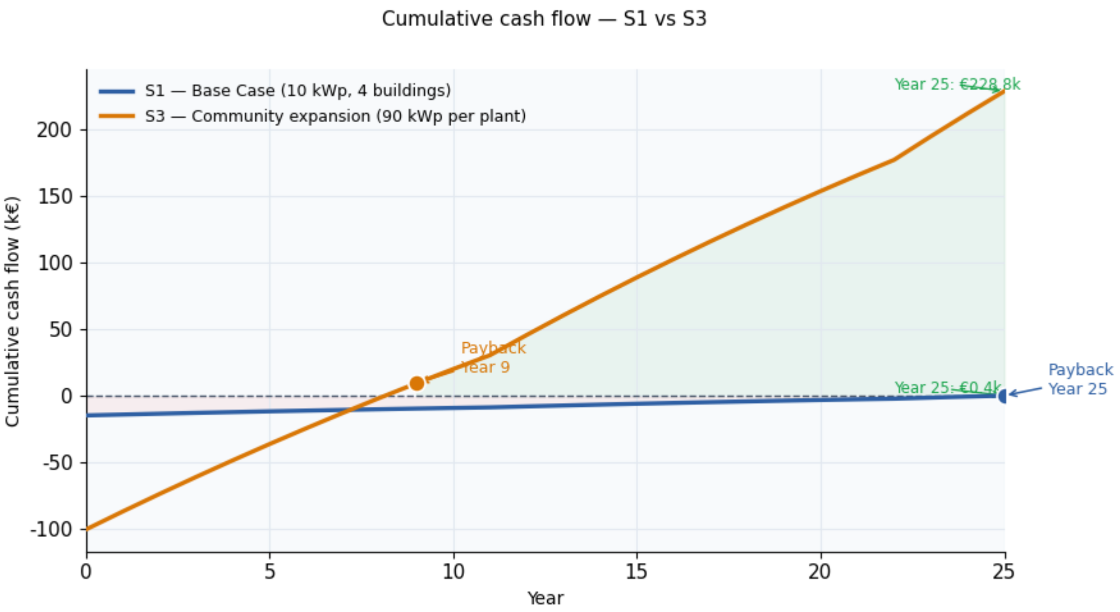


Figure 6.2. Cumulative cash flow for MdV S1 vs S3.

The cumulative cash-flow trajectories in Figure 6.2 make this divergence particularly clear. The S1 baseline (10 kWp, four municipal buildings) remains almost flat throughout the evaluation period, with cumulative cash flow slowly approaching zero and reaching break-even only in Year 25 in undiscounted terms. In contrast, S3 starts with a much larger initial outlay (around −100,000 per plant after capital investment) but then increases sharply and almost linearly, crossing the discounted break-even point in Year 9 and reaching an undiscounted cumulative cash flow of about 228,800 per plant by Year 25. This trajectory corresponds to a discounted NPV of 91,224 per plant (273,672 at community scale), as reported in Table 6.1. The wider gap between both scenarios reflects not only the larger generation base, but above all the higher self-consumption rate in S3, which converts a much greater share of PV production into avoided grid purchases instead of uncompensated exports, together with the absence of battery replacement costs. It should be noted that the nearly linear S3 trajectory reflects the simplified annual model and does not capture variability in participation, plant performance, prices or regulation, so it should be read as a central estimate rather than a precise forecast.

6.1.2 Self-consumption as the critical viability threshold

Figure 6.1.2 maps NPV against self-consumption rate for the S1 configuration across a grid price range of 0.15-0.22 /kWh. The analysis identifies a break-even SC ratio of approximately 0.41 at the reference grid price (0.18/kWh). This threshold is sensitive to energy prices: when the grid price increases to 0.22 /kWh, the break-even self-consumption rate falls to around 0.38, reflecting the higher economic value of each kWh of self-consumed electricity. In all cases, however, the break-even self-consumption rate remains well above the current operating point of 0.307, so the S1 configuration generates a negative NPV across the full range of grid-price assumptions tested. The S3 self-consumption rate of 0.597 therefore lies firmly within the viable zone, while S1 remains significantly below the viability threshold.

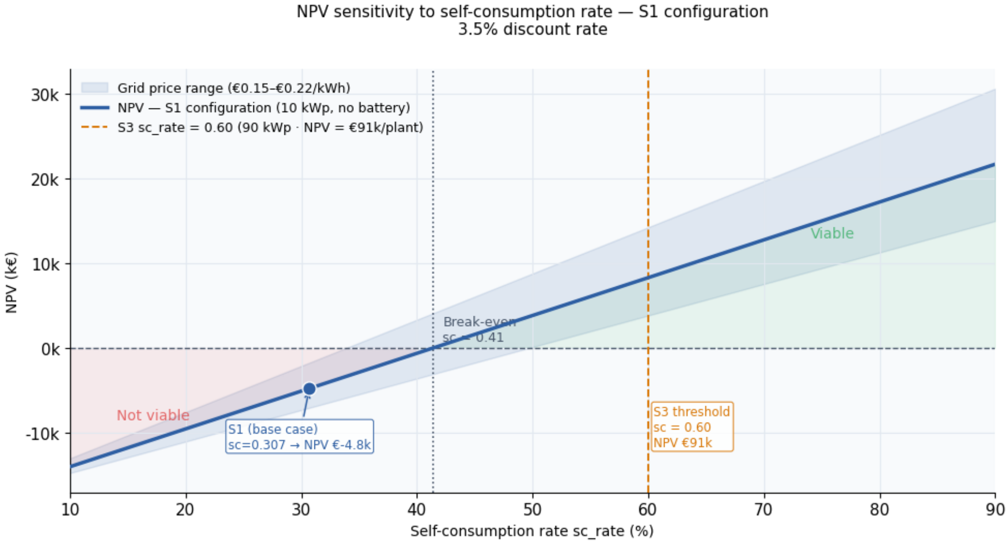


Figure 6.3. NPV Sensitivity to price and self-consumption rate. Note: The shaded band represents the NPV range across grid prices between 0.15 and 0.22 /kWh for each self-consumption rate..

