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Comprehensive Assessment of Energy Saving Potential in Renewable Energy Communities

A Case Study of Guzmán Renovable, Spain

School of Technology and Innovations
MSc in Technology
Master’s Programme in Smart Energy, Major in Smart Grids

Vaasa 2026

UNIVERSITY OF VAASA
School of Technology and Innovations

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Title of the thesis:	Comprehensive Assessment of Energy Saving Potential in Renewable Energy Communities: A Case Study of Guzmán Renovable, Spain
Degree:	Master of Technology
Degree Programme:	Smart Energy, Major in Smart Grids
Supervisor:	Sesil Koutra, Chadi Mahfoud, Koldo Martin Escudero
Year:	2026 **Pages:** 76

ABSTRACT:

Renewable Energy Communities (RECs) are legally recognised collective entities through which citizens generate, share, and manage renewable energy. Despite growing policy recognition under the EU's Clean Energy for All Europeans package, no standardised operational performance assessment tool exists at the community level. This thesis addresses that gap by developing a Key Performance Indicator (KPI) framework designed to evaluate REC performance across energy, economic, and environmental dimensions, with the goals of supporting reductions in energy cost and greenhouse gas (GHG) emissions, applied to the case study of Guzmán Renovable (a REC in Burgos, Spain).

A KPI framework grades its five indicators: Energy Performance Certificate (EPC), Self-Sufficiency, Self-Consumption, Payback Period, and Energy Poverty Rate. These indicators are graded on an A-to-F scale against REC benchmarks from Spain, Belgium, and the Netherlands, then aggregated into a weighted community score. Building Energy Simulation , calibrated against measured data, was applied to the two lowest-energy-performing buildings to quantify envelope and active system retrofit impacts, and analyse the consequences in the REC.

The baseline assessment placed the REC at an overall grade of D, which put most of its KPIs under the average REC performance across Western European benchmarks. Different retrofitting levels were analysed for the two lowest-performing buildings, achieving a maximum of 75% reduction in Primary Energy Consumption and improving their EPC grade from F/G to B.

However, the building-level efficiency gains did not uniformly translate to improvements in other indicators. For the electricity-heated building, the Self-

Consumption Rate decreased by up to 28% under the fixed PV allocation key, while the Self-Sufficiency Rate improved by only 14%. For the biomass-heated building, electrification may increase net greenhouse gas emission due to the Spanish grid carbon intensity. Consequently, the overall REC grade of retrofit scenarios remained at D. These findings indicate that effective REC cost and GHG reduction require coordinated attention to building efficiency, context-sensitive fuel switching, and revision of the PV allocation mechanism to reflect post-retrofit profiles.

KEYWORDS: Renewable Energy Communities, Key Performance Indicators, Building Energy Simulation, Energy Efficiency Retrofit.

AI-Assisted Tools Disclosure:

During the preparation of this thesis, the author made use of AI-assisted tools, including Grammarly (grammar and style checking), Claude (brainstorming and writing support), Perplexity (reference searching and topic exploration), and DeepL (translation assistance) to support writing quality, literature discovery, and language refinement. All research content, analysis, interpretations, and conclusions are the author's own. The author takes full responsibility for the accuracy and integrity of this work.

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Abbreviations

Abbreviation	Full Term
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CAPEX	Capital Expenditure
CEC	Citizen Energy Community
CoP	Coefficient of Performance
CSRD	Corporate Sustainability Reporting Directive
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DHW	Domestic Hot Water
DSM	Demand Side Management
EC	Energy Community
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ETICS	External Thermal Insulation Composite System
GHG	Greenhouse Gas
HP	Heat Pump
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
NMBE	Normalized Mean Bias Error
NZED	Net Zero Emissions Districts framework
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PEF	Primary Energy Factor
PV	Photovoltaic
REC	Renewable Energy Community
RED II	Renewable Energy Directive II
SCR	Self-Consumption Rate

SRI	Smart Readiness Indicator
SSR	Self-Sufficiency Rate (Renewable Coverage Rate)
XPS	Extruded Polystyrene (insulation)

1 Introduction

The decarbonization of Europe's energy system requires action at every scale, from national grids down to individual buildings, including local communities. Renewable Energy Communities (RECs) hold a unique position in this action, as they are legally recognized entities that allow citizens to collectively generate, share, and manage renewable energy, thereby enabling active participation in the energy transition (REScoop.eu, 2021) . The EU Renewable Energy Directive II (RED II) (Joint Research Centre, 2024) and the Clean Energy for All Europeans package (Directorate-General for Energy, 2019) provide the legislative foundation for RECs, establishing their rights and obligations across Member States.

Despite this growing policy recognition, a fundamental operational gap remains. Unlike buildings, which are assessed against well-established energy efficiency standards, such as Energy Performance Certificate (EPC) ratings (European Datawarehouse, 2024), RECs have no standardized tool for evaluating their own performance. Recent efforts by have begun to catalogue various Key Performance Indicators (KPIs) applicable to Energy Communities, such as Giannuzzo et.al (Giannuzzo et al., 2025) with its 25 KPIs or EcoEmpower with its 24 qualitative and quantitative assessment criteria (Luca, 2023). The existing approaches remain insufficiently operationalized, non-graded, or not validated through simulationies or case studies. Energy Communities' managers are therefore still left without a structured way to identify where their community is underperforming, what is driving that underperformance, or how to prioritize improvement.

This thesis addresses this gap by developing a comprehensive KPI-based assessment framework, covering energy, economic, and environmental dimensions, to support the communities analyse the energy cost and GHG emission reduction potentials. It is tailored specifically to Renewable Energy Communities, and demonstrates its application through a real-world case study in a Renewable Energy Community called Guzmán Renovable in Spain. The framework is designed primarily for community managers and members rather than regulatory bodies, to ensure it is practical and actionable. Based on the assessment results of the selected case study, targeted improvement measures are proposed to enhance the overall performance of the community. These measures focus on addressing low-performing indicators and identifying performance gaps. A simulation model is further employed to support the technical analysis and to validate the effectiveness of the proposed interventions.

1.1 Objectives and Research Questions

Objective: To develop a KPI framework and assessment tool for evaluating the technical performance of a Renewable Energy Community (REC) across energy, economic, and environmental dimensions, and generate simulation-supported recommendations for energy performance improvement.

Research Questions:

1. **RQ1:** What KPIs should be used to assess REC's performance to support reductions in energy costs and greenhouse gas emissions?
2. **RQ2:** What targeted recommendations can be proposed to the community based on the analysis of the lowest-performing and most impactful KPIs?

Hypotheses:

1. **H1:** The identified KPIs across energy, economic, and environmental dimensions influence the reductions in energy cost and GHG emissions within Renewable Energy Communities.
2. **H2:** Building Energy Consumption-related KPIs are predicted to show lowest-performance due to older building stock of the community, and retrofit measures applied to low-performing buildings are expected to improve both building-level performance and community-level KPI scores.

1.2 Thesis Structure

Chapter 2 provides the literature review, covering the context and evolution of RECs in Europe, existing performance assessment frameworks, and the identified research gap.

Chapter 3 describes the research methodology. Chapter 4 presents the KPI framework development, including the grading scale rationale for each indicator. Chapter 5 presents the case study community and the data collected. Chapter 6 presents the results and discussion. Chapter 7 concludes the thesis and outlines directions for future work.

2 Literature Review

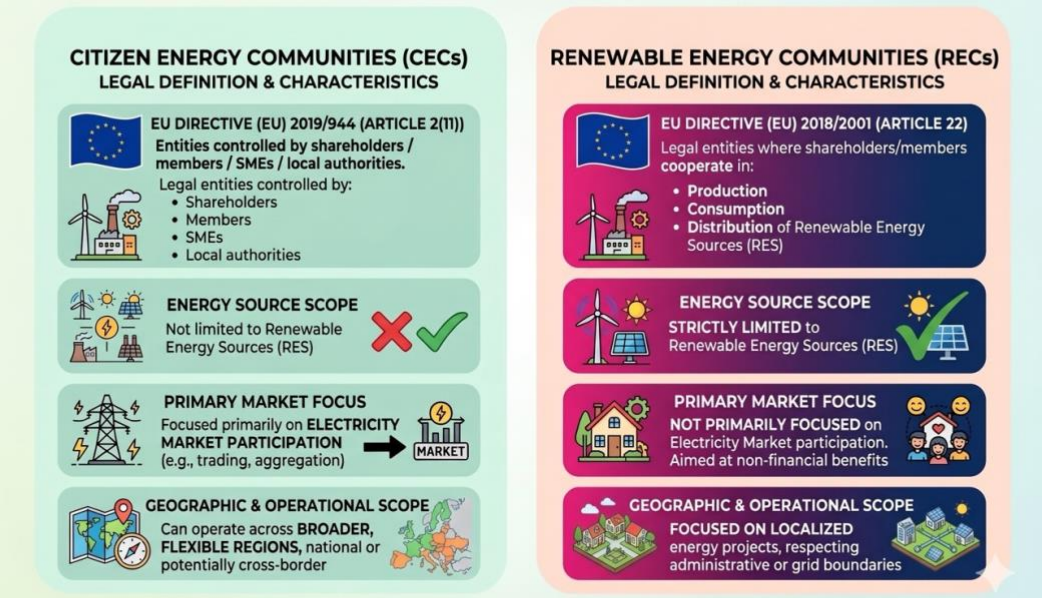
This chapter reviews the current state of Renewable Energy Communities in Europe, examines the key performances dimensions most frequently assessed in the REC literature for community-level assessment, surveys existing frameworks used broadly, and identifies the research gap.

2.1 Renewable Energy Communities in Europe

An Energy Community is a legal entity characterized by *open and voluntary participation, autonomous governance, and a membership located near the energy projects it owns and develops* (Valta et al., 2021). Energy Community is classified into two:

- Renewable Energy Communities (RECs) focus on renewable energy resources.
- Citizen Energy Communities (CECs) could combine both renewable and non-renewable energy sources.

CEC is expected to have a democratic, member-controlled governance model, but it is generally less restrictive than a Renewable Energy Community (REC) about what assets, activities, and members it can include. However, both are promoted as tools to accelerate the green energy transition, which is aligned with the EU's long-term climate-neutrality targets, which aim for at least 75% of total energy consumption from renewable sources by 2050 and approximately 16% of electricity generation from collective projects (European Commission. Joint Research Centre., 2020).



CITIZEN ENERGY COMMUNITIES (CECs)
LEGAL DEFINITION & CHARACTERISTICS

EU DIRECTIVE (EU) 2019/944 (ARTICLE 2(11))
Entities controlled by shareholders / members / SMEs / local authorities.
Legal entities controlled by:
- Shareholders
- Members
- SMEs
- Local authorities

ENERGY SOURCE SCOPE
Not limited to Renewable Energy Sources (RES)

PRIMARY MARKET FOCUS
Focused primarily on ELECTRICITY MARKET PARTICIPATION (e.g., trading, aggregation)

GEOGRAPHIC & OPERATIONAL SCOPE
Can operate across BROADER, FLEXIBLE REGIONS, national or potentially cross-border

RENEWABLE ENERGY COMMUNITIES (RECs)
LEGAL DEFINITION & CHARACTERISTICS

EU DIRECTIVE (EU) 2018/2001 (ARTICLE 22)
Legal entities where shareholders/members cooperate in:
- Production
- Consumption
- Distribution of Renewable Energy Sources (RES)

ENERGY SOURCE SCOPE
STRICTLY LIMITED to Renewable Energy Sources (RES)

PRIMARY MARKET FOCUS
NOT PRIMARILY FOCUSED on Electricity Market participation. Aimed at non-financial benefits

GEOGRAPHIC & OPERATIONAL SCOPE
FOCUSED ON LOCALIZED energy projects, respecting administrative or grid boundaries

Figure 1. Comparison between CEC vs REC (European Commission. Joint Research Centre., 2020)

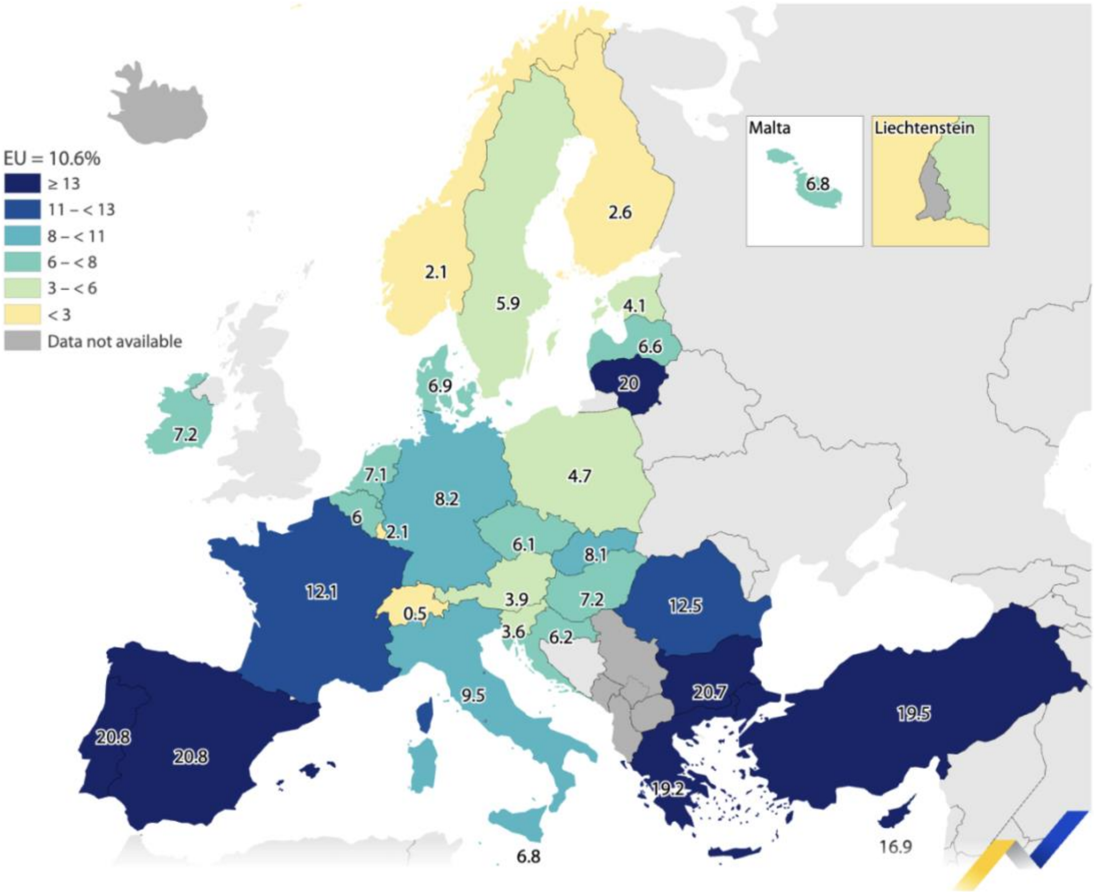
There are currently more than 9,000 Energy Communities across Europe, with Denmark, Ireland, Germany, and the Netherlands recording the highest community membership rates per 1000 capita in Europe, with Denmark reaching approximately 11 members, Ireland around 5, Germany approximately 5, and the Netherlands around 4, as detailed in Appendix 1 **Error! Reference source not found.**(Bukovszki & Abdullah, 2024). This prominence reflects longstanding cooperative traditions, flexible governance mechanisms, and targeted policy instruments such as Denmark, that has a long history of wind farms as one of their forms of energy sharing (Bukovszki & Abdullah, 2024). The distribution is, however, highly uneven, and Southern and Eastern European countries, including Spain , lag considerably behind in terms of established community infrastructure, making the development of assessment tools that work across different national contexts particularly relevant.

This thesis focuses more on the REC than the CEC, as one of the assessment goals is to reduce GHG emissions, which are more relevant to the renewable energy generated in the REC. Solar PV and micro-wind are the most widely adopted technologies in REC settings, with installed capacities typically ranging from a few kW to around 1 MW (Horváth & Szabó, 2018). These technologies are accessible to a wide range of community types and geographies, and their declining costs have made collective renewable generation increasingly viable even without large subsidies.

2.1.1 Energy Poverty

Energy poverty, broadly defined as the inability to afford adequate energy services in the home (European Commission, n.d.), is a significant and growing concern across Europe. Figure 2 shows the distribution of energy poverty across the European Union. *In 2023, 10.6% of the EU population reported difficulty in maintaining adequate domestic temperatures, with Spain and Portugal recording the highest rates at 20.8% each* (Eurostat, 2025). Energy Communities hold considerable potential to address this issue through three mechanisms by lowering electricity bills via renewable energy sharing, enabling vulnerable households to participate through collective investment schemes that reduce individual entry barriers, and supporting demand-shifting to reduce peak costs. Therefore, the Guzmán Renovable case study in Spain was selected, as Spain records one of the highest energy poverty rates in the EU, making it relevant context for assessing REC intervention.

While energy poverty is inherently a social condition, this framework operationalises it as an economic indicator, measured as the share of community members whose energy expenditure exceeds a defined threshold, making it tractable within a quantitative assessment. Including such an indicator is therefore both practically relevant and an underexplored contribution to the REC performance literature.



Source dataset: ilc_mdes01

Administrative boundaries: © EuroGeographics © UN–FAO © Turkstat
Cartography: Eurostat – IMAGE, 01/2025

Figure 2. Energy Poverty across European Union (Eurostat, 2025)

2.1.2 Research Trend in Energy Communities

A review of objective functions used in Energy Community studies provides insight into how performance is typically evaluated in the literature. Economic criteria dominate strongly (73 occurrences), while technical, environmental, and social objectives appear far less frequently, as shown in Table 1. Notably, environmental and social objectives are rarely pursued as primary goals, when they did appear, it was typically as secondary considerations alongside economic criteria (Barabino et al., 2023).

Table 1. Summary of Objective Functions in Energy Community Studies (Barabino et al., 2023)

Dimension	*Total (papers)*	*Key Parameters*
Economic	73	Energy cost (37), total annual/lifetime cost (38), savings (7), operative cost (7), others (15)
Technical	34	Self-sufficiency (8), net-grid exchange (7), self-consumption (6), component sizing (5), others (8)

Environmental	10	CO_2 emissions (6), life-cycle impact (2), renewable fraction (2)
Social	2	Discomfort (2)

Even though these studies focus on optimization, the selection of objective functions reflects broader evaluation priorities in the field. The observed economic bias suggests that current assessment approaches insufficiently capture environmental and social dimensions. Energy poverty, in particular, does not appear as an explicit objective in any of the reviewed studies, despite its policy relevance in the EU context. This gap reinforces the need for a multi-dimensional framework that extends beyond techno-economic optimisation criteria.