This relationship directly addresses RQ4, confirming that financial viability is not primarily a function of PV capacity or battery inclusion, but of the ratio of consumed to generated energy, which is itself determined by the number and consumption profile of participating buildings. Community expansion is therefore a prerequisite for financial viability, not an optional enhancement.

6.1.3 Battery sizing optimization

Using effective self-consumption rates obtained from the R2M Solution engineering research (Gaubeka Gil, 2026), a marginal analysis was also conducted, as seen in Figure 6.4, which examines the financial impact of each extra kWh of battery capacity. Three independent criteria converge on a 20-30 kWh optimal range for the 10 kWp system: the industry thumb rule of 2-3 kWh per installed kWp, the technical inflection point identified in the engineering study beyond which marginal SC ratio improvements fall below 0.5 percentage points per additional kWh, and the financial marginal analysis which confirms that NPV gains per additional kWh are maximised within this interval. The S2 battery capacity of 20 kWh is consistent with all three criteria.

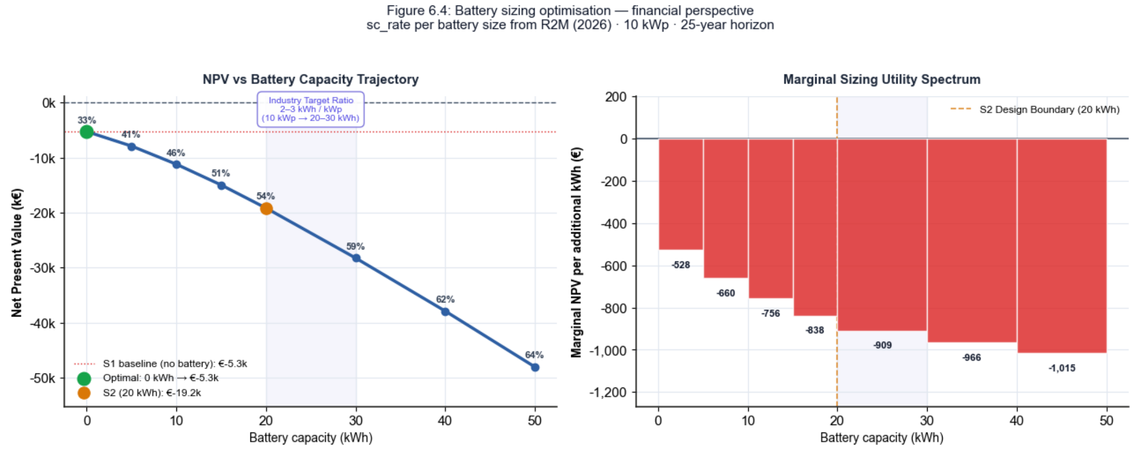


Figure 6.4. Battery Sizing Optimization from financial perspective.

Despite this technically optimal sizing, no battery configuration achieves a positive NPV at the current (31% self-consumption). The battery adds positive marginal NPV in the 5-20 kWh range but is insufficient to overcome the base-case deficit. This confirms that storage investment is financially complementary to community expansion and not a substitute for it, without first expanding community participation to raise above the break-even threshold (41% self-consumption) identified in Section 6.1.2.

It should be mentioned that the battery sizing analysis is subject to a methodological limitation of the engineering model used (R2M solution 2026): the simulation estimates battery utilization from aggregated generation and demand figures rather than optimizing against actual temporal profiles. Consequently, the potential use of the storage is estimated from aggregated generation and demand figures, instead of optimizing the battery cycle based on the actual temporal profile of supply and demand. This leads to apparent underutilization of the battery in the results (with only about 3,700 kWh captured compared to a theoretical potential of 10,000 kWh), reflecting a limitation of the model rather than a design flaw. A fully optimized dispatch model would likely yield higher self-consumption rates for S2 and refine the estimate of the optimal battery sizing. This is a recognized limitation of the present analysis and a clear direction for future research.

6.1.4 Battery cost sensitivity

Figure 6.5 shows the NPV as a function of the self-consumption rate for S1 and for S2 with battery, considering different unit storage costs. The break-even self-consumption rate for S1 is 0.41: below this threshold, the 10 kWp system without storage doesn't achieve a positive NPV. Adding the battery shifts the break-even point upwards, rather than downwards, and considering the current market price of 500/kWh, S2 requires a self-consumption rate of 0.85 to achieve viability, almost double the threshold for S1 and well above the current operating point of 0.307. Even in the most optimistic scenario (free battery), the break-even point only drops to 0.31, just below the value for S1.