2.2 Existing Performance Assessment Frameworks

A range of performance assessment frameworks exists for buildings, districts, and corporate entities. This section reviews the most relevant ones, examining what dimensions they cover, what indicators they use, and what they do not address at the Energy Community level. Table 2 summarises these frameworks and the gaps each presents for REC assessment; across all cases, no single framework combines community-level scope, quantitative energy and economic indicators, and a standardised grading scale.

- **EPC (Energy Performance Certificate)***:* The EPC is the most directly relevant framework for building-level energy assessment. It grades buildings from A to G (European Datawarehouse, 2024).
- **BREEAM (Building Research Establishment Environmental Assessment Method)***:* BREEAM is the world's leading sustainability assessment method for buildings and neighbourhoods. It covers energy use (kWh/m2/year and CO2 emissions), health and wellbeing, transport, water, materials, waste, pollution, land use, and ecology [14]. BREEAM is selected here as the representative green building standard because it is the most widely adopted certification scheme in Europe, including Spain (Salgado, 2025), compared LEED that is mor common in

United States. It is important to understand how building performance is evaluated, as it helps define the KPI assessment in the community

- **SRI (Smart Readiness Indicator)***:* The SRI, introduced under the EPBD, assesses how 'smart' a building is e.g. its capacity to adapt operations to signals from the energy grid and to respond to user needs. It covers heating, cooling, domestic hot water, ventilation, lighting, dynamic envelope, electricity, and monitoring and control systems (CEN/CEN WS SRI, 2024).
- **CSRD (Corporate Sustainability Reporting Directive)***:* The CSRD is a mandatory EU reporting standard for large companies, covering environmental (climate change, pollution, biodiversity, resource use), social (workforce, value chain, communities, consumers), and governance dimensions (Gilbert-d'Halluin, 2024). Although the CSRD was created for corporations, some of the indicators measured in the CSRD are still relevant for the REC, such as the share of renewable energy and GHG emissions, especially since the REC also allows corporations to become members.
- **EcoEmpower Framework***:* EcoEmpower is a monitoring and evaluation framework specifically developed for Energy Communities and one-stop-shop (OSS) support structures (Luca, 2023). It is the most directly applicable framework to the REC, but lacks building-level indicators and does not provide grading scales.
- **REscoop Assessment Tool***:* REscoop is the European federation of energy cooperatives and has developed a community self-assessment tool designed to help cooperatives evaluate their own performance. (Holstenkamp & Kriel, 2022).

Table 2. Comparison of Existing Assessment Frameworks

Framework	Assessment Level	Energy KPIs	Economic KPIs	Environmental KPIs	Grading Scale	Key Gap for RECs
EPC	Individual building	Energy use intensity	Running costs estimate	Building carbon emissions	A–G, national thresholds	Building scope only
BREEAM	Building / neighbourhood	Energy use and emissions	Not included	Building carbon and pollution	Tiered credits system	Design phase only

SRI	Individual building	Smart system levels only	Not included	Not included	Percentage readiness score	Systems readiness only
CSRD	Corporate entity	Renewable share in mix	Not included	Total organisational emissions	Disclosure only	Corporate scale only
Eco-Empower	Energy community	Energy savings and self-consumption	Investment,savings, abatement cost	Avoided community emissions	Not included	No grading or building indicators
REscoop	Energy community	Not included	Qualitative only	Qualitative only	Not included	No quantitative KPIs

A recent contribution by Giannuzzo et al. (Giannuzzo et al., 2025) directly addresses the KPIs requirement for Renewable Energy Community. Through a systematic review of over 200 research papers with covering 316 metrics and applying Multi-Criteria Analysis (MCA), the authors compiled a reference list of 25 KPIs organised across energy, economic, social, and environmental domains, assessed against different usage contexts and target user groups. This work confirms the relevance and feasibility of a KPI-based approach for REC assessment.

Taken together, the reviewed frameworks confirm that building-level assessment (EPC, BREEAM, SRI) and community-level assessment (EcoEmpower, REscoop, Giannuzzo et al.), address different but complementary needs, yet none bridges them into an integrated, graded assessment applicable to a real REC.

2.3 Research Gap

The review reveals a clear and consistent gap. Assessment frameworks either operate at a different scale (building or city level, not the community level), lack the quantitative KPIs structure needed for systematic benchmarking, or do not provide graded performance scales that allow communities to identify specific weaknesses and track improvement over time.

A recent systematic review by Giannuzzo et al. (Giannuzzo et al., 2025), discussed in Section 2.2, represents the closest prior work to this thesis. However, it remains a cataloguing exercise without a graded scale, operational application, or goal-specific focus. For a community seeking to act on its performance, prioritising investments or communicating progress to members, a catalogue without grades or applied demonstration offers limited practical value. The gap between KPI identification and operational assessment therefore remains open.

None of the reviewed frameworks combines all of the following properties simultaneously:

1. designed for the Energy Community as the unit of assessment
2. covers energy, economic, and environmental dimensions through quantitative indicators, focused specifically on two community-level goals: the reduction of energy costs and the reduction of CO_2e emissions
3. uses a standardized, contextually adjustable grading scale (A to G) that makes performance gaps immediately legible to non-specialist users
4. demonstrated through application to a real REC case study, enabling empirical validation of the framework in practice

This thesis develops an assessment framework with precisely accommodate these properties, grounded in the regulatory standards and benchmarks reviewed above. This framework is applied to a case study and combines building energy simulation with community-level KPI scoring into a single integrated assessment workflow. Guzmán Renovable, a REC established in Burgos, Spain, was selected as the case study on the basis of two criteria: the availability of detailed building-level energy data and its location in Spain where energy poverty rates are high as discussed in Chapter 2.1.1.

3 Methodology

This study adopts a mixed-methods, single-case study approach, structured into five sequential stages as illustrated in Figure 3. The methodology is designed to answer research questions by two-milestone methodological workflow: Milestone 1 - Systematic development of the KPI framework; Milestone 2 - Application of Building Energy Simulation to a real case study.

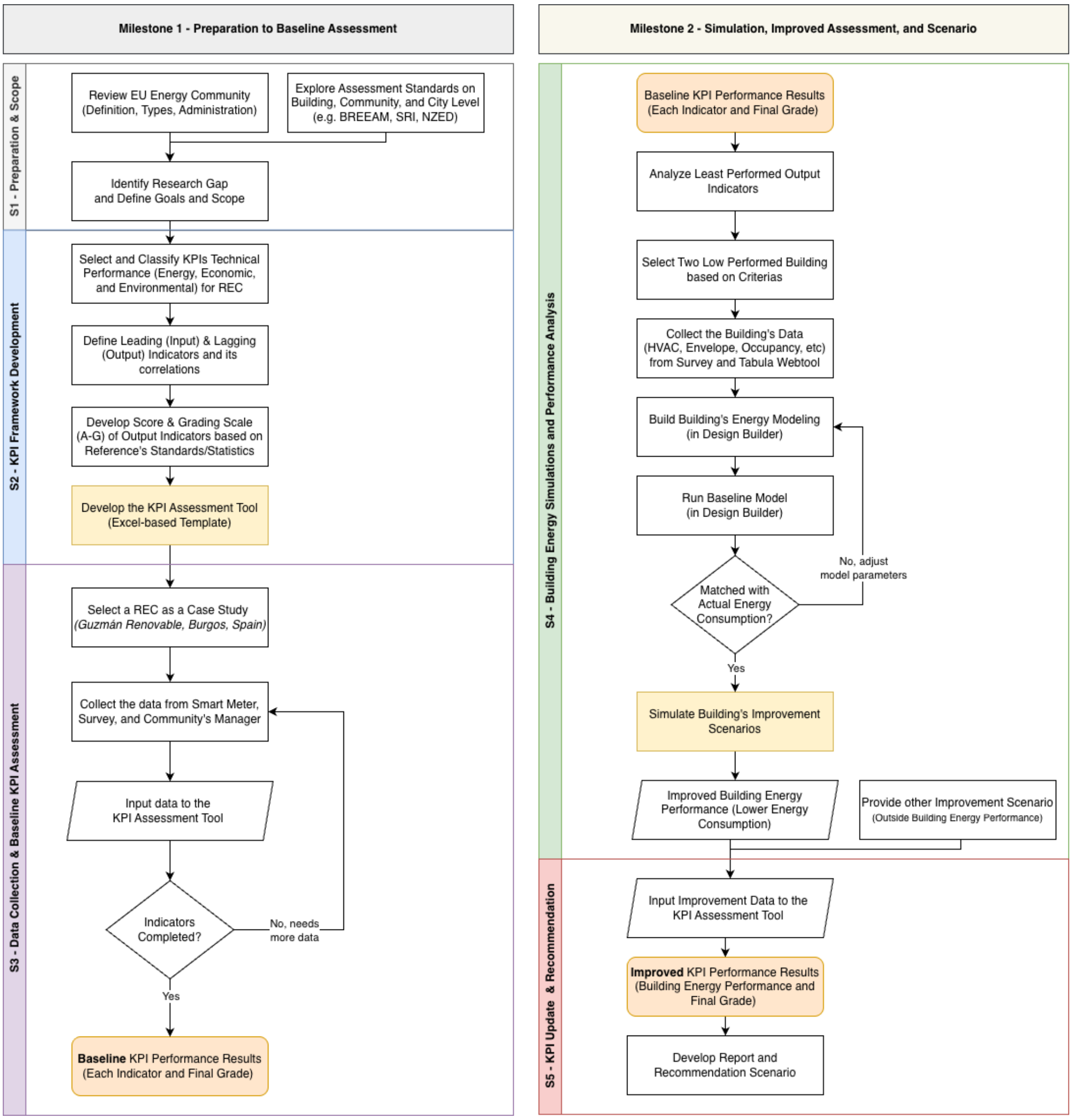


Figure 3. Flow Diagram of Methodology

The following steps for 1st milestone as Preparation to Baseline Assessment stages:

- *S1 - Preparation and Scoping:* The first stage established the theoretical and conceptual foundations of the research. A review of EU Energy Community definitions, types, and administrative frameworks was conducted, followed by a systematic examination of existing assessment standards; from this review, the research gap was identified and the goals and scope were defined.
- *S2 - KPI Framework Development:* Building on the literature review, KPIs were selected based on their frequency in the REC literature, data availability at community level, alignment with EU regulatory standards, and mutual distinctiveness to avoid indicator redundancy, then classified across three technical performance dimensions: energy, economic, and environmental. Grading scales from A to G were then developed for each output indicator to relevant EU and Spanish standards and references.
- *S3 - Data Collection and Baseline KPI Assessment:* A Renewable Energy Community was selected as the case study: *Guzmán Renovable, located in Burgos, Spain*. An Excel-based KPI assessment tool was developed by inputting the data that collected from various sources. the baseline KPI performance results were generated. *This marked the completion of Milestone 1.*

After finishing the 1st milestone, the 2nd milestone: Simulation, Improved Assessment and Scenario are conducted with the following steps:

- *S4 - Building Energy Simulation and Performance Analysis:* The lowest-performing buildings from the baseline assessment were selected per criteria in Chapter 5.4. Building data (envelope, HVAC, occupancy, internal loads) was collected and a model was built in DesignBuilder. The simulated consumption was calibrated against actual data following ASHRAE Guideline 14 (ASHRAE, 2014). Improvement scenarios (insulation, window upgrades, envelope, HVAC) were then simulated to quantify energy reduction potential.
- *S5 - KPI Update and Recommendations:* The improved building energy performance data from Stage 4 was fed back into the KPI assessment tool to

generate updated KPI scores, enabling a direct comparison between the baseline and post-improvement performance. In parallel, the least-performing output indicators from the baseline assessment were analyzed to identify further improvement opportunities beyond building energy performance. This marked the completion of Milestone 2.

Limitations: The KPI framework is restricted to three technical performance dimensions: Energy, Economics, and Environment. Social dimensions, such as participation, trust, governance, are excluded from the assessment as they are beyond the scope of this thesis. However, Energy Poverty is the sole exception, retained as a quantifiable economic proxy to see how affordable the energy to the communities (Section 4.2.5). Additionally, the grading scale thresholds are derived from limited sources: EU regulatory standards and published REC case studies in Western Europe. Therefore, the grading scale is still defined as an approximation.

4 KPI Framework Development

This chapter presents the development of the KPI framework used to assess the technical performance of Renewable Energy Communities. It covers the classification structure of the KPIs, the grading system, and for each output indicator, the relevant literature and benchmarks that informed the grading scale thresholds.

4.1 KPI Structure and Classification

The KPIs are organized into three performance dimensions: Energy, Economics, and Environment. Within each dimension, two types of indicators are distinguished. Output indicators (lagging indicators) capture the measured performance *outcomes of the community and are graded on the A-to-G scale*. Input indicators (leading indicators) represent the causal factors that drive output performance. They are not graded in the final score but are used for root-cause analysis, when an output indicator scores poorly, the input indicators point to the most likely explanations and reasons.

The relationships between indicators are visualized in a KPI correlation diagram in Figure 4., which supports the root-cause analysis process within the assessment tool.

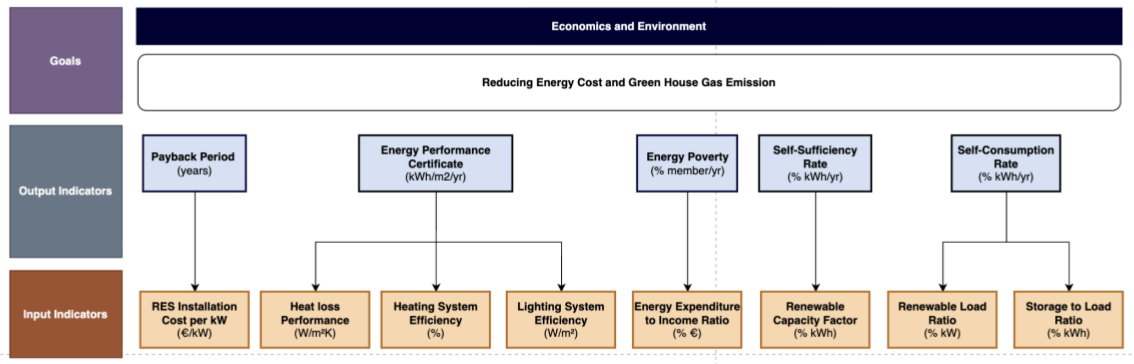


Figure 4. KPI Correlation Diagram (Sasmita, 2026)

4.2 Output Indicator Grading Scales

The grading system converts raw indicator values into a uniform A-to-G scale, making performance levels immediately legible to community managers already familiar with

EPC ratings. Ideally, the preferred approach for deriving thresholds is a percentile-based method, where complete national performance distributions are available: Class G is anchored to the worst-performing 15% of the reference population and Class A to the top performers, following the EPBD Recast methodology (Article 16, 2024) [4] for EPC rating. Initially, this grading method was expected to be applied to all KPIs in defining the grading scale. However, as in most of KPIs: Self-Sufficiency, Self-Consumption, Payback Period and Energy Poverty Rate, the national distribution data of each indicator are not available, the moderate performance band (Class C/D boundary) is established from reported National or European average values in the literature, and the upper and lower class boundaries are then derived from the range of values reported across reference case studies. Each subsection below describes the specific data sources used and the resulting scale. Once all output indicators are graded, each is assigned a weight to produce the final score.

4.2.1 Energy Performance Certificate (kWh/m2/year)

Primary Energy consumption per unit floor area is the most fundamental indicator of building energy performance, and the primary basis for EPC ratings under the EPBD (Dulian, Monika, 2024). At the community level, it captures the aggregate demand-side performance of member buildings and is directly linked to both energy cost and GHG emissions. Higher values indicate poorer performance and greater potential for improvement through retrofitting or operational changes.

$$EPC = \frac{E_{primary}}{A_{floor}} \tag{1}$$

where:

- EPC = Energy Primary Certificate as quantification for energy intensity in a building [kWh/m^2 per year]
- $E_{primary}$ = Primary Energy which energy found in nature that has not undergone any human-engineered conversion or transformation process [kWh]
- A_{floor} = Floor area that is occupied [m^2]

The grading thresholds for Spain are derived from the European DataWarehouse analysis of national EPC distributions across member states (European Datawarehouse, 2024).

These thresholds reflect the actual distribution of Spain's building stock, ensuring that Class A corresponds to genuinely high-performing buildings in the Spanish context, and Class G to the lowest-performing 15%, as seen on Table 3.

Table 3. Grading Scale - Energy Performance Certificate (Spain) (European Datawarehouse, 2024)

Grade	Energy Use (kWh/m2/yr)	Description
A	< 34.1	Very high efficiency: modern buildings with excellent insulation, airtight envelope, often with renewable heating.
B	34.1 - 55.5	Efficient: well-insulated with good heating systems; low demand but not fully optimised.
C	55.5 - 85.4	Moderate: average buildings with standard insulation and typical heating performance.
D	85.4 - 111	Below average: older homes with insufficient insulation; higher heating demand.
E	111 - 136.6	Low efficiency: outdated systems and poor insulation; significant heat loss.
F	136.6 - 170.7	Very low: poorly insulated, often pre-1980 stock, high heating costs.
G	> 170.7	Extremely inefficient: worst performers, major renovation candidates.

In EPC Rating, the energy use or energy consumption is calculated using Primary Energy Factor (PEF) to get real primary energy and excluding the Renewable Energy in the calculation. Therefore, *PEF is used to calculate this indicator by using general PEF constant in EU level equals to 1.92* using the more ambitious trend line from the recent decade (Balaras et al., 2022).

4.2.2 Self-Sufficiency Rate (%)

The Self-Sufficiency Rate (SSR) measures the proportion of the community's total energy consumption covered by its own on-site renewable generation (Giannuzzo et al., 2025). It is the primary indicator of energy independence and directly influences both energy costs and GHG emissions.

$$SSR = \frac{E_{RS,selfcons}}{E_{consumption}} \times 100\% \qquad (2)$$

where:

- SSR = Self-Sufficiency Rate / Renewable Coverage Rate [%]
- E_RS,selfcons = total self-consumed renewable energy generated on-site [kWh]
- E_consumption = total electricity consumption of the community [kWh]

Evidence from European reference cases informs the grading thresholds for this indicator. In the Netherlands (Gercek et al., 2019), smart grid pilots of more than 200 households on two communities reported median SSR values between 18–20% for PV-only households, while it can reach up to 30% for certain households, as seen Figure 6. In Belgium, the HospiGREEN energy-sharing community achieves coverage rates of 34–39%, consistent with residential benchmarks .

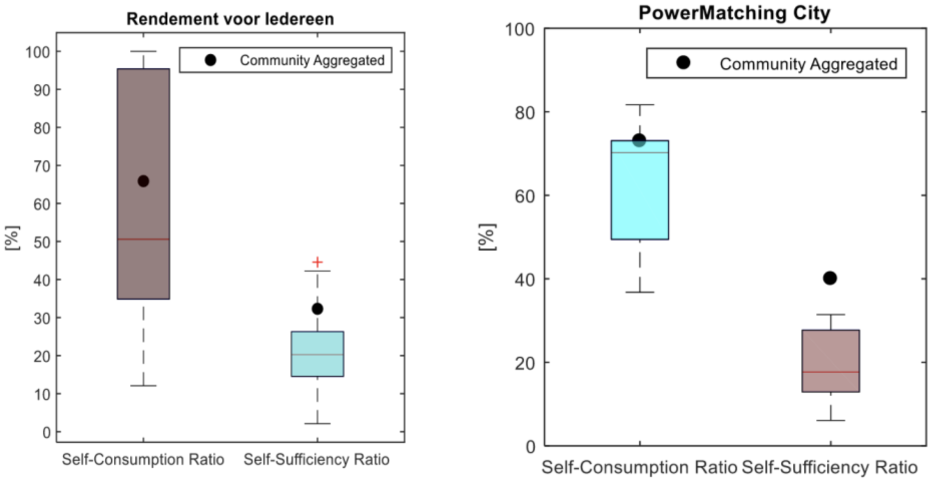


Figure 5. Self-Consumption and Self Sufficiency in Netherlands Project (Gercek et al., 2019)

For Spanish Energy Communities under Royal Decree 244/2019 (Gallego-Castillo et al., 2021), the national average SSR is 34.5% without surplus remuneration (30.4–36.6%) and 44.0% with remuneration (38.3–45.1%). Higher values are observed in southern regions due to greater solar irradiance, while northern regions remain within 30–39%. Overall, PV-only communities without storage typically achieve SSR values of 30–45%. This places standard Spanish communities in Grade C, while those with surplus remuneration or complementary technologies reach Grade B. Based on this evidence, the Renewable Coverage Rate grading scale is presented in Table 4. below.

Table 4. Grading Scale – Self-Sufficiency Rate (Sasmita, 2026)

Grade	Self-Sufficiency Rate	Description
A	≥ 60 %	Ambitious but attainable only for highly optimised RECs with storage.
B	45 - 59 %	Top-quartile of today's projects (e.g., best HospiGREEN participants).
C	30 - 44 %	Typical well-functioning community; Spanish national average with remuneration (~44%) and without remuneration (~35%) both fall in this band.
D	19 - 29 %	Lower-performing communities; Median in Netherland's projects.
E	10 - 19 %	Minimal renewable penetration.
F	5 - 9 %	Little local generation.
G	< 5 %	Negligible renewable integration

4.2.3 Self-Consumption Rate (%)

The Self-Consumption Rate (SCR) measures the proportion of locally generated renewable energy that is consumed on-site by community members, rather than exported to the grid (Giannuzzo et al., 2025). A high SCR indicates good alignment between local production and consumption patterns, which is a primary determinant of the economic return on the renewable investment. EcoEmpower lists self-consumption as a primary energy indicator, and it is also referenced in the CSRD energy mix metric. From the perspective of the Spanish regulatory framework, a higher SCR reduces the volume of surplus energy compensated at the lower market-price-based rate under Royal Decree 244/2019, directly improving the net economic outcome for community members.

$$SCR = \frac{E_{RS,selfcons}}{E_{RS,generated}} \times 100\% \qquad (3)$$

where:

- SCR = Self-Consumption Rate [%]
- E_RS,selfcons = total self-consumed renewable energy generated on-site [kWh]
- E_RS,generated = total renewable energy generated on-site [kWh]

Evidence from European pilots demonstrates a wide range of SCR values, determined primarily by the alignment between local generation profiles and community load patterns.

- For Spanish residential communities under Royal Decree 244/2019 (Instituto para la Diversificación y Ahorro de la Energía, 2024), report a national average SCR of 46.7% (regional range: 42.1-75.0%), with higher values in northern regions where PV systems are sized relative to consumption (Gallego-Castillo et al., 2021).
- In Belgium, the HospiGREEN energy-sharing community achieved SCR values of 89-94% across both project phases, attributable to the continuous and predictable electricity consumption of its hospital and industrial participants rather than any particular generation technology (Viadere, 2025).
- In the Netherlands, residential smart grid pilots recorded SCR values of approximately 50-70%, with community-level performance consistently exceeding individual performance through demand-response coordination (Gercek et al., 2019).

The Spanish national average of 46.7% is adopted as the primary reference for Grade D, as it most closely reflects the regulatory and technical context of the case study community. From the distribution of self-consumption rates across these studies, the grading scale is shown in Table 5.

Table 5. Grading Scale - Self-Consumption Rate (Sasmita, 2026)

Grade	Self-Consumption Rate (%)	Description
A	>= 90%	Excellent: optimal on-site use of renewable generation, minimal export.
B	75 - 89%	Very high: strong demand-generation alignment; northern Spanish regions (Basque Country 75%, Cantabria 74%) reach this band due to conservative PV sizing relative to demand.
C	60 - 74%	Good: typical for mature solar or mixed-generation communities with coordination.
D	45 - 59%	Moderate: European average range; Spanish national average (46.7%) falls here. Standard PV-only setup without advanced flexibility or storage.
E	30 - 44%	Low: PV-only or early-stage communities with high grid export.
F	15 - 29%	Very limited: oversized generation or poorly aligned loads.

Grade	Self-Consumption Rate (%)	Description
G	< 15%	Minimal: negligible local renewable use; effectively grid-dependent.

In this case study, the SCR and SSR is calculated using hourly data, rather than daily, monthly or yearly aggregates. This higher level of resolution inflates the apparent SCR because surpluses and deficits cancel each other out within the aggregation window, which masks the true temporal mismatch between generation and demand.

4.2.4 Payback Period (years)

The payback period is the primary economic viability indicator for the community's renewable investment (Giannuzzo et al., 2025). It is referenced in the EPC framework (payback indicators for retrofit) and in the EcoEmpower investment metrics. It varies significantly by electricity tariff, subsidy level, and installed capacity relative to energy consumption.

$$PP = \frac{CAPEX}{(\Delta C_{elec} - C_{O\&M})} \quad (4)$$

where:

- PP = Simple Payback Period [years]
- CAPEX = total capital expenditure of the community's renewable energy installation [€]
- ΔC_elec = annual electricity cost saving through on-site renewable generation [€/year]
- C_O&M = annual operation and maintenance cost of the shared installation [€/year]

Payback periods reported across European Energy Communities vary considerably by country and regulatory context.

- In Spain, Gallego-Castillo et al. (2021) found annualised savings ratios of 11–20% without surplus remuneration and 14–32% with it (Gallego-Castillo et al., 2021).
- In Manso-Burgos et al. (2021) estimated a 25% cost reduction achievable through tariff optimisation (Manso-Burgos et al., 2021).
- In Belgium, residential systems achieve paybacks of 3.5–9 years depending on region (Belgasolar, 2025) (Pauline, 2025), though Viadere (2025) found break-even unachievable through energy-sharing alone under normal tariff conditions,

with autonomous viability only during the 2021–2023 energy crisis (Viadere, 2025).

- In the Netherlands, Li and Okur (2023) report the highest third-party investor returns at a 15-year horizon, with member households benefiting most from joint self-investment (Li & Okur, 2023).

Based on the payback period evidence compiled from Spain, Belgium, and the Netherlands, the grading thresholds below were developed as presented in Table 6.

Table 6. Grading Scale - Investment Payback Period (Sasmita, 2026)

Grade	Payback Period (years)	Description
A	<= 5	Excellent: strong self-consumption, generous subsidies or citizen co-funding.
B	6 - 8	Very good: well-structured REC with competitive financing and moderate subsidies.
C	9 - 12	Good: European midpoint payback (~9-10 years), SCCALE 203050 (2023).
D	12 - 15	Moderate: lower tariffs, smaller installations, or limited subsidies; typical for Spanish PV-only communities without storage (e.g., Guzmán Renovable baseline: 15.24 years).
E	16 - 19	Challenging: feasible only with strong community engagement or social value.
F	20 - 25	Low return: slow cash flow or policy uncertainty, capital-intensive projects.
G	> 25	Non-viable: unattractive under normal economics without grants.

4.2.5 Energy Poverty Rate (% of members)

The energy poverty rate tracks the proportion of community members whose energy expenditure represents a disproportionate share of household income. This indicator is included in both the NZED framework (as a co-benefit indicator) and is broadly referenced in EU energy policy through the Social Climate Fund and the revised Energy Efficiency Directive (2023/1791) (Neumann et al., 2022). Including it in the REC assessment framework reflects the expectation that communities should actively contribute to reducing, not merely ignoring, energy poverty among their members.

$$EPR = \frac{N_{poverty}}{N_{total}} \times 100\% \qquad (5)$$

where:

- EPR = Energy Poverty Rate [%]
- N_poverty = number of community members whose energy-cost-to-income ratio exceeds the defined threshold
- N_total = total number of community members

There are different methods to identify Energy Poverty (see the details on Appendix 2):

- The 2M (Twice Median Share) method states a household is energy poor if its energy expenditure share exceeds twice the national median (Delbeke, Bart and Meyer, Sandrine, 2019).
- The Boardman rule states that if the energy cost of a household is beyond 10% of its total income, the household is considered to be in energy poverty (Delbeke, Bart and Meyer, Sandrine, 2019). 10% threshold chosen as it is represented twice the median energy spend of all UK households at the method was developed in 1991 (Delbeke, Bart and Meyer, Sandrine, 2019).
- The LIHC method states an household belong to energy poverty if the required energy costs are above national median and residual income (after energy costs) is below the poverty line (*E04_BDOC_Energy_Poverty_Indicators_Report_EPAH_EN*, 2022).

2M method is popular nowadays over Boardman's 10% rule or the LIHC approach for its cross-national adaptability and alignment with EU-harmonized (*E04_BDOC_Energy_Poverty_Indicators_Report_EPAH_EN*, 2022). *However on this thesis, Boardman rule was preferred for simplicity*, as the 2M (Twice Median Share) required national data which might be changing over time.

In Spain, as in most southern European countries, energy poverty rates are: 20.8% of the Spanish population reported difficulty heating their homes adequately in 2023 (Eurostat, 2025). The EU-wide average rate of 10.6% serves as the reference for the Class C/D boundary, with the Spanish national rate of 20.8% (2023) anchoring Class E, and Class G set at rates exceeding 30%, which represent structurally severe situations requiring targeted intervention. The classification of energy poverty is defined in Table 7.

Table 7. Grading Scale - Energy Poverty Rate (Sasmita, 2026)

Grade	% of Members in Energy Poverty	Interpretation
A	0 - 5%	Very low: well below EU average; community is actively protecting vulnerable members.

Grade	% of Members in Energy Poverty	Interpretation
B	>5 - 10%	Low: better than most national averages in southern Europe.
C	>10 - 15%	Around national average for better-performing EU countries.
D	>15 - 20%	Above EU average; approaching Spanish national rate.
E	>20 - 25%	High: at or above Spanish national average (~20.8%).
F	>25 - 30%	Very high: a quarter to a third of members are energy poor.
G	>30%	Severe: structurally problematic; targeted intervention urgently needed.

4.3 Weighting Factor

After each Output Indicator is converted to specific grade, is assigned a numerical score based on its grade: A = 7, B = 6, C = 5, D = 4, E = 3, F = 2, G = 1. These scores are then weighted according to each indicator's relative importance (Weights were assigned based on each indicator's centrality to the REC's core objectives. Energy Performance Certificate receives the highest weight (30%) as the primary determinant of energy cost and greenhouse gas emissions, and the indicator most directly addressed by retrofit interventions. SSR and SCR are equally weighted at 20% each, as complementary measures of renewable integration: one captures demand coverage, the other generation utilisation. Payback Period and Energy Poverty Rate each receive 15%, reflecting their relevance to economic viability while acknowledging their greater sensitivity to external factors such as tariff structures and household income.

Table 8. and converted to Grade A-G (

Table 9.)

Weights were assigned based on each indicator's centrality to the REC's core objectives. Energy Performance Certificate receives the highest weight (30%) as the primary determinant of energy cost and greenhouse gas emissions, and the indicator most directly addressed by retrofit interventions. SSR and SCR are equally weighted at 20% each, as complementary measures of renewable integration: one captures demand coverage, the other generation utilisation. Payback Period and Energy Poverty Rate each receive 15%, reflecting their relevance to economic viability while acknowledging their greater sensitivity to external factors such as tariff structures and household income.

Table 8. KPI Weighting Score (Sasmita, 2026)

Parameter	Weight (%)
Energy Primary Certificate	30%
Self-Sufficiency Rate	20%
Self-Consumption Rate	20%
Payback Period	15%
Energy Poverty	15%
Total	

Table 9. KPI Final Grade (Sasmita, 2026)

Total Score - Final Grade						
A	B	C	D	E	F	G
6.5–7.0	5.5–6.5	4.5–5.5	3.5–4.5	2.5–3.5	1.5–2.5	1.0–1.5

5 Case Study: Guzmán

This chapter introduces the Energy Community selected for the case study, describes its background and organisational context, and presents the data collected for the baseline KPI assessment.

5.1 Community Overview

Guzmán Renovable (Figure 6) is a Renewable Energy Community (REC) in Guzmán village, Burgos, Spain, operating as a collective self-consumption arrangement under Royal Decree 244/2019. Members share the output of a jointly owned PV installation through a regulated distribution coefficient, receiving a monthly credit against their electricity bills proportional to their assigned share. The community was selected as the case study for three reasons: it represents a rural REC in 'Empty Spain' (España Vaciada), a socially significant context characterised by depopulation and limited infrastructure access. It was established as a non-profit association in January 2022 in response to rising energy costs (Guzmán Renovable, 2026), making it a recent and well-documented example and complete hourly smart meter data and PV generation records for 2024–2025 are available, satisfying the data requirements of the KPI framework developed in Chapter 4.

Figure 6. Guzmán Renovable Community Meeting and PV Installation (Guzmán Renovable, 2026)

To understand better context of this Renewable Energy Community, Table 10 summarises the community's key characteristics.

Table 10. General Information about Guzmán Renovable (Guzmán Renovable, 2026)

Category	Description
Name	Guzmán Renovable
Location	Guzmán, Ribera del Duero, Burgos, Spain
Guzman's Population	~100 inhabitants
Legal Form	Non-profit association
Established	January 2022
Type	Rural REC - collective self-consumption
Members	Private households, municipality, local entities, hotel
Number of Members	14 (including the municipality)

The community secured NextGenerationEU funding and installed a 30.3 kWp PV system in July 2023. The system was connected with a shared self-consumption configuration in November 2024, 18 months after installation (Guzmán Renovable, 2026). Table 11 provides the full specification. The PV production is shared using fixed-allocation key that was determined by the community manager on quarterly or yearly basis based on the building electricity consumption data. The list of allocation key or energy sharing key of each building in 2025 can be seen on Appendix 3.

Table 11. Installed PV Specification and Investment (Guzmán Renovable, 2026)

Attribute	Value
Technology	Photovoltaic (PV) Solar Energy
Installed Capacity	30.3 kWp
Estimated Annual Production	42,128 kWh/year
Total Investment	EUR 44,253
Public Funding Received	EUR 24.352 (CE IMPLEMENTA - MITECO, NextGenerationEU)
Technical Advisory	Energetica Coop
PV Installation Start	July 2023
Grid Connection	November 2024

5.2 Building Portfolio and Data Availability

The 14 members occupy distinct buildings including residential units, a municipal office, local facilities, and a hotel. Energy consumption patterns differ considerably across members. Data were collected through three sources: (1) hourly electricity consumption from smart meters installed; (2) a structured survey distributed to all 14 members requesting floor area, heating system type, fuel consumption, and tariff information; and (3) annual PV generation records provided by the system installer. The survey form is reproduced in the Appendix. Table 12. summarises the building portfolio.

Table 12. Building Properties in Guzmán Renovable

ID	Type	Occupancy pattern	Active hours	Floor Area (m²)	Electricity tariff	Main heating	Auxiliary heating	DHW system
B1	Hotel			845				
B2	Warehouse			429				
B3	Residential	Permanent	Morning, Evening	99	Time-of-use	Electric Resistance		Electric Resistance
B4	Residential	Permanent	All Day	284	Unknown	Biomass Boiler	Electric Resistance	Electric Heat Pump
B5	Residential	Permanent	All Day	125	Time-of-use	Biomass Boiler	Biomass Boiler	Electric Resistance
B6	Residential	Permanent		108	Unknown			
B7	Residential	Permanent	All Day	125	Unknown	Oil Boiler		Oil Boiler
B8	Residential	Permanent	Evening	150	Fixed	Oil Boiler		Oil Boiler
B9	Residential	Permanent	All Day	160	Unknown	Oil Boiler	Electric Resistance	Oil Boiler
B10	Residential	Intermittent	All Day	200	Time-of-use	Oil Boiler	Biomass Boiler	
B11	Residential			160				
B12	Medical Facility			100				
B13	Residential	Intermittent	Morning, Afternoon	85	Fixed	Biomass Boiler	Biomass Boiler	Biomass Boiler
B14	Residential	Intermittent	Afternoon, Evening	200	Fixed	Biomass Boiler	Electric Resistance	

Further details of the building’s properties:

- *Occupancy*: The intermittent occupancy means that the owner only visited or live there during occasional seasons, like weekend or holidays. Not like permanent, which live there almost every day.