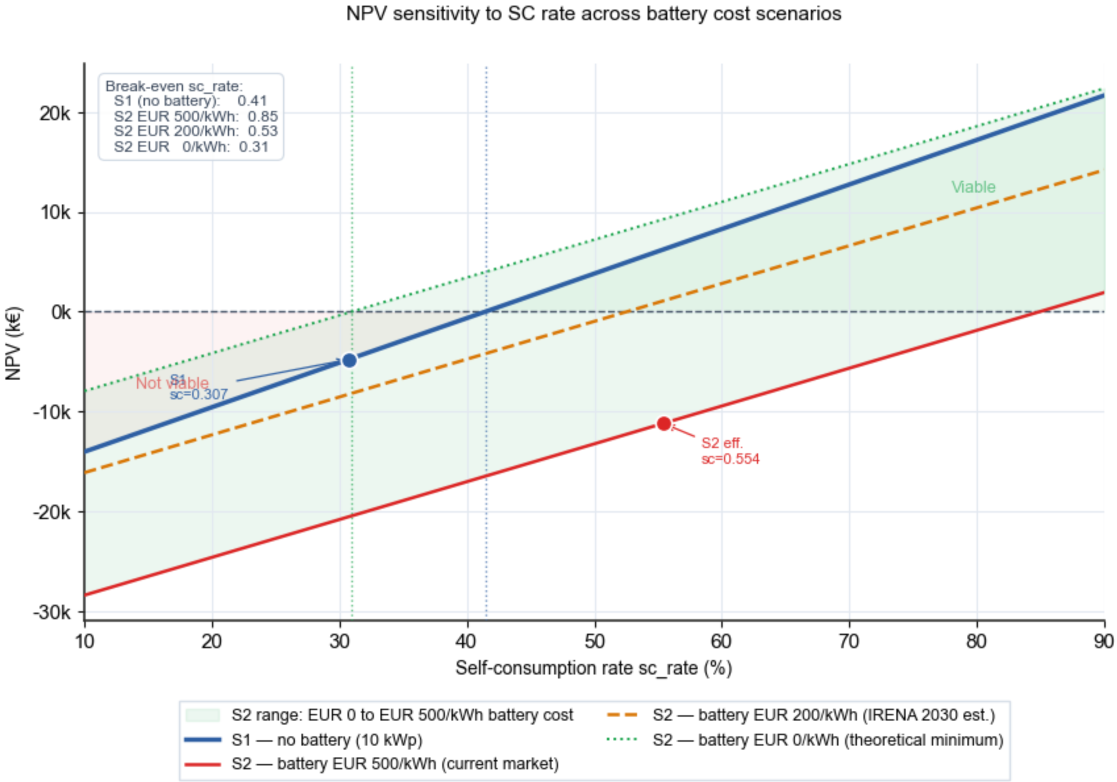


Figure 6.5. NPV sensitivity to self-consumption battery costs.

Even at the *International Renewable Energy Agency* projected cost of 200 /kWh for stationary lithium-ion storage by 2030 (International Renewable Energy Agency [IRENA], 2017), the S2 break-even self-consumption point to sits at 0.53, above S1's threshold rather than below it. The only way to push S2's break-even SC ratio below S1's is to make the battery effectively free,which is not viable, and even then the improvement is marginal (0.31 vs 0.41). This confirms that battery cost reduction alone cannot restore financial viability at the current level of community participation: the required self-consumption rate is achievable only through community expansion of the scale represented by S3.

6.2 Social Module Results

The social module assessment yields a Governance Index of 0.80, a Participation Index of 0.69, and a composite Social Score of 0.75 out of 1.0. These results suggest a community in which institutional conditions are comparatively strong, as the municipality provides a stable governance base, ensures continuity through its public role, and has already articulated mechanisms to prioritize permanent residents. At the same time, the lower Participation Index indicates that social inclusion is still at an early stage, since citizen involvement remains mostly aspirational rather than formally embedded in the current project design.

This interpretation aligns with the interview evidence. While the initiative is still conceived primarily as a municipal project, local representatives expressed openness to future resident involvement and identified the cooperative model as a plausible legal form. Nevertheless, the absence of a formally constituted entity and the limited development of structured participatory mechanisms indicate that the project remains in an early social and organizational phase.

The barrier assessment identifies economic capacity as the main implementation risk, with a High score (3/3). According to the interview, the municipality's limited budget is the principal constraint for investment for energy projects as available resources are already largely absorbed by basic local needs. Administrative complexity is assessed as Medium (2/3), as no specific person has been assigned to lead the process and the project is being advanced with only limited external support. By contrast, social barriers appear comparatively low, since residents show interest in the initiative and tend to view a collective energy scheme as more feasible than individual household solar investment (Figure 6.6).

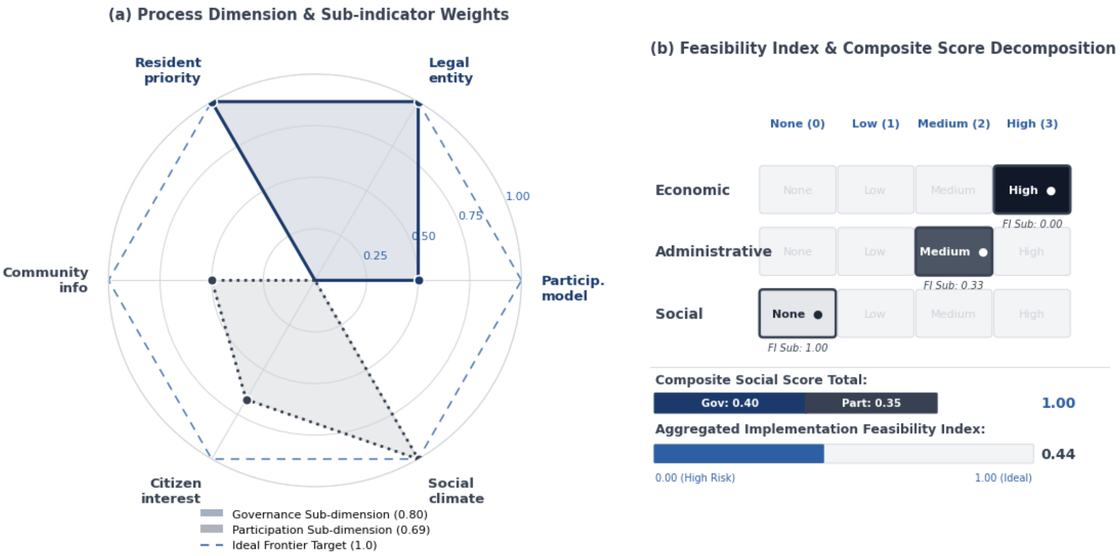


Figure 6.6. Social module results. (a) Indicators for Governance and Participation dimensions. (b) Barrier severity for Feasibility Index..