- *Type of Tariff:* Time of Use means that the electricity tariff will be varied across hours (peak, mid or off-peak). While some owners do not know the tariff labelled as unknown.

Some cells remain blank, as the corresponding survey forms were not returned. While the majority of buildings are residential, non-residential cases are also present, including a hotel, a warehouse, and a medical facility. To ensure complete coverage for the KPI assessment, the following study-specific assumptions were formulated by the author where directly measured data were unavailable.

1. *Floor area values* are obtained from member-submitted surveys. Where a member reported only an approximate range rather than a precise figure, the floor area was determined and validated using Google Earth aerial imagery viewed from above. The assumed floor area does not account for wall thickness.
2. *Space heating and domestic hot water (DHW) consumption* is derived from reported fuel quantities (oil, firewood, or pellets) for buildings equipped with non-electric heating systems. *Where such data are unavailable, an oil or gas boiler is assumed as the heating source, with a final energy consumption for heating estimated at three times the non-heating electricity consumption*, based on the consumption patterns observed in comparable buildings within the community.
3. *The electricity tariff* is determined individually for each building based on the electricity bills provided by the respective members. As each bill represents a single billing period rather than a complete annual record, the total electricity expenditure for 2025 cannot be derived directly. For cost calculations, the average unit energy cost (EUR/kWh) is therefore computed from the available billing sample for each building. For buildings where no billing data are available, the mean unit energy cost calculated across the remaining buildings is applied as a substitute value.

Some cells are left blank as the survey form were not sent back, which coming from the buildings are not residential (Public Facilities, Hotel, or Warehouse).

5.3 Building Selection for Energy Simulation

For prioritization, *only two buildings that were simulated* due to time constraints. The candidates for building’s energy modelling were screened against three criteria:

(1) Residential use

(2) Permanent Occupancy: The members live there every day, not just during weekends/holiday

(3) HVAC: Use electric appliances for space heating or Domestic Hot water Heating (DHW), so that consumption patterns are directly visible in the smart meter data and have impact on the SCR.

Based on survey result and preliminary research, *the building 3 and 5 were selected*, since both buildings meet all of the criteria. Moreover, building 3 and 5 among the buildings that had worst Energy Performance Rating (EPC) that belongs to F and G grade respectively. Lastly, they are located next to each other, which the energy consumption and sharing pattern be analysed further. Based on Figure 7. below, Building 3 (B3) is located on the center, while Building 5 (B5) is on the right side.

Figure 7. B3 and B5 on Google Earth

An exploratory data analysis was conducted to characterise the electricity consumption behaviour of Buildings 3 and 5 (B3 and B5) using two years of hourly power meter data collected during 2024 and 2025. The objective was to identify the annual magnitude, the seasonal variation and the daily pattern of each building before the data was used to configure the building energy simulation presented in Section 5.4.

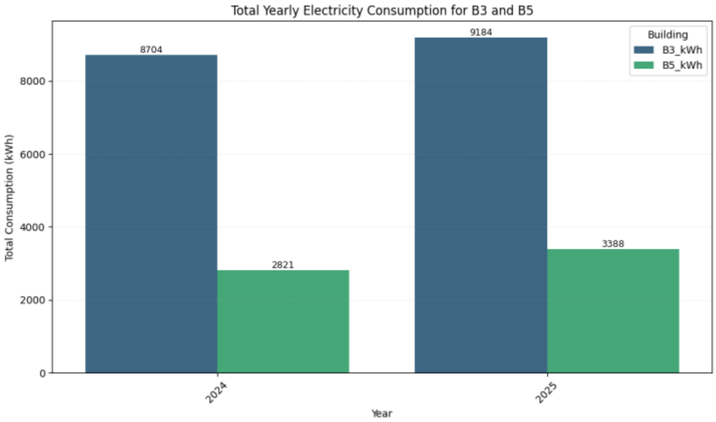


Figure 8. Annual Electricity Consumption B3 and B5

A first observation drawn from the annual aggregated data is the substantial difference in annual electricity consumption between the two buildings, which is *explained by the different heating systems adopted by each household. B3 uses an electric storage heater for space heating while B5 uses a biomass boiler, so that a significant share of thermal consumption in B3 appears in the electricity meter whereas in B5 it is covered by biomass and therefore remains invisible to the electricity measurement.* According to IDAE residential benchmarks for Spain, the average household consumes between 2,700 and 3,800 kWh per year of non-heating electricity (Endesa, 2026). On this basis, the annual electricity consumption of B5 falls within the expected range for an unconditioned residential load. The same benchmark cannot be directly applied to B3 because its measurement includes the space heating contribution, which inflates the observed electricity consumption beyond the residual household appliance load.

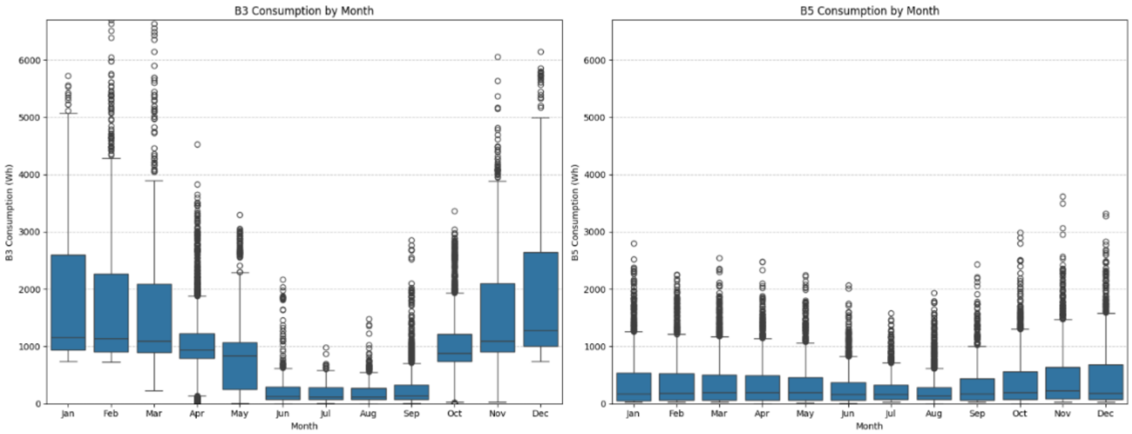


Figure 9. Box Plot of Energy Consumption (Wh) of B3 and B5

As shown in Figure 9., the monthly box plots of the hourly load (in Watt-hours) reveal a clear seasonal pattern for both buildings, with higher consumption during the cold months and lower consumption during the warm months. This seasonal variation is consistent with four physical drivers:

- *Increased artificial lighting consumption:* Guzmán has around 15 dark hours per day in December compared with approximately 9 hours in June, which increases the number of hours during which artificial lighting is needed.
- *Higher DHW energy consumption:* Cold water inlet temperatures are significantly lower in winter than in summer, which requires the electric boiler to deliver more energy to reach the same target temperature.
- *Extended indoor activity*: Longer periods spent indoors during winter months increase the cumulative use of home appliances, cooking equipment, and entertainment devices.
- *Absence of cooling equipment*: the absence of a summer cooling peak in the data is consistent with the survey finding that neither household owns electric air conditioning.

For B3 the contrast between the heating and the non heating months is particularly marked. Between June and September the hourly readings drop to *a flat baseline of approximately 165 to 250 Wh, which corresponds to the residual appliance and lighting load once the electric heating is switched off,* as shown in *Figure 10.* below.

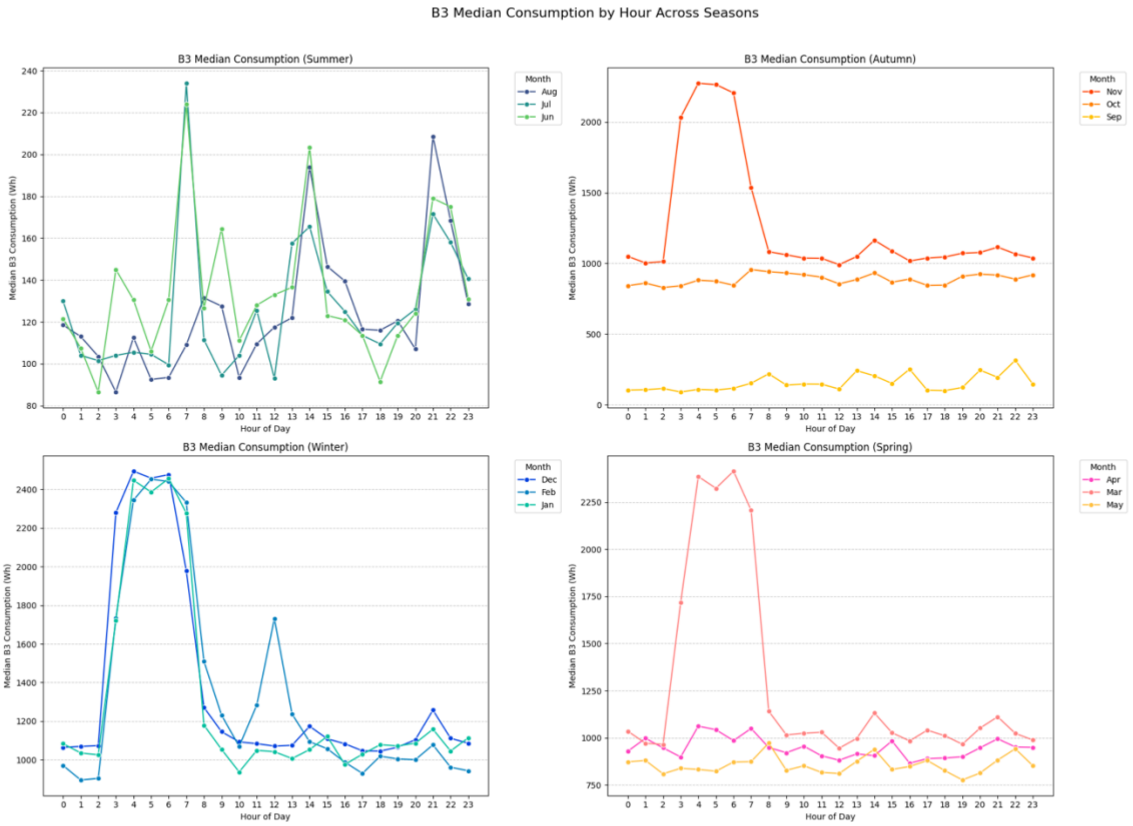


Figure 10. B3 Median Consumption by Hour Across Seasons

The hourly consumption pattern of each building is then examined using the median value of the two year dataset (2024 to 2025) to filter out atypical peaks and isolate the recurrent daily behaviour.

For Building 3, the patterns identified in the median hourly profile (Figure 10.) are summarised below.

- *Highest peak between 02:00 and 07:00:* during the cold season *(November to March) electricity consumption peaks between 02:00 and 07:00*, because the occupant programmes the electric heater timer to operate during the off peak tariff window offered by the electricity supplier.
- Midday (13:00 to 15:00) and evening (after 19:00) peaks: these peaks coincide with the return of the occupant for lunch or rest in the afternoon and with the end of the working day in the evening, when cooking, lighting and entertainment loads are active simultaneously.

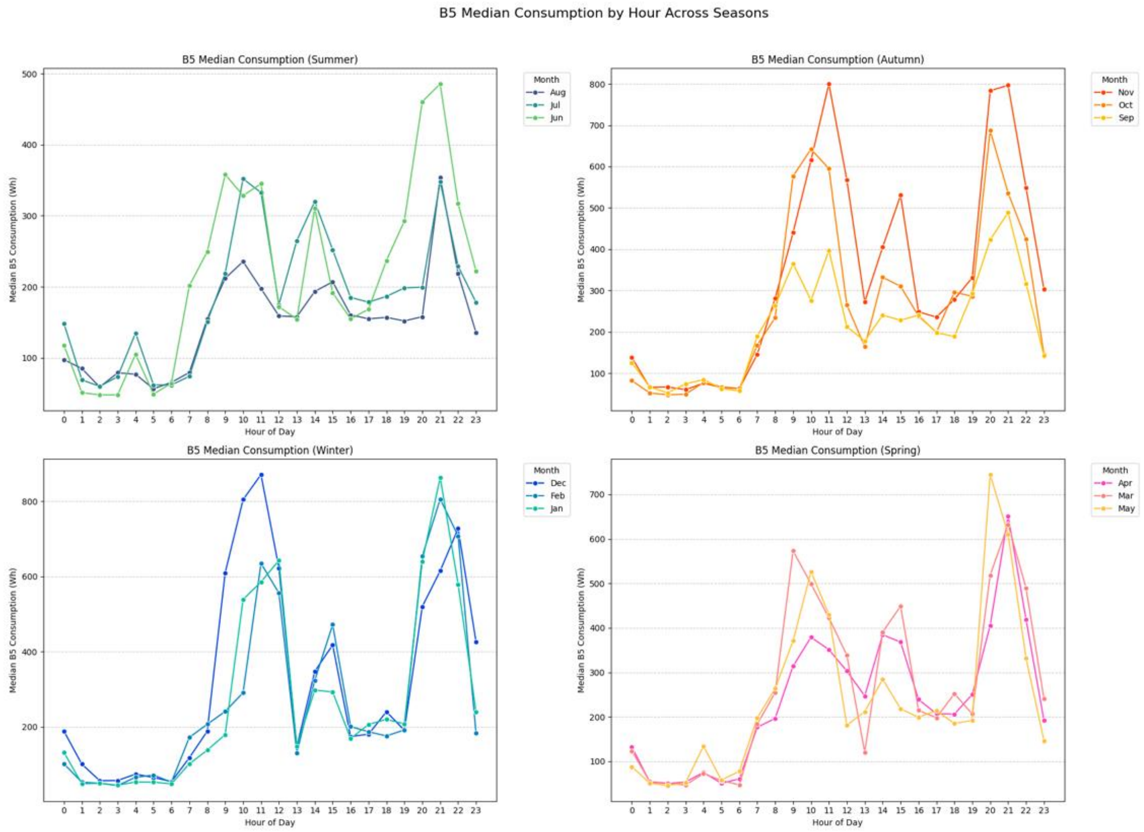


Figure 11. B5 median Consumption by Hour Across Seasons

For Building 5, the patterns identified in the median hourly profile in Figure 11. are summarised below.

- *Morning peak between 09:00 and 11:00* and evening peak between 20:00 and 22:00*:* these peaks correspond to the morning routine after the household wakes up and to the return of the occupants at night, when cooking, bathing and leisure activities drive the electricity consumption.
- *Midday peak between 13:00 and 15:00:* a secondary peak coinciding with lunch time, similar in shape but lower in magnitude than the one observed in B3.

Overall, both buildings show residential daily profile shaped by the waking, lunch and evening routines, with the notable exception of the early morning heating peak that is specific to B3 during the cold season.

5.4 Configuration of Building Energy Simulation

The simulation methodology is structured as a ten-step workflow, progressing from geometric modelling through baseline calibration to retrofit scenario analysis. The details are shown in Appendix 4. Each stage builds upon the outputs of the preceding one, ensuring that the final energy performance indicators reflect a validated representation of the actual building stock.

Building 3D geometry is constructed in DesignBuilder using member survey data and Google Earth imagery, with the Guzmán EPW 2025 file applied as the weather boundary condition (Step 1). Baseline parameters are then assigned from survey responses and the Tabula database, covering occupancy patterns, envelope U-values, and HVAC and DHW system types (Step 2) as presented in Appendix 5. Steps 3 to 5 constitute the schedule calibration procedure, applied to B3 and B5 for which hourly smart meter data is available. Annual targets are first established: the non-heating electricity share is set at 25% of total consumption for B3 and at the full smart meter total for B5, while annual heating targets are set at 75% of B3 electricity and derived from reported biomass fuel quantities for B5 (Steps 3a and 3b). B5 uses 85% of its final energy for heating, therefore for B3, it is approximated that it uses 70-80% of its final energy for heating as B3 uses more efficient heating system (CoP of electric heater is 1.0 compared to Biomass Boiler: ~85%).

Monthly DHW energy consumption’s are then calculated using sensible heat equation:

$$Q = m \cdot Cp \cdot \Delta T \qquad (6)$$

where:

- $Q = heat\ energy\ transferred\ [kWh]$
- $m = mass\ flow\ rate\ of\ water\ [kg/hr]$
- $Cp = specific\ heat\ capacity\ of\ water\ [kWh/kg \cdot K]\ (\approx\ 0.001163\ kWh/kg \cdot K)$
- $\Delta T = temperature\ difference\ between\ supply\ and\ return\ [K]$

The calibrated model is simulated in Step 6, and performance is evaluated against measured data using *monthly MBE and CV-RMSE in accordance with ASHRAE Guideline 14, with acceptance thresholds of 5% and 15% respectively* (Step 7) (ASHRAE, 2014). Once calibration is confirmed, three cumulative retrofit scenarios are defined: R1 (double glazing), R2 (R1 + wall and roof insulation), and R3 (R2 + heat pump + LED) (Step 8). All scenarios are simulated per building (Step 9), and results are reported as percentage reductions in energy consumption, CO2 emissions, and energy cost relative to the baseline (Step 10).

The two calibration metrics are defined as follows:

$$MBE = \frac{\sum(y_{sim,i} - y_{meas,i})}{\sum y_{meas,i}} \times 100\% \tag{7}$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum(y_{sim,i} - y_{meas,i})^2}{n}}}{\bar{y}_{meas}} \times 100\% \tag{8}$$

where:

- $\bar{y}_{meas}$= mean of all measured monthly values [kWh]
- n = number of months in the evaluation period
- $y_{meas,i}$= measured monthly energy value for month i [kWh]
- $y_{sim,i}$ = simulated monthly energy value for month i [kWh]

The details of parameters in DesignBuilder can be found on Appendix 5. Simulation Parameters for Building 3 and 5. It summarises the key building parameters adopted for both buildings. The general parameters were collected through the community survey; the envelope thermal properties were derived from the TABULA typology database for the Spanish 1901–1936 (Loga et al., 2026) building stock as from the survey both buildings are more than 100 years old. It has a pre-regulation construction period predating Spain's first thermal building standard: characterised by solid masonry walls with no insulation layer, single-glazed windows, and high thermal transmittance values. Retrofit target U-values for walls, roof, and glazing were set in accordance with Advanced Refurbishment envelopes in TABULA.

The retrofit scenario matrix defines three scenario packages applied to B3 and two to B5.

- *Retrofit R1* replaces single-glazed windows with double glazing (U-value 1.4 W/m²K); this scenario is omitted for B5 because double glazing is already installed in its as-built envelope.
- *Retrofit R2* adds XPS wall and roof insulation to achieve the target U-values (U-value 0.5 W/m²K); reduces the natural air-change rate from 0.45 to 0.30 ac/h. The envelope renovation is prioritized to reduce the energy consumption (passive design) before add new active design like heat pump.
- *Retrofit R3* extends R2 by replacing the space and water heating systems with an air-to-water heat pump (COP 3.0 for space heating, COP 2.50 for DHW) and upgrading lighting from halogen to LED (5.0 to 1.5 W/m² per 100 lux). Room electricity and appliance loads are held constant across all scenarios.

6 Results and Discussion

This chapter presents the results of the baseline KPI assessment for Guzmán Renovable and the building energy simulation for Buildings 3 and 5. Chapter 6.1 reports the KPI scores and grades across all output and goal indicators computed for the 2025 reference year, drawing on hourly power meter data and the electricity cost analysis developed in Chapter 5. Chapter 6.2 presents the calibration results and retrofit simulation outcomes for Buildings 3 and 5, and discusses their implications for the community's energy performance trajectory.

6.1 Baseline KPI Assessment

The baseline KPI assessment evaluates Guzmán Renovable across its full portfolio of 14 member buildings for the 2025 reference year, applying the five output indicators and two goal indicators defined in Chapter 4. Per-building values are first computed from metered consumption, allocated PV generation, and survey-based income data; these are then aggregated at the community level to derive a single grade and weighted score per indicator. The indicator scores are subsequently combined into an aggregate performance score using the weighting scheme established in Section 4.3. Table 13. Building-Level KPI Result, reports the building-level results for the four metric-based output indicators, providing the disaggregated basis for the community-level synthesis presented in KPI. All variables used for the calculation can be seen on Appendix 6-8. The heating consumption for EPC ratings of B1, B2, B4, B11 and B12 was estimated at three times their electricity consumption, based on the pattern of other buildings, due to unavailable data.

Table 13. Building-Level KPI Result

Building	EPC Rating	EPC Grade	Self Consumption	Self Sufficiency	Energy Cost / Income (Energy Poverty)
	kWh/m²/yr	A – G	%	%	%
B1	53.2	B	48.2%	45.5%	N/A
B2	105.3	D	62.8%	30.5%	N/A
B3	166.8	F	53.2%	16.4%	6.2%

Building	EPC Rating	EPC Grade	Self Consumption	Self Sufficiency	Energy Cost / Income (Energy Poverty)
	kWh/m^{2}/yr	A – G	%	%	%
B4	42.0	B	38.5%	25.9%	N/A
B5	184.0	G	55.2%	26.6%	3.8%
B6	103.3	D	29.3%	8.1%	N/A
B7	126.7	E	67.4%	34.4%	12.3%
B8	125.3	E	49.6%	29.9%	N/A
B9	84.6	C	75.3%	34.1%	10.2%
B10	47.1	B	68.7%	29.6%	3.2%
B11	77.2	C	69.6%	25.4%	N/A
B12	86.4	D	54.1%	24.3%	N/A
B13	175.7	G	51.1%	23.3%	2.7%
B14	16.4	A	37.6%	20.3%	N/A

Table 13 above reveals substantial heterogeneity across the building stock:

- EPC ratings span the full A (B14) to G range (Building 5 and Building 13)
- Building's self-sufficiency rates vary from 8.1% (Building 6) to 45.5% (Building 1)
- Self-consumption rates range from 29.3% (Building 6) to 75.3% (Building 9).
- Energy-cost-to-income ratios were available only for six buildings due to incomplete survey returns with values between 2.7% (Building 13) and 12.3% (Building 7).

Table 14 presents the consolidated KPI scorecard, in which each indicator is reported with its community-level metric value, grade, normalised score, weight, and weighted score.

Table 14. Community-Level KPI Result

Indicator	Metric Value	Grade	Score (1-7)	Weight	Weighted Score
Energy Performance Certificate (kWh/m^{2}/yr)	94.87	D	4	30%	1.20

Self-Sufficiency Rate	27.33%	D	4	20%	0.80
Self-Consumption Rate	53.13%	D	4	20%	0.80
Payback Period	11.86 years	C	5	15%	0.75
Energy Poverty Rate	14.29% (2/14 members)	C	5	15%	0.75
Aggregate Score		**D**			**4.30**

Two observations follow from the scorecard. First, three of the five output indicators receive Grade D, signalling that most of the community's indicators performs at the lower middle of the assessment scale on the economic and environment dimensions. Second, both the payback period (Grade C, 11.86 years) and the energy poverty indicator (Grade C, 14.29%) perform above the Grade D band; the energy poverty result reflects two of the six surveyed members exceeding the 10% threshold, and is contingent on the limited income-data coverage discussed in Section 6.1.5.

Table 15. Goal indicators for Guzmán Renovable, 2025.

Goal Indicator	2025 Percentage Saving	2025 Absolute Saving
GHG Reduction vs. grid baseline	26.45%	1,541 Kg CO_{2e}
Net Energy Cost Reduction	27.33%	€ 3,541.06

These two goal indicators translate the indicator-level scorecard into community-level impact, shown on Table 15. The 26.45% reduction in greenhouse-gas emissions versus the grid baseline reflects the share of consumption met by the on-site PV system and quantifies Guzmán Renovable's direct environmental contribution; it is bounded by the same self-sufficiency ceiling identified in Chapter 6.1.3, so further GHG reduction depend primarily on expanding renewable generation or reducing absolute consumption through retrofitting. The 27.33% net energy-cost reduction captures the economic benefit retained by members after accounting for self-consumed generation and exported surplus, and confirms that the community delivers a tangible household-level saving; the payback period (Grade C, 11.86 years) reflects the upfront capital investment, while this metric reflects the recurring annual benefit once the system is operating.

Taken together, the two figures show that, even at its current configuration, the community already produces a measurable environmental and economic dividend for its members; the retrofit scenarios examined in Section 6.2 are therefore aimed at lifting both indicators by addressing the consumption side that the baseline PV deployment alone cannot address. These figures are indicative estimates based on a static average tariff, an LCOE approach for PV cost recovery, and the Spanish operative grid emission factor; lifecycle PV emissions are excluded. Full assumptions and derivations are provided in the Appendix 5.

6.1.1 Energy Performance Certificate

Figure 12 reports the Energy Performance Certificate (Primary Energy Consumption per Floor Area) value assigned to each member building and shows how the community is distributed across the EPC scale, where Building 3, 5, and 13 achieved the lowest EPC ratings, as shown in Figure 12.

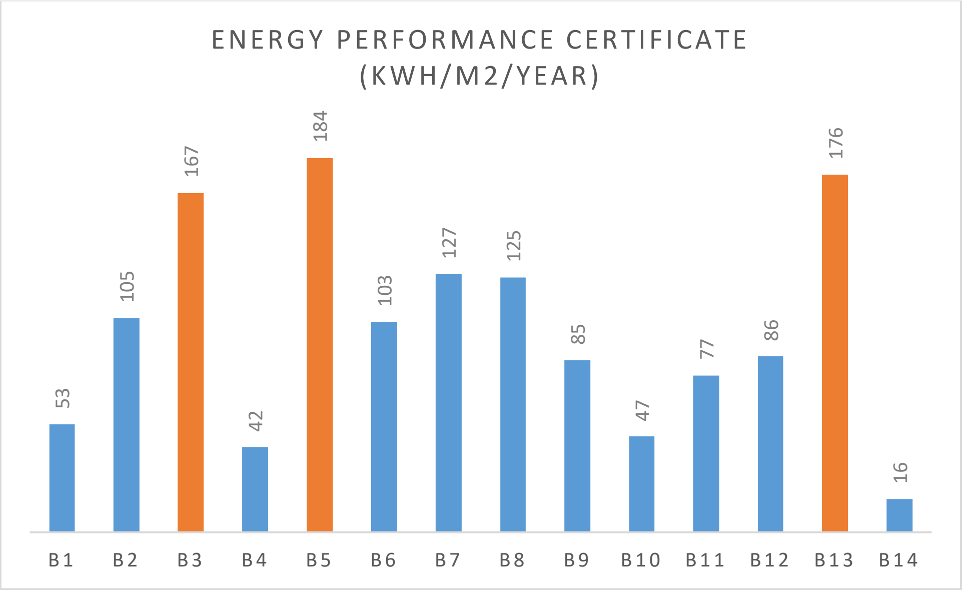


Figure 12. Building's Energy Performance Certificate Calculated Value

Table 16 complements the figure by reporting the three indicators that underline each certificate: total final energy consumption, total primary energy consumption, and primary energy consumption per unit of conditioned floor area (kWh/m²/year) or EPC.

The latter indicator determines the EPC rating displayed in on Figure 12, so the figure conveys the headline classification while the table exposes the absolute and area-normalised values from which it is derived. In Table 16, colour coding reflects the rank of each residential building on each indicator independently, with green denoting the lowest (best) value and red the highest (worst); white cells identify the three non-comparable members (B1 hotel, B2 warehouse, and B12). Buildings B1, B2, B4, B11, and B12 include estimated heating consumption in their totals because heating data were unavailable, and consequently both their absolute values and the EPC bands shown for them in Figure 12 carry proportionate uncertainty.

Table 16. Comparative energy performance ranking of member's buildings

Building	Floor Area (m²)	Final Energy (kWh)	Primary Energy (kWh)	EPC Value (kWh/m²/yr)	EPC Grade	Notes
B1	845	37,276	44,917	53.2	B	Estimated heating, Non Residential
B2	429	36,407	45,172	105.3	D	Estimated heating, Non Residential
B3	99	9,184	16,509	166.8	F	
B4	284	10,110	11,897	42.0	B	Estimated heating
B5	125	20,588	22,963	184.0	G	
B6	108	5,918	11,110	103.3	D	
B7	125	13,202	15,838	126.7	E	
B8	150	16,001	18,790	125.3	E	
B9	160	11,088	13,533	84.6	C	
B10	200	7,465	9,421	47.1	B	
B11	160	9,834	12,323	77.2	C	Estimated heating
B12	100	6,882	8,642	86.4	D	Estimated heating, Non Residential
B13	85	13,694	14,933	175.7	G	
B14	200	2,726	3,278	16.4	A	

Colour scale – personalized on each column (residential buildings only):

🟩	Best performance	🟨	Intermediate performance	🟥	Worst performance

Three findings emerge from the comparative ranking.

- B5 records the highest values on all three indicators (Grade G), confirming it as the highest-priority renovation target. B14 sits at the opposite extreme (Grade A), partly due to its intermittent occupancy pattern. B1 is classified to Grade B even with primary-energy, but the big floor area compensated it.
- Divergences between final and primary energy rankings reflect heating system fuel type. B3 provides the clearest illustration: despite moderate final energy, its electric storage heaters are subject to the EU grid primary energy factor of 1.95 (Balaras et al., 2022), compounded by a small floor area, yielding a Grade F certificate. B4 shows the opposite: comparable final energy converts to a much lower primary energy, because biomass heating carries a near-unity factor and its larger floor area dilutes the intensity to Grade B.
- B6 illustrates a further nuance: despite low absolute energy use, its small floor area concentrates the intensity metric, yielding only a Grade D certificate. A building with low total consumption can thus still underperform on the area-normalised metric that governs EPC classification.

Key Takeaways: Taken together, these findings indicate that heating-system fuel type is the primary driver of divergence between the final and primary energy ranks: buildings relying on electric resistance heating, such as B3, incur a disproportionate primary energy penalty relative to biomass users such as B4 and B5 with comparable thermal loads. The energy primary consumption metric, which determines the EPC grade, depends additionally on floor area, so buildings with high absolute consumption distributed over large footprints may achieve better EPC grades than smaller, lighter-consuming counterparts.

6.1.2 Self-Consumption Rate

The community self-consumption rate (SCR) of 53.13% reflects the share of the 28,435 kWh total allocated PV output that is consumed by members rather than exported. The Table 17 is the direct result of the fixed allocation key mechanism: each member is assigned a fixed share of PV generation, and any fraction of that share not consumed during the generation interval is automatically exported to the grid based on the hourly data.

Table 17. Building-level Self-Consumption rate

Building	Alloc. Key (%)	Building SCR (%)	Unconsumed RS (kWh)	Note
B1	31.0%	48.2%	4,563	
B2	15.6%	62.8%	1,647	
B3	9.9%	53.2%	1,323	
B4	6.0%	38.5%	1,042	Intermittent-like pattern; heating est.
B5	5.7%	55.2%	731	
B6	5.7%	29.3%	1,151	Largest unconsumed share; RS underutilised
B7	4.5%	67.4%	417	
B8	4.4%	49.6%	637	
B9	4.0%	75.3%	283	Highest SCR in community
B10	3.2%	68.7%	286	
B11	3.1%	69.6%	272	
B12	2.7%	54.1%	355	
B13	2.7%	51.1%	377	
B14	1.4%	37.6%	244	Intermittent occupancy

Table 17 reports building-level SCR and unconsumed renewable energy, ranked by SCR. Buildings with the lowest SCR are the primary contributors to inefficiency, such as:

- Under the fixed allocation mechanism, a larger allocation key does not guarantee higher SCR: B1, with the largest share (31.0%), achieves only a moderate SCR of

48.2%, while smaller-share buildings such as B9 (4.0%) reach 75.3%. Consequently, percentage-based SCR alone understates B1's contribution to the community's export surplus; absolute unconsumed volume is an equally necessary lens for evaluating allocation efficiency.

- B6, B4, and B14 record the lowest building-level SCRs where its most shared allocations were exported to the grid. B6's poor SCR reflects a structural temporal mismatch between PV generation and consumption; B14's low SCR is a direct consequence of intermittent occupancy limiting daytime consumption.
- Conversely, buildings with concentrated daytime occupancy and flexible loads notably B9, B11, B10, and B7 consistently achieve high SCRs, confirming that occupancy schedule and load profile are more decisive than allocation size in determining how efficiently a member captures its renewable share.

An important counterfactual is revealed when the fixed allocation constraint is removed. If all 14 members were permitted to draw from the community PV pool without pre-assigned shares, optimally matched to their real-time consumption, *the community SCR could reach 65%,* with total self-consumed energy of 18,345 kWh against total production of 28,427 kWh in 2025. *Under the current fixed allocation scheme, the observed 12% shortfall relative to this optimal represents energy exported due to temporal mismatches of each building’s allocation..*

This 3,236 kWh surplus exported under the current scheme receives compensation at the applicable export tariff that varies among members depends on their electricity contract. Export tariffs in Spain are typically three to four times lower than retail electricity purchase prices. The exported surplus therefore generates far less revenue than the savings that would have been achieved had the same energy been consumed internally, displacing grid purchases at the average retail tariff (€0.15–0.20/kWh), representing a substantially larger economic benefit. *The fixed allocation mechanism therefore introduces a structural inefficiency that reduces the community’s overall economic return from its PV investment.*

Key takeaway: The 12% gap between the observed community SCR and the theoretically optimal value under unconstrained allocation is related to the static nature of the fixed allocation key. Transitioning to a dynamic redistribution mechanism could recover approximately 3,236 kWh of internally consumable energy annually. Where dynamic allocation is not feasible, a rebalancing of the fixed key reducing shares assigned to chronically low-SCR members and reallocating to high-efficiency buildings represents a practical near-term measure to improve community-level self-consumption.

6.1.3 Self-Sufficiency Rate

The self-sufficiency rate (SSR) for each building is defined here as the share of total electricity consumption met by on-site renewable energy actually consumed, expressed as a percentage. The community-level SSR of 27.33% places the community in Grade D. At building level, SSR is governed by three interacting aspects:

(i) the fixed allocation key, which determines how many kWh of community PV output are assigned to each member;

(ii) the building-level self-consumption rate (SCR), which is the fraction of that allocated renewable energy actually consumed rather than exported; and

(iii) the building's total electricity consumption.

Table 18 presents all three components alongside the resulting SSR and cost saving percentage (how much on-site renewables reduce its total electricity cost) for each member building. Colour coding reflects the rank of SSR and cost saving, with green colour indicating the best-performing building.

Table 18. Building's Self-Sufficiency rate

Building	Alloc. Key (%)	SSR	Cost Saving (%)	Observation
B1	31.0%	45.5%	54.9%	Largest allocation; highest SSR
B2	15.6%	30.5%	32.1%	
B3	9.9%	16.4%	18.3%	
B4	6.0%	25.9%	25.2%	
B5	5.7%	26.6%	28.2%	
B6	5.7%	8.1%	12.2%	Same alloc. as B5; low SCR causes low SSR
B7	4.5%	34.4%	24.5%	Low alloc.; high SCR and low elec. consumption yield high SSR

Building	Alloc. Key (%)	SSR	Cost Saving (%)	Observation
B8	4.4%	29.9%	17.7%	
B9	4.0%	34.1%	24.6%	High SCR (75%) compensates smaller allocation
B10	3.2%	29.6%	23.0%	
B11	3.1%	25.4%	18.8%	
B12	2.7%	24.3%	17.5%	
B13	2.7%	23.3%	17.2%	
B14	1.4%	20.3%	11.0%	

Table 18 reveals that the allocation key and SSR are broadly correlated, but the relationship is moderated by each building's SCR. Three patterns warrant specific attention:

- B1 achieves the highest SSR and cost saving in the community, consistent with holding the largest allocation share. This outcome is expected under a proportional allocation system and therefore provides limited insight into efficiency; the more informative comparison involves buildings with similar allocation keys but divergent outcomes.
- B6 vs B5 (same allocation key, divergent SSR): Both B5 and B6 hold identical allocation keys of 5.7%, corresponding to approximately 1,630 kWh of assigned renewable energy. B5 achieves an SSR of 26.6%, whereas B6 records only 8.1%. The underlying cause is B6’s building-level SCR of 29.3%, the lowest in the community, meaning that 70.7% of its allocated renewable energy is exported to the grid rather than consumed on-site. Even if B6’s allocation were increased, the structural mismatch between PV generation hours and B6’s consumption profile would continue to constrain its SSR. Correspondingly, B6’s cost saving of 12.2% remains the lowest among members with a comparable allocation.
- *B7 and B9 (smaller allocation key, higher SSR):* Despite receiving a smaller share of the community's renewable output than B4 or B5, both buildings achieve a higher SSR. This happens because both buildings consume most of their allocated renewable energy on-site (high SCR) and have a relatively low overall electricity

consumption, so even a modest allocation covers a large proportion of what they actually use.