The redistribution analysis estimates the potential social impact of allocating part of the annual surplus under a 25% solidarity mechanism. This surplus is not interpreted as electricity that can be directly transferred to third parties, but rather as an indicator of the additional vulnerable demand that could be incorporated into the collective self-consumption arrangement through a revised allocation of sharing coefficients. In S1, the annual surplus of 10,391 kWh would translate into a solidarity allocation of 2,598 kWh/year, sufficient to incorporate approximately 5 vulnerable households, corresponding to 34.7% of the estimated 15 vulnerable households identified in this area, with annual savings of around 90 per household. In S3, the annual surplus rises to 54,265 kWh/year per plant, increasing the solidarity allocation pool to 13,566 kWh/year allowing the incorporation of about 27 households per plant, thus approaching full coverage of the vulnerable population. This nearly fivefold increase in potential social impact per plant reinforces the case for community expansion, alongside the financial viability results discussed in Section 6.1.

6.3 Final Remarks

The combined financial and social results reveal a consistent structural pattern: in its current municipal configuration, the MdV initiative remains below the threshold of financial viability, largely because the self-consumption rate is too low. Community expansion is the path to both financial and social viability because this simultaneously raises the self-consumption rate above the 0.41 break-even point and increases the surplus that can be used to integrate vulnerable households under preferential conditions. Therefore, in this case, social and economic success are not contradictory; rather, both depend on the transition from a purely municipal enterprise to a local energy community truly integrated within the community.

A key methodological result is that careful treatment of dynamic variables (particularly the discount rate, electricity price growth, and technological degradation) is essential for obtaining reliable financial indicators over a 25-year horizon. Incorporating battery State-of-Health degradation and conservative assumptions about grid-price escalation results in lower but more robust investment metrics than static approaches and highlights how sensitive the viability is to the choice of cost of capital. Under current market and policy conditions, neither the baseline configuration nor the storage-enhanced scenario achieves financial viability. Positive returns appear only when self-consumption approaches 0.60 in the community expansion scenario (S3). For S2, even under optimistic assumptions for battery costs, the improve in performance cannot compensate the fundamental mismatch between generation and demand when the participating group remains too small. The MdV case makes this sensitivity concrete, the difference between a negative NPV of $-4,796$ in S1 and a positive NPV of 273,672 in S3 is not primarily a function of system size, but of the SC ratio that each configuration makes achievable.

The municipality occupies both sides of the investor-beneficiary relationship, which eliminates the traditional financial friction that usually shapes discussions about profit-sharing in commercially organized energy communities, giving the distributive dimension a distinctive character. How the energy surplus will be distributed if the community grows beyond the municipal facilities is the primary distribution question, not who captures the financial return. The self-consumption threshold identified for viability provides a concrete baseline for this debate, and the marginal battery analysis shows that storage only adds positive value within a comparatively small capacity range. In reality, finding a single “optimal” technical configuration is less important for long-term viability than reaching a level of participation that sustains the required self-consumption ratio, which is simultaneously a technical and a governance challenge.

The simulated solidarity mechanism for the community-scale configuration suggests that, once sufficient surplus is available, vulnerable households could receive substantial support as active members of the local energy community, integrated under appropriate allocation coefficients rather than treated as passive recipients of donated energy. Whether this potential is realised depends more on the municipality’s capacity to build and maintain the necessary institutional arrangements than on the underlying energy balance, which is generally favourable. The governance assessment indicates that the foundational conditions for such an inclusive design are present, while the economic barrier analysis confirms that external support or further cost reductions remain necessary to unlock them. Mediana de Voltoya thus occupies a critical juncture: the technical and institutional groundwork for a socially inclusive and financially sustainable energy community exists, but its materialisation requires treating governance design and community expansion as primary design objectives rather than secondary implementation details.

6.3.1 Methodological Considerations

These findings carry several methodological qualifications that bear on how the results should be read. The financial module operates on an annual aggregation logic rather than hourly simulation, which introduces a 3.6 percentage point deviation in effective self-consumption rate for S2 relative to the engineering model. The battery analysis is shaped by this same constraint: the dispatch algorithm in the companion study optimises for self-sufficiency rather than economic return, which is appropriate given the community-energy objectives of the project, but means that the financial value of storage is likely understated and the estimated optimal battery size should be treated as indicative. A financially optimised dispatch model would probably point towards a smaller battery than the 20 kWh selected for S2.

On the input side, the reference consumption dataset does not capture the seasonal demand increase associated with MdV's summer population, and the S3 financial results depend on simulated self-consumption values that are pending final validation from the engineering study. The social vulnerability and redistribution indicators are based on contextual estimates rather than a formal municipal energy poverty register, and total community figures for S3 are extrapolated from plant-level outputs rather than directly modelled at system scale. The scenario-specific WACC differentiation introduced in Chapter 5 improves the conceptual treatment of financing risk, though a full recalculation under a more granular capital structure would refine the economic indicators further.

None of these limitations invalidate the core findings. They do, however, define the boundary within which the results should be interpreted: as robust indicative estimates of the performance range and structural dynamics of the Mediana de Voltoya initiative, rather than as precise forecasts of financial or social outcomes.

Chapter 7

Conclusion and future work

This thesis developed and applied an integrated financial and social assessment framework to the Mediana de Voltoya Local Energy Community case. By combining a discounted cash-flow model with a governance- and participation-based social module, the study shows that the viability of rural LECs depends not only on technology and cost, but also on how participation, risk and benefit allocation are structured.