Key takeaway: Allocation key alone is an insufficient predictor of SSR. A building with a high allocation but poor temporal alignment between PV generation and consumption (low building SCR), like B2, will under-utilise its share and record a low SSR, whereas a low-allocation building with high occupancy-aligned consumption can outperform. Consequently, cost saving follows a similar pattern: B6 receives the same allocation as B5 but delivers only one-quarter of B5’s cost saving.

6.1.4 Payback Period

The community-level simple payback period of 11.86 years places the REC in Grade C, computed as total CAPEX divided by the net annual benefit (aggregate electricity savings minus O&M costs). The result reflects the uneven distribution of cost savings: members with low SSR or low cost saving, such as B6 and B14, contribute disproportionately little to the shared savings pool, extending the community-level payback relative to what a more efficient allocation could achieve. A transition to dynamic allocation, which would increase community SCR from 53% toward 65%, would raise aggregate annual savings and shorten the payback period, illustrating the direct financial incentive for improving the allocation mechanism.

6.1.5 Energy Poverty Rate

Energy poverty is assessed against the 10% energy-cost-to-income threshold for the six members who provided income survey data. Table 19 presents the annual energy cost and computed cost-to-income ratio for each. Buildings without income data are excluded from the poverty rate denominator, as noted in the data availability caveat.

Table 19. Energy Poverty assessment by building, 2025

Building	EPC Grade	Energy Cost (€/yr)	Cost/Income (%)	Threshold	Note
B3	F	1,683	6.2%	Below	Grade F building; cost ratio below threshold due to moderate income
B5	G	1,491	3.8%	Below	Grade G building; high income avoids poverty classification
B7	E	1,844	12.3%	ABOVE	Only energy-poor member; income-driven, not solely EPC-driven
B9	C	1,522	10.2%	ABOVE	Only energy-poor member; income-driven, not solely EPC-driven
B10	B	1,061	3.2%	Below	Intermittent occupancy; low energy cost/income ratio
B13	G	1,051	2.7%	Below	Intermittent occupancy; low actual energy cost

Of the six buildings with income data, two exceed the 10% poverty threshold: B7 at 12.3% and B9 at 10.2%. Both fall within the same low-income bracket, confirming that household income is the primary driver of energy poverty classification in this community. A critical finding is that neither B7 (Grade E) nor B9 (Grade C) carries the worst EPC rating in the portfolio; three other buildings (B3 Grade F, B5 and B13 Grade G) carry worse EPC ratings yet remain below the poverty threshold owing to more favourable income levels. This confirms that energy poverty in this community is driven primarily by the combination of absolute energy cost and household income, rather than by building thermal performance alone.

The contrast between B3 and B7 is illustrative. B3 has a Grade F EPC and uses electric resistance heating, resulting in the second-highest energy intensity among residential buildings; nonetheless, its cost-to-income ratio of 6.2% remains comfortably below the threshold, owing to a relatively high household income. B7, by comparison, uses an oil-fired boiler and has a lower energy intensity than B3, but a lower household income renders its energy cost burdensome, producing a ratio of 12.3%. B9, in the same low-income bracket as B7, records a ratio of 10.2%, a marginal exceedance that nonetheless classifies it as energy-poor under the applied definition.

The current REC allocation reduces the energy cost for both affected members by approximately 24–25%, yet neither B7 nor B9 crosses below the poverty threshold after this benefit is applied. This indicates that the allocation key, as currently configured, provides insufficient relief to the most income-constrained members.

Key takeaway: Energy poverty in this community is income-driven, not EPC-driven. Both affected members (B7 and B9) share the same low-income bracket, while buildings with worse EPC ratings (B3 Grade F, B5 and B13 Grade G) remain below the threshold owing to higher incomes. The current allocation key provides insufficient relief to the most vulnerable members; a needs-based or income-weighted distribution would be a more effective instrument to tackle energy poverty.

6.1.6 Effect of Intermittent Occupancy

Three buildings, B10, B13, and B14, are recorded as having intermittent or occasional occupancy patterns. Their energy consumption profiles reflect this reduced presence:

- B14 records the lowest total final energy in the community (2,426 kWh) and the best EPC rating (Grade A, 16.4 kWh/m²/year). Intermittent occupancy directly curtails heating, lighting, and appliance loads, resulting in performance that is effectively decoupled from envelope quality.
- B10 achieves Grade B on EPC and the second-lowest primary energy (8,886 kWh) despite a floor area of 200 m² comparable to other buildings. Its energy cost-to-income ratio is (3.2%) as the household it was not occupied daily.
- B13 records an energy cost-to-income ratio of 2.7%; its intermittent use pattern (morning and afternoon occupancy only) similarly produces a low absolute energy cost despite a Grade G EPC rating.

These observations indicate that intermittent occupancy correlates with lower absolute energy consumption and, consequently, lower energy cost regardless of EPC grade.

Ideally, EPC grades for intermittently occupied buildings would be normalised to a full-occupancy assumption, enabling a like-for-like comparison with permanently occupied members. This adjustment was not applied, as insufficient occupancy data precluded a reliable full-occupancy energy estimate without introducing significant uncertainty. From the perspective of SCR, intermittent occupants are also away during peak PV generation hours, resulting in lower building-level SCRs (B14: 37.6%; B10 is an exception at 68.6%, suggesting concentrated weekend or daytime presence). The current fixed allocation key does not differentiate between permanently and intermittently occupied buildings; as a result, buildings with systematically low daytime consumption receive the same proportional share as permanently occupied members with similar contracted capacity, contributing to the community-wide SCR deficit described in Section 6.1.3.

6.2 Building Energy Simulation Results

This section presents the building energy simulation results in two stages. The first stage demonstrates model accuracy by comparing each building's calibrated baseline against measured electricity data from 2025, with performance assessed against the acceptance thresholds of ASHRAE Guideline 14 (ASHRAE, 2014). The second stage applies the three retrofit packages defined in Section 5.4 to the calibrated baseline, quantifying the achievable savings in energy consumption for each building. The building 3D design can be seen on Figure 13.

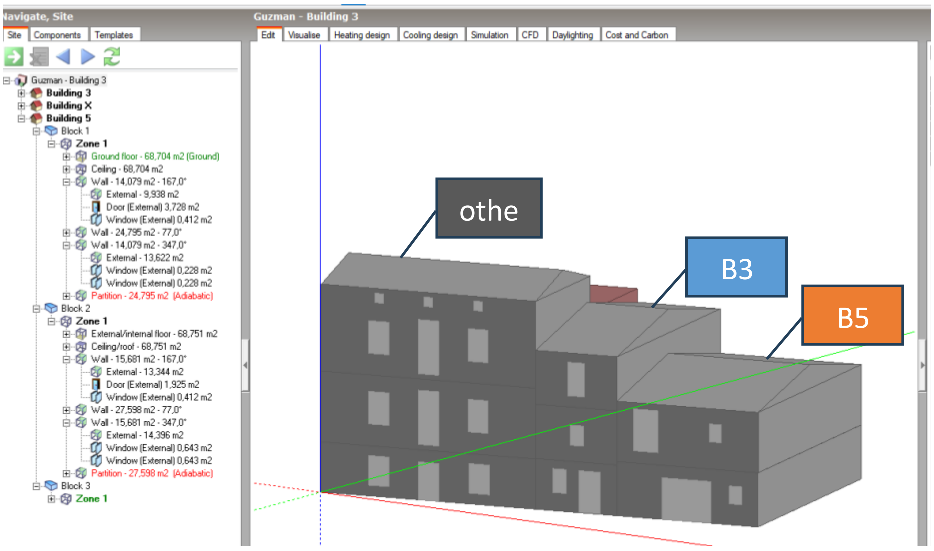
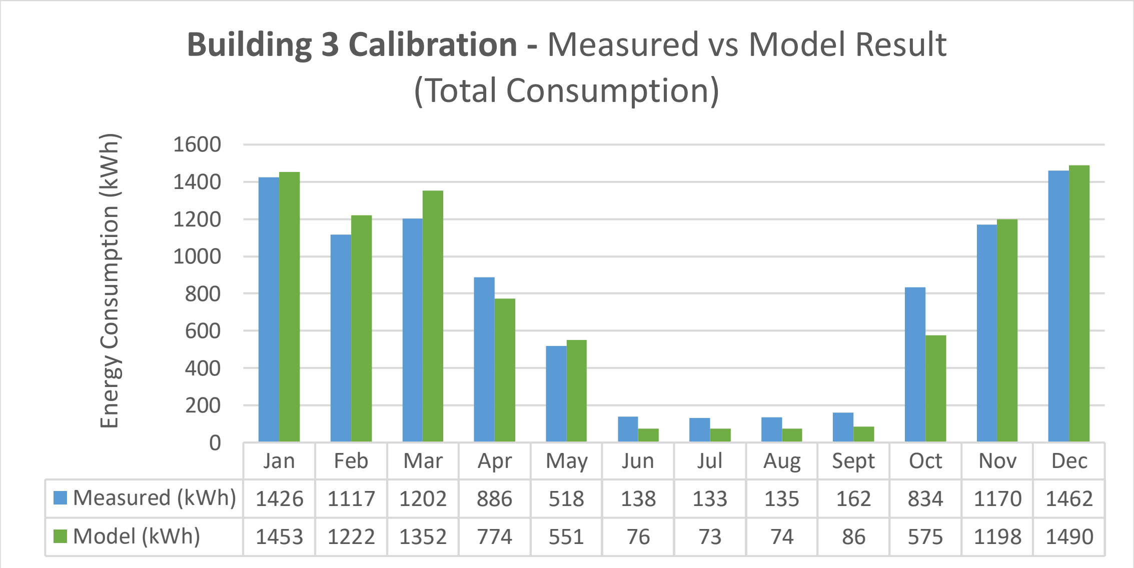


Figure 13. Simulated Geometry in DesignBuilder

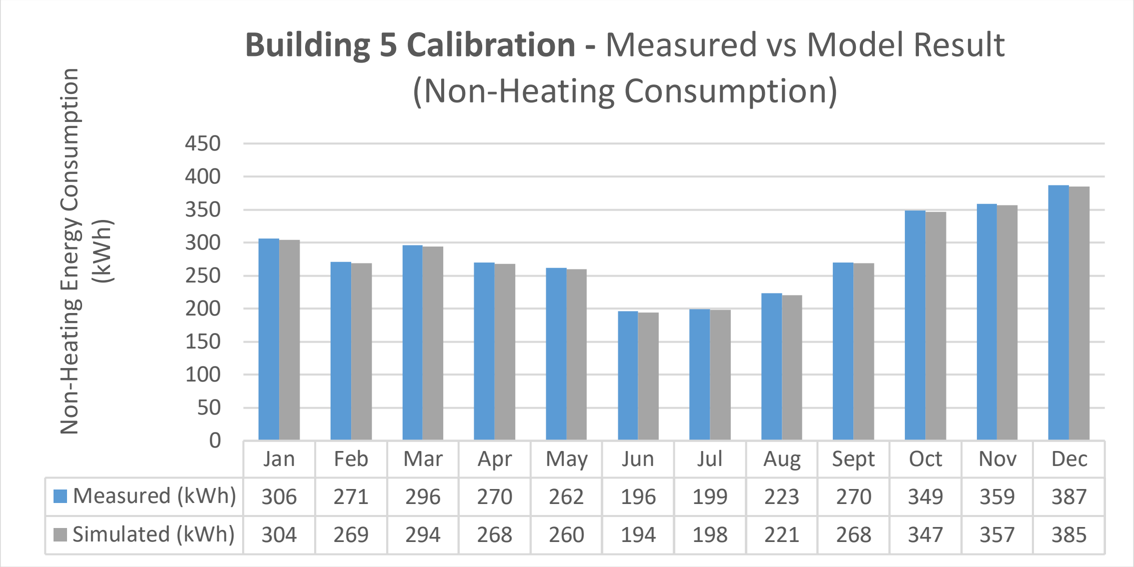
6.2.1 Building's Energy Calibration Performance

The calibrated model for Building 3 reproduces its 2025 measured annual electricity consumption with high fidelity, as shown in Figure 14. Both error metrics fall comfortably within the ASHRAE Guideline 14 acceptance thresholds, confirming that the model is a reliable basis for retrofit scenario evaluation.



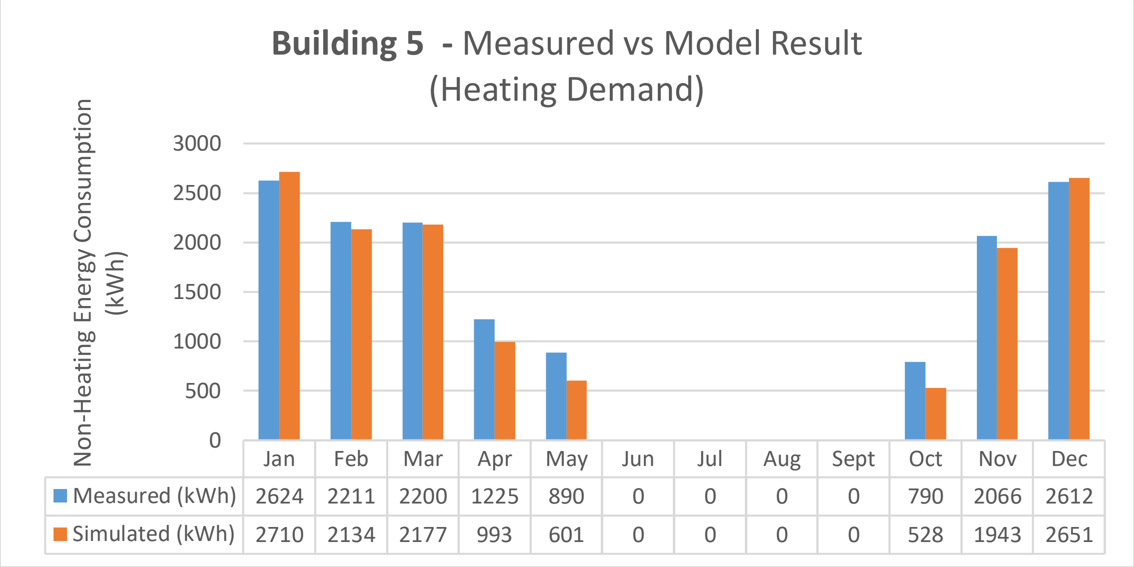
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
🟦 Measured (kWh)	1426	1117	1202	886	518	138	133	135	162	834	1170	1462
🟩 Model (kWh)	1453	1222	1352	774	551	76	73	74	86	575	1198	1490

Figure 14. Building 3 - Baseline Calibration (Total Consumption)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
■ Measured (kWh)	306	271	296	270	262	196	199	223	270	349	359	387
■ Simulated (kWh)	304	269	294	268	260	194	198	221	268	347	357	385

Figure 15. Building 5 - Baseline Calibration (Non-Heating Consumption)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
■ Measured (kWh)	2624	2211	2200	1225	890	0	0	0	0	790	2066	2612
■ Simulated (kWh)	2710	2134	2177	993	601	0	0	0	0	528	1943	2651

Figure 16. Building 5 - Baseline Calibration (Heating Demand)

Building 5 requires a split calibration approach because its biomass heating system is not sub-metered. The electrical end uses (room electricity, lighting, and domestic hot water) are calibrated independently against measured consumption and show a near-exact match (Figure 15).

The heating component is validated against a degree-day-derived monthly target, with the simulated demand falling within the ±5% annual threshold (Figure 16). It should be noted that this represents heating demand rather than heating consumption: the heating demand is the thermal energy required to maintain comfort, while the heating consumption considers efficiency of the delivery system. This distinction becomes significant in the retrofit scenarios, where COP-adjusted consumption values are reported.

The calibration performance metrics for both buildings against the ASHRAE Guideline 14 thresholds are summarised in Table 24.

Table 20. Summary of Calibration's Performance B3 and B5

Building / End Use	NMBE (%)	CV(RMSE)(%)	Threshold	Result
B3 - Total electricity (heating + non-heating)	2.81	13.78	±5% / 15%	PASS
B5 - Total electricity (non-heating only)	0.65	0.66	±5% / 15%	PASS
B5 - Biomass heating	6.04	11.54	±5% / 15%	PASS

Note: The heating energy reported in the calibration model *represents heating demand (zone heating in DesignBuilder),* the amount of heat required to maintain thermal comfort, rather than heating consumption, which accounts for thermal efficiency of the heating system. This distinction becomes significant in the retrofit scenarios discussed in subsequent sections, where heating consumption figures (CoP-adjusted) are used instead. Additionally, *for B3, the calibration model assumes heating is supplied to only two of the three floors,* reflecting the building's single-occupant use pattern; heating all floors would overestimate the actual energy demand.

6.2.2 Energy Saving’s Scenario of Building 3

The baseline energy profile of Building 3 is dominated by space heating, which accounts for approximately three-quarters of total annual consumption. This concentration reflects two compounding factors: an uninsulated building envelope and an electric storage heater operating at a COP of 1.0, the least efficient heating technology modelled. As a result, any retrofit that addresses either the envelope or the heating system is expected to yield disproportionately large reductions relative to the total baseline. Full end-use detail is provided in Table 25.

Table 21. Comparison of B3 Final Energy Consumption (kWh)

B3 Category	Baseline	R1 (Glaz)	R2 (R1 + Wall,Roof)	R3 (R2 + HP,LED)
Room Electricity	1,315	1,315	1,315	1,315
Lighting (Electricity)	300	300	300	90
DHW (Electricity)	577	577	577	231
Heating	6,732	6,651	2,104	743
Total Energy (kWh)	**8,925**	**8,843**	**4,297**	**2,379**

Retrofit R1 (glazing upgrade only) produces a negligible energy saving. This outcome is physically expected as window area represents a small fraction of the total building envelope, so reducing glazing heat loss cannot compensate for the dominant transmission losses through uninsulated walls and roof.

Retrofit R2 (full envelope insulation) delivers the largest single step-change in performance. By insulating walls, roof, and improving airtightness, the package reduces space heating consumption by more than two-thirds and cuts total annual consumption roughly in half. This confirms that the thermal envelope is the primary performance constraint for Building 3.

Retrofit R3 adds system-level upgrades to the insulated envelope: an air-to-water heat pump for space heating, a heat pump boiler for domestic hot water, and LED lighting. The incremental saving over R2 is driven almost entirely by the heating system replacement, which reduces electricity consumed per unit of thermal output by a factor of three. Under R3, room electricity becomes the dominant end use, a reversal of the pre-renovation profile where heating dominated; this reflects the intended outcome of decoupling thermal comfort from high-carbon, inefficient resistance heating. Full details are in Table 25.

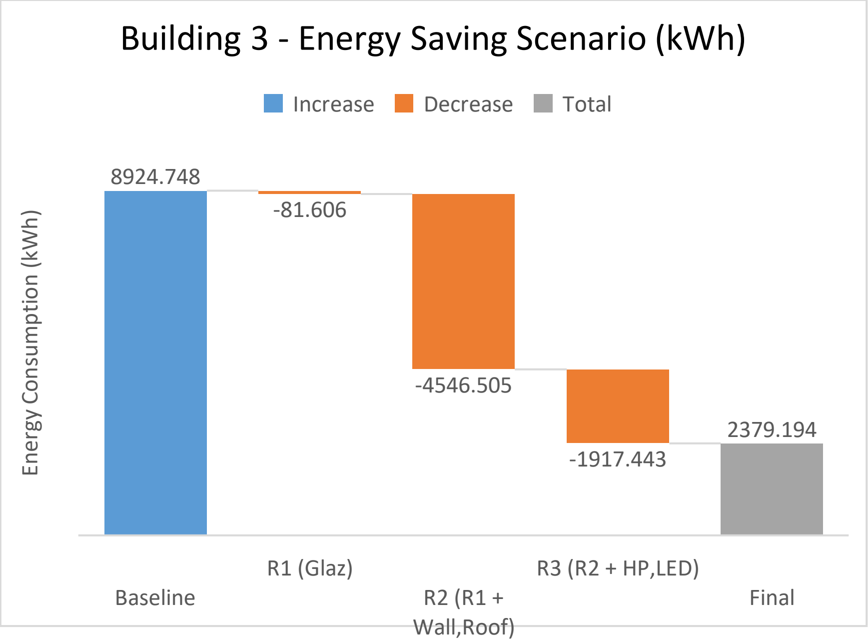


Figure 17. Simulation of Building 3 Energy Saving Potential (Final Energy)

6.2.3 Energy Saving's Scenario of Building 5

Building 5 is assessed under R2 and R3 only. Because double glazing is already installed in the as-built envelope, Retrofit R1 would produce results equivalent to the calibrated baseline and is therefore not applied.

Table 22. Comparison of B5 Energy Consumption (kWh)

Category	Baseline	R2 (Wall,Roof)	R3 (R2 + HP,LED)
Room Electricity	1,362	1,362	1,362
Lighting (Electricity)	288	288	86
DHW (Electricity)	1,716	1,716	686
Heating	16,162	4,265	1,247
Total Energy (kWh)	**19,528**	**7,631**	**3,382**

Building 5 presents a more extreme baseline than Building 3 as space heating via a biomass stove accounts for over four-fifths of total annual consumption, with the remaining consumption distributed across domestic hot water, room electricity, and lighting. This concentration reflects both an uninsulated envelope and the low assumed thermal efficiency of the combustion system. Because biomass heating treated as carbon neutral under EU accounting (Bourguignon, 2015), this fuel mix has contrasting implications for energy and emissions outcomes under retrofit, which are explored in Section 6.3. Full end-use detail is provided in Table 26.

Retrofit R2 applies the same envelope insulation package as in Building 3, with comparable relative reductions in space heating consumption. However, because Building 5 carries a substantially larger absolute heating load at baseline, the R2 package delivers a far greater absolute energy saving than in Building 3. This illustrates a general principle as identical retrofit measures applied to a poorly performing baseline yield larger absolute savings, even when the relative improvement is similar.

Retrofit R3 replaces the biomass stove with an air-to-water heat pump (COP 3) and upgrades the domestic hot water system (2.5) and LED lighting, achieving the deepest consumption reduction of all scenarios. The incremental saving from R2 to R3 is larger for Building 5 than for Building 3 because the heat pump operates on a higher residual thermal load as the greater the heating consumption remaining after envelope improvement, the more impactful the system upgrade. This step-wise logic reinforces that envelope and system retrofits are complementary rather than competing interventions as shown in Figure 20.

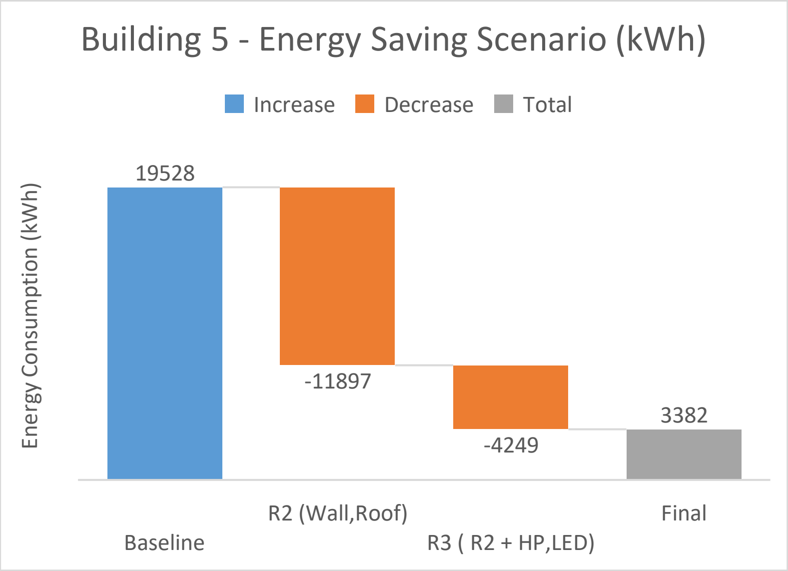


Figure 18. Simulation of Building 5 Energy Saving Potential (Final Energy)

6.2.4 Key Takeaways of Retrofit Scenarios

Across both buildings, the magnitude of retrofit savings is governed primarily by two factors: the pre-retrofit thermal envelope quality and the baseline heating system efficiency. Buildings starting from a higher absolute energy consumption yield larger absolute savings from the same intervention package, while their relative reductions remain broadly comparable. The R2 envelope package confirms that wall and roof insulation is an effective and consistent first-stage measure regardless of building size or heating system type.

Under the full R3 scenario, both buildings achieve EPC Grade B, representing a two-to-three grade uplift from their pre-retrofit classification. This positions them within the well-insulated band of the Spanish assessment scale and brings the community's weighted average EPC meaningfully closer to the Grade C threshold. These findings validate Hypothesis H2: targeted deep renovation, combining envelope insulation with heating system electrification, is a necessary complement to shared PV deployment for achieving sustained community-level energy performance gains. The PV system addresses generation while retrofit addresses the demand side that generation alone cannot reduce.

6.3 Retrofit Impact to GHG and Cost Reduction

This section evaluates the impact of Retrofit Scenarios R2 (envelope insulation) and R3 (envelope insulation combined with system upgrades) on the KPI framework outputs for Guzmán Renovable. Because retrofit capital costs are applied exclusively to Buildings 3 and 5 in the present assessment, the analysis focuses on per-building energy, cost, and emission outcomes for those two members before situating their contributions within the community-level KPI scorecard. Results are presented across three dimensions: energy consumption and EPC rating; annual energy cost and CO_2e emission; and the renewable energy utilisation indicators of self-sufficiency and self-consumption.

6.3.1 Building-Level Energy, Cost, and Emission Impacts

Building 3 achieves successive EPC grade uplifts under each retrofit scenario, as shown in Table 23. Envelope insulation alone advances the rating by two grades; the addition of system upgrades advances it by a further grade to reach Grade B. The progression confirms that both the envelope and the heating system are binding constraints on this building's performance, and that addressing them in sequence yields compounding benefits.

Building 5 follows the same EPC progression as Building 3 (F/G to C under R2, to B under R3), despite starting from a worse baseline. The key reason is that its dominant energy load at baseline is biomass heating, which is both thermally inefficient and entirely displaced by the heat pump under R3. Consequently, the full R3 package achieves a deeper absolute reduction in Building 5 than in Building 3, illustrating that the buildings with the greatest need benefit most from deep renovation. Details are provided in Table 23.

Table 23. Retrofit's Impacts on Final and Primary Energy Unit

Metric	Baseline	Retrofit 2 (R2)	Retrofit 3 (R3)
Building 3			
Total Final Energy (kWh)	9,184	4,297	2,379
Primary Energy (kWh)	16,509	7,543	3,989
Primary Energy Consumption per Area (kWh/m²/yr)	167	76	40
EPC Grade	F	C	B
Building 5			
Total Final Energy (kWh)	20,588	7,631	3,382
Primary Energy (kWh)	22,963	9,786	5,745
Primary Energy Consumption per Area (kWh/m²/yr)	184	78	46
EPC Grade	G	C	B

Annual cost reductions follow the energy savings trajectory closely for Building 3, where all energy is sourced from the grid (Figure 19). The R3 heat pump upgrade contributes the largest share of cost saving by reducing electricity consumed per unit of thermal output by a factor of three. Building 5 presents a more nuanced picture as its baseline energy cost is lower than Building 3's because biomass fuel is cheaper per kWh than grid electricity. The R3 retrofit substitutes this low-cost biomass load with grid electricity, which partly offsets the benefit of reduced consumption. The result is that Building 5's post-R3 cost saving is proportionally smaller than Building 3's, despite achieving a deeper percentage reduction in energy consumption.

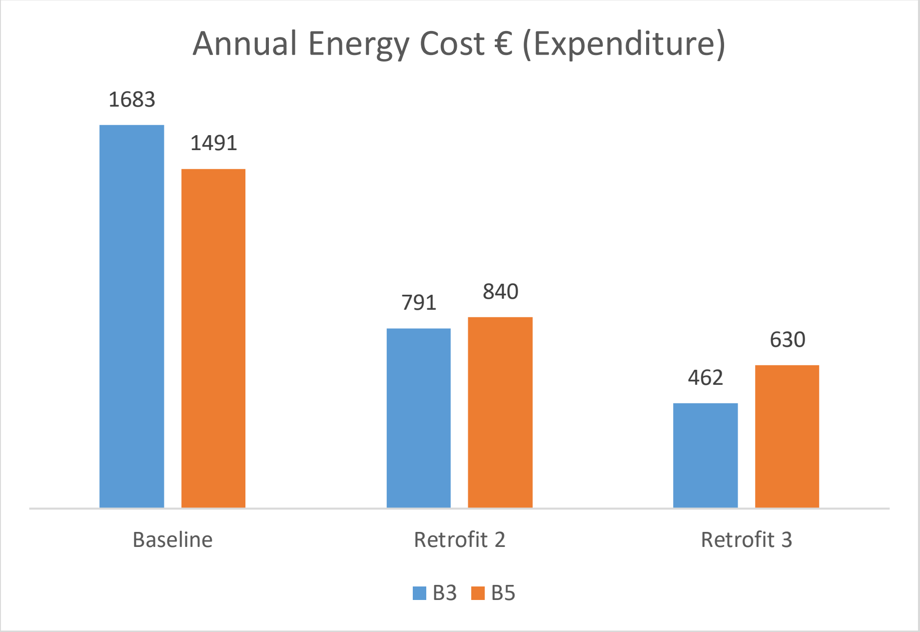


Figure 19. Retrofit's Impacts on Annual Energy Cost (€)

The emission trajectories are fundamentally different between the two buildings, as illustrated in Figure 20. For Building 3, CO_2e emissions fall progressively with each retrofit scenario, because all energy is from the grid and efficiency gains directly reduce grid electricity consumption. For Building 5, however, emissions remain unchanged across all scenarios. This outcome arises from a structural feature of EU carbon accounting: biomass combustion carries a zero CO_2e factor, so the large biomass heating load at baseline contributes nothing to measured emissions. Replacing it with a high-efficiency heat pump introduces the Spanish grid carbon intensity, which offsets the gains from consumption reduction. These findings show a critical limitation of electrification-based retrofits applied to biomass-heated buildings, which is fuel-type composition, not energy reduction depth alone, determines the CO_2e outcome.

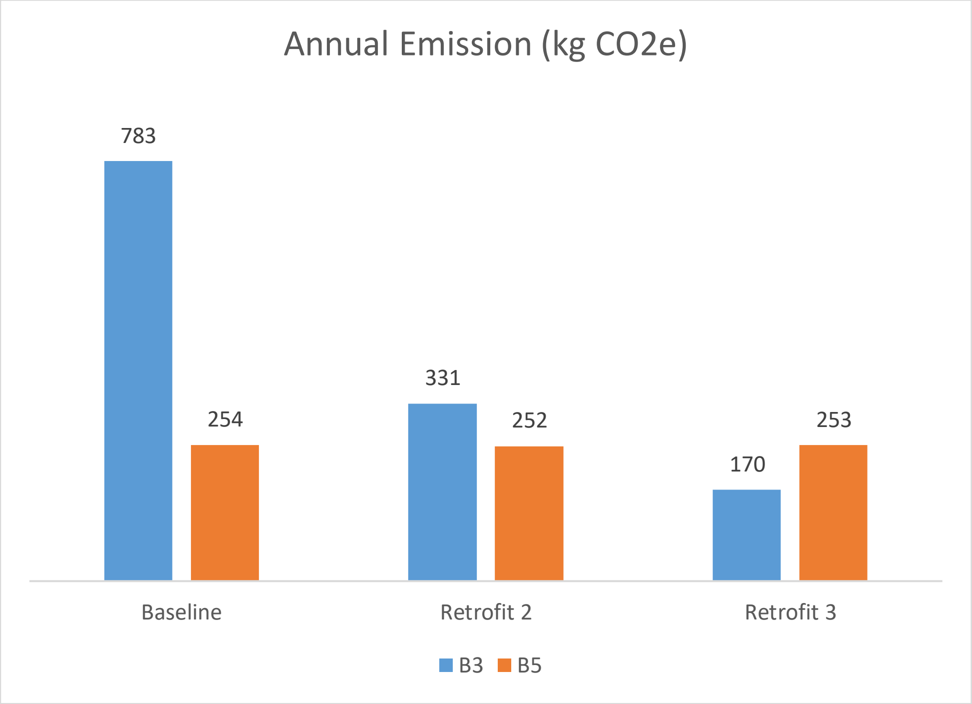


Figure 20. Retrofit’s Impacts on Annual Emission

6.3.2 Self-Sufficiency and Self-Consumption Trade-Offs

Table 24 reveals that the SCR and SSR response to retrofit differs fundamentally between the two buildings, reflecting the interaction between each building's energy carrier mix and the fixed PV allocation mechanism. To compute SCR and SSR under retrofit scenarios, the total energy output from simulation was disaggregated using hourly electricity profile from the physical power meter, as the simulation model was calibrated only at the monthly level and therefore lacks the hourly resolution required for accurate SCR and SSR estimation.

Table 24. Retrofit's Impacts on Self Consumption and Self-Sufficiency Rate

Metric	Baseline	Retrofit 2 (R2)	Retrofit 3 (R3)
Building 3			
Self-Consumption	53%	37%	25%
Self-Sufficiency	16%	24%	30%
Building 5			
Self-Consumption	55%	55%	55%
Self-Sufficiency	27%	27%	27%

Two distinct patterns emerge from Table 24 regarding renewable energy utilisation under retrofit:

- Building 3 SCR deteriorates progressively across all scenarios because the fixed allocation key assigns a renewable share calibrated to the pre-renovation consumption level. As envelope and system improvements reduce consumption, an increasing fraction of that allocation cannot be absorbed on-site and is exported. SSR rises in parallel, since the denominator (total consumption) shrinks in retrofit scenarios.
- Building 5 SCR and SSR remain at their baseline values under both R2 and R3, as shown in Table 24. Under R2, the retrofit measures act solely on the biomass space heating system; the electricity consumption pattern is unchanged, leaving both metrics unaffected. Under R3, although the heat pump replaces the biomass boiler and introduces electricity consumption for space heating, the overall electricity profile at Building 5 remains consistent with the baseline because the efficiency gains in lighting and other end-uses offset the new electrical load. As a result, retrofit depth does not translate into any change in renewable energy utilisation metrics for this building under the current fixed allocation framework.

Allocation key adjustment is relevant primarily for Building 3: the PV allocation key is fixed to pre-renovation consumption profiles and is not updated when a member retrofits. Any demand-side intervention should therefore be accompanied by a reassessment of the community allocation, redistributing surplus shares to members with higher residual demand. Without this adjustment, SSR will continue to improve mechanically while SCR deteriorates for Building 3, overstating actual on-site renewable integration. For Building 5, the allocation key revision has no immediate effect on SCR and SSR given the stable electricity profile, but remains advisable should future retrofits alter the electrical load pattern.

6.3.3 Retrofit Investment and Break-Even Analysis

A simple payback analysis was conducted to assess the economic viability focusing on retrofit scenario 2 and 3 as retrofit 1 is only applicable for B3. It uses investment costs from the CYPE Generador de Precios bill of quantities (Burgos, 2025) (CYPE Ingenieros, S.A., 2026) and annual monetary savings computed against applicable energy tariffs. The analysis assumes constant savings over time and excludes the discount rate for simplification. Findings are presented in Table 25.

Table 25. Retrofit Investment and Simple Break-Even Point

Cost Breakdown	B3		B5	
	Retrofit 2	Retrofit 3	Retrofit 2	Retrofit 3
Retrofit Cost	8,598 €	19,769 €	12,044 €	23,393 €
Potential Annual Saving	891 €	1.220 €	651 €	861 €
Retrofit Break Even Point	**9.7 yrs**	**16.2 yrs**	**18.5 yrs**	**27.2 yrs**

- For Building 3, the R2 package achieves break-even at 9.7 years, well within the 15-year horizon. The R3 package, at 16.2 years, marginally exceeds this threshold; its economic case therefore depends on whether a longer appraisal horizon or additional co-benefits, such as improved thermal comfort, are factored into the decision. R2 recovers its investment more quickly because its upfront cost is lower relative to the savings it generates.
- For Building B5, the R2 break-even of 18.5 years is extended relative to B3 because the baseline heating cost is low: the biomass stove delivers space heating at €0.070/kWh vs electricity from grid (€0.152/kWh), limiting the financial benefit of demand reduction. The R3 break-even is beyond typical retrofit financing horizons for B5, and this marginal economic case is compounded by the negligible CO_2e benefit discussed in the preceding section: replacing carbon-neutral biomass with grid electricity increases measured carbon intensity per unit consumed even as absolute emissions remain essentially unchanged.