A central methodological conclusion is that the correct parametrization of dynamic variables, especially CAPEX, discount rate, electricity price trajectories and technology degradation, is critical for obtaining reliable indicators of financial viability over a 25-year horizon (RQ1). The MdV case demonstrates how employing conservative and risk-differentiated assumptions results in lower but more reliable NPV and IRR numbers than static techniques and highlights how financing conditions can affect viability.

Regarding the economic feasibility of Spanish LECs (RQ2), the results show that neither the baseline municipal configuration (S1) nor the storage-enhanced scenario (S2) achieves a positive NPV or an IRR above the cost of capital under current conditions. Financial viability is reached only in the community expansion scenario (S3), where a higher participation scale raises the self-consumption rate to 0.597 and produces a clearly positive NPV and a strong IRR. Battery cost reductions improve performance only marginally and do not offset low PV utilisation when the group remains too small.

The MdV case also shows that ownership structure strongly shapes the way benefits are distributed (RQ3). Because the municipality is both investor and main beneficiary, the classic investor–user conflict is limited; the more relevant issue is how future surplus should be allocated once the community expands. In this matter, the minimum self-consumption threshold identified in the analysis (around 0.41 for the reference configuration) provides the clearest answer to the viability question (RQ4): below this value, the project remains unprofitable, while above it, the NPV progressively improves. Therefore, the results indicate that the scale of participation and demand aggregation are more decisive than the inclusion of batteries for achieving financial viability.

From a social perspective, the analysis suggests that meaningful redistribution becomes possible only once the community reaches sufficient scale (RQ5 and RQ6). Under the expanded scenario, surplus energy could support vulnerable households if they are incorporated into the LEC under suitable allocation coefficients, rather than treated as external recipients of donated energy. The governance assessment indicates that the institutional basis for such an arrangement exists, although the economic barrier analysis confirms that external support or further cost reductions are still needed for implementation.

In the future, the model should be refined through hourly financial simulations, economically optimized battery management, improved representation of seasonal demand, and more detailed financing structures. As Voltoya's Mediana initiative evolves, the framework could also be updated with real-world operational data, allowing this pre-assessment to become a post-assessment. Another key issue is replacing the current self-sufficiency-oriented management logic with a price-sensitive predictive control strategy (optimizing battery charge and discharge cycles based on time-of-use tariffs). This could significantly improve the NPV of storage configurations, such as S2, by shifting municipal consumption away from peak price periods. This would transform the battery from a self-consumption tool into an active demand management asset, potentially altering both the optimal sizing analysis and the financial justification for the investment.

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Appendix

To enhance the readability of the methodology chapter while ensuring full transparency and reproducibility, detailed parameter tables, auxiliary equations, and implementation specifications are provided in the appendices. These materials complement the descrip-tions presented in Sections 4.2.1 and 4.2.2 and contain the complete information required to replicate the financial and social assessment modules developed in this thesis.

Appendix A documents the financial model assumptions, benchmark parameters, and sup-porting equations. *Appendix B* presents the complete coding structure of the social mod-ule, including indicator definitions, admissible values, normalization procedures, and weighting schemes used to derive the composite social indicators.

Appendix A. Financial Module: Parameter Tables and Auxiliary Equations

This appendix provides the complete set of input parameters, benchmark values, and auxiliary equations referenced in Section 4.2.1, to ensure full replicability of the financial model in other Local Energy Community case studies.

A.1 Technical and Economic Input Variables

The following table lists all input variables accepted by the financial module, organized by category. Technical variables describe the physical characteristics of the energy system; economic variables define the financial conditions of the investment appraisal.

Category	Variable	Description	Unit
Technical	Installed PV capacity	Total photovoltaic capacity of the project	kWp
	Battery capacity	Installed storage capacity; activates storage-related calculations when included	kWh
	Demand curves	Hourly or representative electricity consumption profiles	—
	PV generation profile	Estimated photovoltaic electricity generation profile	—
Economic	PV unit cost	Unit cost of the PV system; entered manually or derived through interpolation from market tables	€/kWp
	Storage unit cost	Unit cost of battery storage; follows the same interpolation logic as PV unit cost	€/kWh
	Commercial margin	Percentage markup applied to installer base cost to obtain the final sales price	%
	Subsidies	Public support or direct aid reducing the net initial investment	€
	OPEX (O_0)	Operation and maintenance costs in Year 1	€/year
	OPEX ratio	Annual operating cost expressed as a percentage of CAPEX	%
	Project lifetime	Analysis period used for the financial evaluation	years
	Discount rate (r)	Minimum required return / opportunity cost of capital	%
	Inflation rate (f)	Annual inflation factor used to escalate monetary values over time	%
	Electricity price growth rate (g)	Annual growth rate used to update the price of grid electricity	%
	PV degradation rate (d)	Annual reduction in PV output due to system ageing	%
	Financing parameters	Debt share, interest rate, grace period, and loan duration for financed scenarios	%, %, years

Table A.1. Complete list of technical and economic input variables accepted by the financial module.

A.2 Adopted Parameter Values

The values below correspond to the base-case parameterisation used for the Mediana de Voltoya case study. Discount rates are scenario-differentiated to reflect differences in investment risk; all other parameters are shared across scenarios unless noted otherwise.

Parameter	Symbol	Typical Range (Literature)	Value Adopted	Source / Justification
Discount rate — S1	r_1	3% – 8%	3.5%	Small-scale PV-only system; lower financing risk consistent with mature technology at community rooftop scale
Discount rate — S2	r_2		5.0%	PV with battery storage; elevated rate reflects additional technical and operational complexity
Discount rate — S3	r_3		4.5%	Large-scale PV-only; intermediate rate accounts for scale while recognizing absence of storage risk
Project lifetime	T	20 – 30 years	25 years	Standard appraisal horizon for grid-connected PV assets in Spain
PV degradation rate	d	0.3% – 0.8% / yr	0.5% / year	Mid-range of manufacturer specifications; consistent with Pascual et al. (2021)
Electricity price growth rate	g	1% – 3% / yr	2.0% / year	Moderate growth assumption aligned with Spanish energy market projections; treated as scenario input
OPEX (% of CAPEX)	—	0.5% – 1.5%	1.5%	Conservative upper bound; consistent with maintenance cost benchmarks for Spanish PV installations
Inflation rate	f	2% – 3%	2.5%	Aligned with ECB medium-term price stability target
Grid electricity price (base yr)	p_0	—	0.18 €/kWh	Reference retail electricity price for the case study period (2024–2025)
Battery unit cost	—	400 – 700 €/kWh	500 €/kWh	Based on recent market data; LFP chemistry; applies to S2 only
Battery OPEX	—	—	5 €/kWh/yr	Derived from literature benchmarks for lithium-ion residential storage
Commercial margin	m	—	10%	Standard installer markup applied to system base cost
VAT rate	—	—	10%	Spanish reduced VAT rate applicable to solar energy installations
Export compensation price	p_{sale}	—	0.00 €/kWh	No surplus compensation mechanism assumed for the reference period
Public subsidies	S	—	0 €	EU grant application unsuccessful; no public support assumed for base scenarios
Self-consumption ratio — S1	SC ratio	—	0.307	Derived from hourly demand generation interaction (R2M Solution, 2026).
Self-consumption ratio — S2 (effective)	SC ratio	—	0.554	Endogenously adjusted by the battery model; calibrated against hourly optimization results.
Self-consumption ratio — S3	SC ratio	—	0.597	Derived from community-scale simulation; pending final validation from the engineering study.

Table A.2. Input parameter values adopted in the financial module. Scenario-specific WACC values reflect a risk-adjusted cost of capital approach consistent with IEA (2024) and Steinbach & Staniaszek (2015).

A.3 CAPEX Estimation — Equations and Values

Capital expenditure is estimated through a sequential adjustment procedure. The installer base cost is first computed by interpolating unit costs from a market price table and adding battery costs where applicable. A commercial margin and VAT are then applied; public subsidies are deducted prior to VAT.

A.3.1 CAPEX Equation Sequence

Component	Equation	Description
Unit Cost Estimation	$C(P) = C_i + C_{i+1-c_i} \frac{(P - P_i)}{P_{i+1} - P_i}$	Interpolates unit cost based on installed capacity using market data breakpoints
Installer CAPEX	$CAPEX_{inst} = P_{PV} \times C_{PV} + E_{bat} \times C_{bat}$	Base investment cost: PV and battery components, before margin or taxes
CAPEX with Margin	$\mathrm{CAPEX}_m = CAPEX_{inst} \times (1 + m)$	Applies commercial margin (m) to installer base cost
Net CAPEX	$\mathrm{CAPEX}_{net} = CAPEX_m - S$	Deducts applicable public subsidies (S) from gross investment
Final CAPEX	$\mathrm{CAPEX}_{final} = CAPEX_{net} \times (1 + VAT)$	Applies VAT; relevant for end-user perspective where tax is non-recoverable

Table A.3.1. Sequential CAPEX adjustment equations. P_{pv} = installed PV capacity (kWp); E^{bat} = battery capacity (kWh); m = commercial margin; S = subsidy amount; VAT = applicable tax rate.

A.3.2 CAPEX Parameter Values Adopted

Parameter	Symbol	Notes
PV unit cost	C_{pv}	**900 – 1,200 €/kWp;** size-dependent; interpolated from market table at 10, 50, and 100 kWp breakpoints
Battery unit cost	C^{bat}	**500 €/kWh**; based on recent market data; LFP chemistry; applies to S2 only
Commercial margin	m	**10%**; applied to installer CAPEX
VAT rate	—	**10%**; Spanish reduced VAT rate applicable to solar energy installations
Subsidies	S	**0 €**; EU grant application unsuccessful; no public support assumed for base scenarios

Table A.3.2. CAPEX parameter values adopted in the model. PV unit costs are interpolated from a three-point market curve at 10, 50, and 100 kWp. Battery unit cost applies to S2 only.

A.4 OPEX Estimation and Battery Parameters

Annual operating costs are estimated as a fixed percentage of installer CAPEX, escalated by inflation. When battery storage is included, a supplementary O&M cost is added per usable kWh, adjusted annually for battery degradation.

A.4.1 OPEX Equation Sequence

Component	Equation	Description
Base OPEX (PV)	$OPEX_{PV} = CAPEX_{Inst} \times r_{OPEX}$	Annual PV operating cost as a fixed ratio of installer CAPEX
Base OPEX (Battery)	$OPEX_{bat,t} = E_{bat} \times r_{OPEX} \times SoH_t$	Battery Operation& Management per usable kWh, adjusted for degradation in year t
Total Base OPEX	$OPEX_{base,0} = OPEX_{PV,0} + OPEX_{bat,0}$	Combined annual operating cost when storage is included (Year 0)
Inflation-Adjusted OPEX	$OPEX_{T,t} = OPEX_{base,,0} \times (1+f)^t$	Total OPEX in year t, escalated by cumulative inflation factor f

Table A.4.1. OPEX estimation equations. f = annual inflation rate; r_{OPEX}*= OPEX ratio applied to installer CAPEX;* $r_{OPEX,bat}$*= battery-specific O&M rate per kWh; SoH*^{t} *= State of Health in year t.*

A.4.2 Battery Technical Parameters

The following parameters govern the battery degradation model. The model applies a dual-trigger replacement logic: the battery is replaced either at a scheduled year or when the State of Health falls below the end-of-life threshold, whichever occurs first. Cycle degradation is activated from Year 2.

Parameter	Symbol	Typical Range	Value Adopted	Notes
Depth of Discharge	DoD	0.80 – 0.95	**0.90**	LFP chemistry; usable capacity = nominal × DoD × SoH
Round-Trip Efficiency	RTE	0.85 – 0.95	**0.88**	88% of stored energy is ultimately recovered as usable electricity
C-rate	C	0.5 – 1.0 C	**0.5 C**	Maximum charge/discharge power = 50% of nominal capacity per hour
Annual cycles	—	300 – 365	**365**	One full equivalent cycle per day assumed as operational baseline
Initial State of Health	SoH	—	**1.00**	Full capacity assumed at commissioning
End-of-life SoH threshold	SoH_{eol}	0.70 – 0.80	**0.70**	Battery replacement triggered when SoH falls below this threshold
Calendar degradation	—	0.3% – 0.8% / yr	**0.5% / year**	Applied every year from Year 1 regardless of cycling
Cycle degradation	—	2% – 4% / year	**3.0% / year**	Applied from Year 2 onward; capacity loss due to charge/discharge cycling
Replacement schedule	—	10 – 15 years	**Year 12**	Dual trigger: Year 12 or SoH < 0.70, whichever occurs first
Battery OPEX	—	3 – 8 €/kWh/yr	**5 €/kWh/yr**	Annual O&M cost per usable kWh; escalated by inflation

Table A.4.2. Battery technical parameters adopted in the model. Values correspond to LFP chemistry. Cycle degradation onset in Year 2 reflects the standard assumption that degradation effects are negligible during the first year of operation.

A.5 Discounted Cash Flow Framework — Auxiliary Equations

The financial module computes project viability through a standard discounted cash flow (DCF) framework. Annual net cash flows are discounted at the scenario-specific WACC to produce the NPV. The IRR is solved numerically as the rate that sets NPV to zero. Payback period is identified as the first year in which cumulative discounted cash flows become positive. These equations expand the KPI definitions given in Table 4.1 of the main text.

KPI / Component	Equation	Description
Annual PV Generation	$E_t = E_0 \times (1-d)^t$	Output in year t accounting for cumulative PV degradation (d) from base-year generation E_0
Grid price evolution	$P_{cap} = P_0 \times (1+\ g)^t$	Grid electricity purchase price in year t, escalated at annual rate (g) from base price P_0
Self-consumption savings	$SCSavings = E_t \times sc_rate \times P_{cap}$	Annual savings from electricity generated and directly consumed
Surplus export revenue	$Revenue =\ E_{surplus}\ \times\ P_{sale}$	Annual revenue from surplus electricity exported to the grid at compensation price (P_{sale})
Total annual savings	$TSavings = SC\ Savings_t +\ \text{Revenues}$	
Total OPEX	$OPEX_t = OPEX_{base,0} \times (1+f)^{\text{t}}$	First-year total OPEX escalated annually by inflation rate f
Free Cash Flow	$FCF\ _t =\ T\ Savings_t -\ OPEX\ _t -\ Taxes\ _t$	Annual net cash flow; initial outlay recorded as negative at t = 0 ($FCF^0 = -CAPEX$)
Net Present Value (NPV)	$NPV = -CAPEX + \sum_{t=1}^{T} \frac{FCF_t}{(1+r)^t}$	Discounted sum of all net cash flows; positive NPV indicates financial viability
Internal Rate of Return (IRR)	$IRR\text{:}\ \sum_{t=0}^{T} \frac{FCF_t}{(1+r^*)^t} = 0$	Discount rate r* at which NPV equals zero; solved numerically
Payback Period	$A_t = \sum_{j=0}^{t} FCF_j\ \ (\text{where } A_t > 0)$	Cumulative discounted cash flow; payback at first year A^t becomes positive

Table A.5. Auxiliary equations of the DCF framework. r = scenario-specific WACC; T = project lifetime; d = PV degradation rate; g = electricity price growth rate; f = inflation rate; sc_rate = effective self-consumption ratio. The payback period uses cumulative discounted cash flows (A^t), consistent with Table 4.1.

General Notes

All monetary values are expressed in nominal terms. Discount rates are scenario-differentiated: 3.5% for S1 (PV-only, small scale), 5.0% for S2 (PV with battery storage), and 4.5% for S3 (large-scale PV-only), consistent with a risk-adjusted cost of capital approach (Steinbach & Staniaszek, 2015; IEA, 2024).

The self-consumption ratio (sc_rate) is an exogenous input derived from the companion engineering study (Gaubeka, 2026) for S1 and S2, and from simulation for S3. In S2, the effective sc_rate is adjusted annually in proportion to battery State of Health. Complete scenario-specific input values are provided in Chapter 5.

Appendix B. Social Module: Parameter Tables and Weighting Scheme

This appendix provides the full coding structure for the social module indicators referenced in Section 4.2.2, together with the normalization procedures and weighting schemes used to compute the composite indices. Blue shading = Governance & Inclusiveness and Participation & Engagement dimensions; teal shading = Distribution of Benefits & Vulnerability; grey shading = Barriers & Enabling Conditions (contextual layer).

B.1 Full Social Module Coding Structure

The following table presents the complete set of social module variables, including admissible values, variable type, and a methodological description of each indicator. This coding structure operationalises the conceptual framework described in Section 4.2.2 and translates qualitative and documentary evidence into structured inputs for the assessment tool.

Dimension	Variable	Type	Admissible Values	Description
Governance & Inclusiveness	*participation_model*	Categorical	0 = municipal 1 = mixed 2 = open / community-led	Dominant governance model. Higher values indicate greater community autonomy and democratic control.
	legal_entity_exists	Binary	True / False	Whether a formal legal entity has been established. Enables enforceable rights and durable governance.
	legal_entity_type	Categorical	municipality; association; cooperative; mixed; other	Citizen-led forms (association, cooperative) score 1; municipal forms score 0, reflecting degree of democratic member control.
	resident_priority_exists	Binary	True / False	Whether local residents or priority groups receive preferential access conditions.
Participation & Engagement	*community_info_level*	Ordinal	0 = none 1 = limited 2 = active	Level of information directed at the community. A precondition for meaningful participation.
	citizen_interest_level	Ordinal	0 = none 1 = low 2 = medium 3 = high	Perceived level of citizen interest in joining or engaging with the initiative.
	support_conflict_index	Ordinal	−1 = conflict 0 = neutral 1 = supportive	Overall social climate. Rescaled from [−1, 1] to [0, 1] for aggregation.

Dimension	Variable	Type	Admissible Values	Description
Distribution of Benefits & Vulnerability	*energy_poverty_presence*	Binary	True / False	Whether energy vulnerability has been identified in the area of intervention.
	vulnerable_households_est	Scalar	Integer ≥ 0	Estimated number of households in energy vulnerability. Denominator for coverage rate.
	support_mechanism_enabled	Binary	True / False	Whether a solidarity or redistributive mechanism is foreseen.
	support_share_pct	Scalar	0 – 100 (%)	Percentage of annual surplus allocated through the support mechanism.
	beneficiary_selection_rule	Categorical	none; income; age; income_age; municipal_screening; other	Criterion used to identify eligible beneficiaries.
Barriers & Enabling Conditions	*economic_barrier_level*	Ordinal	0 = none 1 = low 2 = medium 3 = high	Relevance of economic barriers (membership fees, upfront costs). Weight in Feasibility Index: 0.50.
	social_barrier_level	Ordinal	0 = none 1 = low 2 = medium 3 = high	Relevance of social barriers (low trust, limited information networks). Weight: 0.30.
	administrative_barrier_level	Ordinal	0 = none 1 = low 2 = medium 3 = high	Relevance of administrative barriers (registration, regulatory complexity). Weight: 0.20.

Table B.1. Social module variables and full coding structure. Barrier variables are inverted before aggregation into the Implementation Feasibility Index so that higher index values indicate fewer barriers.

B.2 Weighting Scheme for Composite Indicators

The following tables document the normalisation procedures and assigned weights used to compute the Governance Index, Participation Index, Social Score, and Implementation Feasibility Index. Weights are grounded in the theoretical framework of Section 2.4 but remain normative choices adjustable for sensitivity analysis.

B.2a Governance Index

Sub-indicator	Normalisation	Weight	Rationale
participation_model (0 = municipal … 2 = open)	÷ 2 → [0, 1]	0.40	Primary structural determinant of community autonomy. Central to procedural justice literature.
legal_entity_exists (True / False)	Boolean → 0 or 1	0.35	Necessary condition for enforceable rights. Weighted as a threshold indicator.
legal_entity_type (citizen-led bonus)	1 if {association, cooperative}; else 0	0.25	Captures degree of democratic member control. Binary encoding avoids overclaiming finer gradients.
Governance Index	Weighted sum, capped at 1.0	Σ = 1.00	

Table B.2a. Governance Index — normalisation and weights.

B.2b Participation Index

Sub-indicator	Normalisation	Weight	Rationale
citizen_interest_level (0 = none … 3 = high)	÷ 3 → [0, 1]	0.40	Most direct signal of actual participatory engagement and social receptivity.
community_info_level (0 = none, 1 = limited, 2 = active)	÷ 2 → [0, 1]	0.35	Information provision is a structural precondition for meaningful participation.
support_conflict_index (−1 = conflict … 1 = supportive)	(value + 1) ÷ 2 → [0, 1]	0.25	Partly exogenous to initiative design; receives the lowest weight accordingly.
Participation Index	Weighted sum, capped at 1.0	Σ = 1.00	

Table B.2b. Participation Index — normalisation and weights.

B.2c Social Score

Component	Default Weight	Note
Governance Index	0.50	Configurable via score_weights parameter.
Participation Index	0.50	Configurable via score_weights parameter.
Social Score	—	Weighted average; weights must sum to 1.0. Equal weighting reflects the assumption that process quality and engagement are of equivalent importance.

Table B.2c. Social Score — composite weighting. Default equal weights can be adjusted via the score_weights configuration parameter.

B.2d Implementation Feasibility Index

Sub-indicator	Normalisation	Weight	Rationale
economic_barrier_level (0 = none … 3 = high)	Inverted: (3 − value) ÷ 3 → [0, 1]	0.50	Insufficient financing is the primary empirical constraint on LEC participation. Highest weight reflects observed primacy in the literature.
social_barrier_level (0 = none … 3 = high)	Inverted: (3 − value) ÷ 3 → [0, 1]	0.30	Community engagement and social capital provide structural resilience; can undermine well-designed governance models.
administrative_barrier_level (0 = none … 3 = high)	Inverted: (3 − value) ÷ 3 → [0, 1]	0.20	Procedural complexity is a real but typically secondary constraint, more amenable to policy intervention.
Feasibility Index	Weighted sum → [0, 1]	Σ = 1.00	Higher values indicate fewer barriers and greater implementation feasibility. Reported alongside the Social Score.

Table B.2d. Implementation Feasibility Index — normalisation and weights. Barrier sub-scores are inverted so the index is directionally consistent with the Social Score (higher = better).

Methodological note on subjectivity. All weights above encode normative choices grounded in the theoretical framework and remain contestable. The tool exposes all weights as configurable parameters so that alternative assumptions can be tested without modifying the underlying methodological structure.