The R2 envelope package therefore represents the primary recommended intervention for both buildings from both an economic and a carbon perspective. R3 investment is conditionally justifiable for B3 and only warranted for B5 if it is supported by government funding or biomass fuel prices rise substantially or grid carbon intensity decreases, making the fuel substitution economically and environmentally favourable.

6.3.4 Overall Community KPI Scorecard Implications

Table 26. Updated Community-Level KPI after B3 and B5 Retrofit

Output Indicator	Baseline	Retrofit 2	Retrofit 3
Energy Performance Certificate (kWh/m2)	D	C	C
	95	82	81
Self-Sufficiency Rate	D	D	D
	27%	29%	30%
Self-Consumption Rate	D	D	D
	53%	52%	50%
Payback Period (Years)	C	D	D
	11.9	12.1	12.3
Energy Poverty	C	C	C
	14%	14%	14%
Total Score	4.3	4.45	4.45
Final Grade	D	D	D

Table 26 presents the updated community-level KPI scorecard. The overall grade remains D across all scenarios, due to a dilution effect: retrofitting two of fourteen buildings cannot shift aggregate performance, dominated by the twelve unchanged members. Key indicator outcomes:

- Energy Performance Certificate (EPC Rating): reaches Grade C under R2 and R3 due to less primary energy consumption in Building 3 and 5.
- Self-Sufficiency Rate: the improvement is marginal and the indicator remains Grade D throughout. B3 and B5 together represent only a small share of community-wide electricity consumption; the largest consumers, which hold the greatest potential to move this indicator, are outside the current retrofit programme.
- Self-Consumption Rate: a slight decline under retrofit for Building 3, whose reduced electricity consumption limits its ability to absorb its proportional PV

allocation during generation hours. Building 5 SCR remains unchanged across all scenarios, as its electricity consumption profile is not materially altered by either the envelope or the active systems retrofit.

- Payback Period: the community-level indicator worsens slightly from Grade C to D under both retrofit scenarios due to the B3 consumed less PV energy after retrofit were applied (lower SCR) under fixed allocation, which contribute to lower community's cost saving.
- Energy Poverty Rate: unchanged across all scenarios, since the two energy-poor members are not among the retrofitted buildings. This confirms the finding from Section 6.1.5: energy poverty in this community is income-driven, and building retrofit alone cannot address it without a complementary adjustment to the allocation key.

R2 and R3 achieves same aggregate weighted score, driven entirely by its Grade C outcome in Energy Performance Certificate (EPC). However, R3 does not deliver additional overall improvement despite the biomass substitution. While the transition from biomass to grid electricity reduces final energy use, it also increases primary energy consumption from the grid, limiting gains in the EPC-related indicators. In addition, R3 slightly worsens the PV Payback Period because the fixed allocation key results in greater surplus PV energy and lower effective self-consumption within the community. Consequently, R2 emerges as the preferred community-level intervention under the current framework. Any future transition toward R3 should therefore be accompanied by a revision of the community allocation key to better distribute PV generation and capture the benefits of the retrofit strategy.

7 Conclusion and Future Work

This thesis developed and applied a graded, multi-dimensional KPI framework for assessing Renewable Energy Communities (RECs), addressing a gap identified in the literature where existing frameworks lack operational grading on the multi-dimensions (energy, economics, and environmental), application to a real REC case study and retrofit scenario analysis through building energy simulation. The framework was built around five output indicators, namely the Energy Performance Certificate (EPC), Self-Sufficiency Rate (SSR), Self-Consumption Rate (SCR), Payback Period, and Energy Poverty Rate, each graded on an A–G scale aligned with Western European REC benchmarks. These indicators are aggregated into a weighted community score, with each indicator’s weight reflecting its relative importance to REC goals to reduce community’s energy cost and GHG emissions. Applied to Guzmán Renovable in Burgos, Spain, the framework produced a community Final Grade D, indicating that its most of KPIs belong to the average benchmark performances.

Targeted retrofit interventions of two worst-performing buildings deliver substantial improvements that increase their EPC grades from F/G to Grade B maximum. The envelope retrofit is the recommended primary intervention, as it recovers its investment within an economically justifiable horizon (between 10-18 years) and is effective regardless of the building’s energy carrier: electric resistance or boiler heater. Active-system upgrades, especially with heat pump, by contrast, are carrier-dependent: they are conditionally beneficial where a building is fully electrified (electric resistance heater), but counterproductive where biomass is the heating fuel: under current EU accounting rules, biomass is treated as carbon-neutral, so displacing it with grid electricity substitutes a zero-carbon fuel with a carbon-intensive one, while biomass costs are generally lower than grid electricity, making the fuel switch both environmentally and economically counterproductive.

Another finding concerns the divergent response of renewable energy utilisation metrics to retrofit. SSR and SCR do not respond symmetrically. In fully electrified buildings, reducing consumption improves SSR but deteriorates SCR: as demand falls, the building can no longer absorb its full allocated PV share and surplus is exported to the grid. Where a building’s electricity profile is unchanged by retrofit; for instance, where envelope measures act only on a biomass heating system, SSR and SCR remain unaffected. These findings indicate that retrofit programmes for electrified buildings should be accompanied by a reassessment of the community PV allocation key, to avoid excessive surplus export.

The finding that the community scorecard remains at Final Grade D despite 2 out of 14 buildings improvements, as they contribute small portion of the total community’s energy consumption. The significant Final Grade improvement can be achieved if improvement are also applied to more buildings or biggest contributors such as Hotel and Warehouse members in Guzmán Renovable.

Several directions for future works would strengthen and extend the findings of this study:

- *Hourly calibration against dynamic grid tariffs: The current model is calibrated to monthly energy totals, which is sufficient for EPC-based grading but limits the accuracy of SCR and cost indicators.* Recalibrating against hourly smart-meter profiles and time-of-use tariffs would improve both cost and SCR accuracy, since the financial value of on-site renewable consumption depends on the hour of coincidence between generation and consumption, and would enable more precise modelling of allocation-key adjustments.
- *PV allocation key optimisation: As demonstrated in this thesis, a static allocation key becomes sub-optimal after a member’s retrofit. Future work should model the effect* of revising the allocation key following a member's retrofit, redistributing surplus renewable shares to members with higher residual consumption. This would quantify the SCR improvement currently foregone and provide a concrete governance recommendation for the community operator.
- *Comparative benchmarking across REC case studies: A wider range of REC case studies are required* to establish more representative A–G grading thresholds for each indicator. The current thresholds rely on a limited empirical base, which restricts their generalisability. Future benchmarking should incorporate national and regional contexts, accounting for variations in climate and community.

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Appendices

Appendix 1. Ratio of Energy Community per 1000 citizens in EU (Bukovszki & Abdullah, 2024)

*Ratio of Energy Community's members per 1000 citizens in the country.

Appendix 22. Different Methodology for Energy Poverty

(*E04_BDOC_Energy_Poverty_Indicators_Report_EPAH_EN*, 2022)

Aspect	Boardman (10% Rule)	Low Income High Costs (LIHC)	2M (Twice Median Share)
Origin / Reference	Boardman (1991)	Hills (2011, UK DECC)	European Commission / EPOV / EPAH
Formula / Definition	Household is energy poor if: $\frac{E_i}{Y_i} \geq 10\%$	Household is energy poor if: (1) Required energy costs are above national median, and (2) Residual income (after energy costs) is below the poverty line	Household is energy poor if: $\frac{E_i}{Y_i} \geq 2 \times Median \frac{\mathrm{E}}{\mathrm{Y}}$
Core Concept	Fixed 10% threshold of income spent on energy	Combination of high energy costs and low income	Relative measure comparing households to national median energy burden
Type of Indicator	Absolute	Relative & income-sensitive	Relative
Use Case / Application	Historical benchmark, national monitoring	National policy design (especially UK)	EU-wide comparison and harmonized reporting
Typical Threshold (EU)	≥ 10% of income	Relative to poverty line and national median costs	≥ 8-12% of income (depending on country median)

Legend:

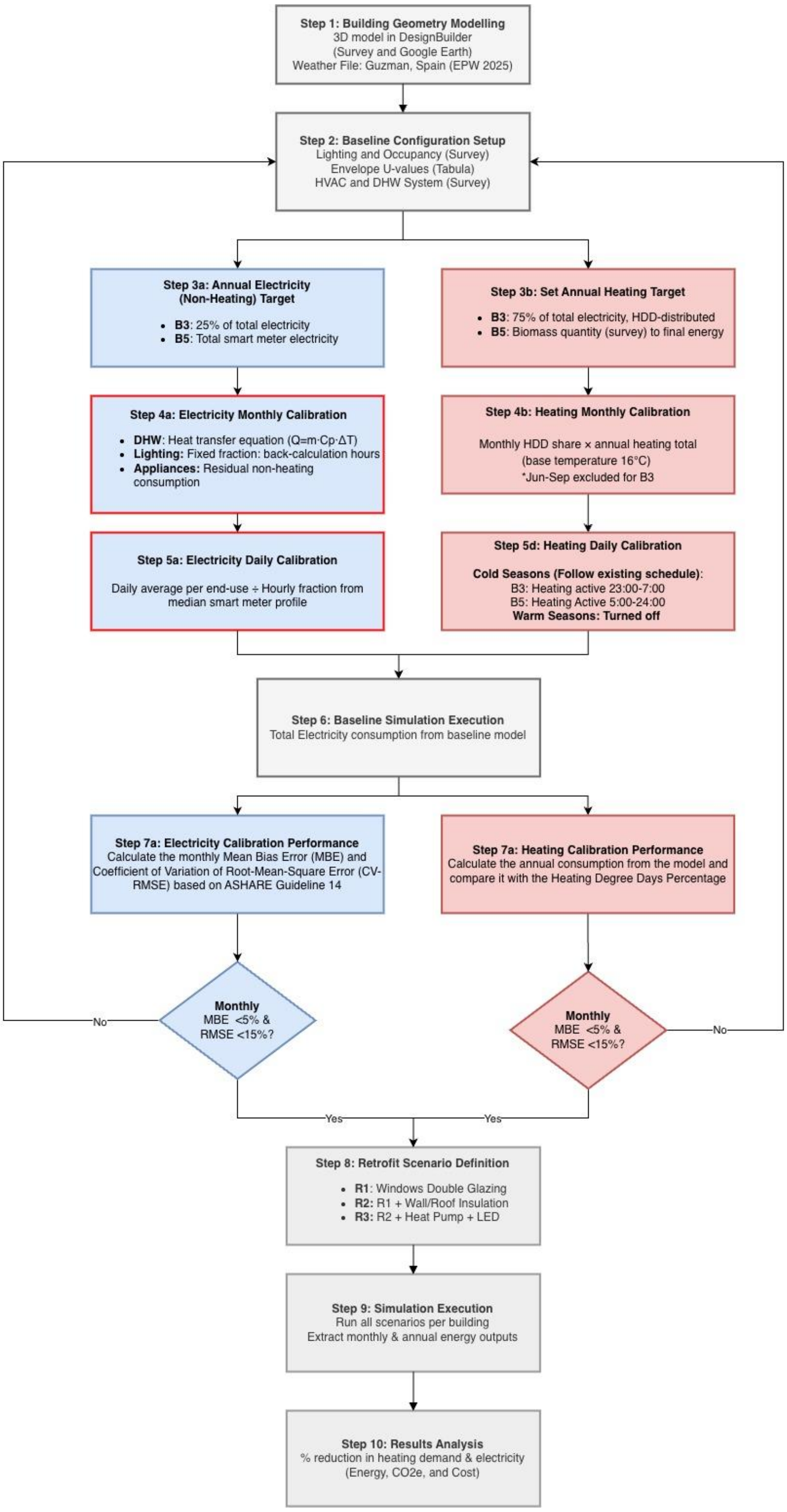
- **E_i** - Energy expenditure of household *i* (e.g., heating, electricity, fuels)
- **Y_i** - Total disposable income of household *i*
- **E_i / Y_i** - Share of household income spent on energy
- **Median (E / Y)** - The median value of all households' energy-expenditure shares in a given country

Appendix 33. Allocation Key of Membership

Building	Alloc. Key (%)	Allocated RS (kWh)
B1	31.0%	8,804
B2	15.6%	4,423
B3	9.9%	2,829
B4	6.0%	1,696
B5	5.7%	1,631
B6	5.7%	1,627
B7	4.5%	1,277
B8	4.4%	1,262
B9	4.0%	1,145
B10	3.2%	911
B11	3.1%	895
B12	2.7%	772
B13	2.7%	772
B14	1.4%	391

**Determined by the total consumption profile by community's manager. Potentially to be updated quarterly or yearly basis.*

Appendix 4. Building Energy Simulation Methodology Diagram



Appendix 5. Simulation Parameters for Building 3 and 5

General Building Parameters

Parameter	Building B3	Building B5	Reference
Weather file	Guzmán 2025 EPW		NASA EPW Data
Conditioned floor area (m2)	99	112	Collected Survey and Floor calculation
Number of occupants	1 adult	2 adults + 2 children	Collected Survey
Occupied months	All year		Collected Survey
Heating setpoint (C)	22	20	Collected Survey
Illuminance target (lux)	100		Assumption for living room (ASHRAE Standard)
Domestic hot water demand (L/day)	28	84	Spanish INE Standard - one person 28 L/day for adult, assume for one child 14 L/day
DHW delivery temperature (C)	60		Spanish INE Standard
Mains water supply temperature (C)	6		Water temperature on Jan from seatemperature.net

Envelope Thermal Properties

Building Element	Baseline B3 (W/m2K)	Baseline B5 (W/m2K)	Retrofit R1/R2 (W/m2K)
External walls	2,561		0,5
Roof	4,167		0,46
Ground floor	0,85		0,85
Windows (U-value)	4,6	1,4	1,4
Air tightness (ac/h Natural)	0,45		0,3
Reference source	Tabula typology	Tabula typology	Renovation Target in Tabula

Activity - DHW and Appliances Demand

End Use	Baseline B3	Baseline B5	Reference
Miscellaneous (appliances) power density (W/m2)	6	6	Tuning result in Designbuilder

DHW demand per floor area (L/m2-day)	0,28	0,75	Calculation from daily DHW consumption / floor area

Active System - Lighting, HVAC, and DHW Systems			
System	Baseline B3	Baseline B5	Retrofit R3 (both buildings)
Space heating fuel	Electricity (Storage Heater)	Biomass	Electricity (heat pump)
Space heating - CoP	1	0,85	3
Domestic hot water fuel	Electricity (Resistance)		Electricity (heat pump)
Domestic hot water - CoP	1		2,5
Cooling system	None		None (unchanged)
Lighting power density (W/m2 for 100 lux)	5	5	1,5
Lighting System	Halogen Bulb		LED

Retrofit Scenario Matrix		
Scenario	B3	B5
Baseline	Existing	Existing
R1 (Glazing) - B3 only	Change to **double glazing** (U-Value 1.4)	**No change** (double glazing already implemented)
R2 (Glazing + Wall/Roof)	Add **insulation** (XPS) on wall and roof and reduce **air** tightness to 0.3 ach	

R3 (Glazing + Wall/Roof + HP/LED)	Replace to **Heat Pump** for water and space heating, along with the **LED** for lighting

***Source: Tabula Data – Spain, Continental, Single-Family House (Loga et al., 2026) and Survey**

Appendix 6. Installed PV Specification

Aspect	Specification
Type	Photovoltaic
Capacity (kWp)	30,3
Tilt degree	10
Azimuth degree	50% East- 50% West
Commissioning Date	2024-01-01
Owner	Guzman Renovable REC
Allocation Rule	Constant allocation quarterly
Series	LONGI LR5-66HPH 505
Investment Cost - CAPEX (€)	€ 33.951,68
Maintenance Cost Euro - OPEX (€)	€ 679,03
Lifetime Year	25
RS Carbon Manufactured (kgCO2e)	24543
RS_Carbon_Intensity (kgCO2e/kWh)	0
RS_Energy Primary Factor	1
RS_Energy Cost (€/kWh)	0,03

*Carbon Intensity and Renewables Energy Cost (€/kWh) is calculated from datasheet of the PV.

Appendix 7. Grid Import and Export Tariff

Building ID	National Grid Carbon Intensity (kgCO2e/kWh)	Supplier Grid Carbon Intensity (kgCO2e/kWh)	Grid Electricity Power Tariff	Grid Electricity Variable Tariff (€//kWh)	Grid Export Price (€/kWh)
B1	0,102	0,102	14,88	0,139	0,05
B2	0,102	0,102	14,88	0,139	0,05
B3	0,102	0,154	16,7	0,153	0,05
B4	0,102	0	12,4	0,158	0,037
B5	0,102	0	13,5	0,152	0,08

B6	0,102	0,102	14,88	0,139	0,05
B7	0,102	0,154	21,8	0,137	0,08
B8	0,102	0,154	15,9	0,1	0,01649
B9	0,102	0,102	14,88	0,139	0,05
B10	0,102	0	9,6	0,149	0,03
B11	0,102	0,102	14,88	0,139	0,05
B12	0,102	0,102	14,88	0,139	0,05
B13	0,102	0,102	14,88	0,139	0,05
B14	0,102	0,062	14.3	0,124	0,05

*Data from electricity contract of each building. The grey box means the data was estimated using the other building references or national data.

Appendix 8. Thermal Value of Heating System (Non-Electric)

Building ID	Heating Type	Caloric Value kWh kg/l	Boiler Efficiency	Heating Carbon Intensity kgCO2e/kWh	Heating Energy Primary Factor	Heating Tariff Euro kg/l	Heating Tariff Euro kWh
B1	Unknown	10,7	85%	0,271	1,10	1,25	0,117
B2	Unknown	10,7	85%	0,271	1,10	1,25	0,117
B3	Electric Resistance						
B4	Biomass Boiler	4	85%	0	1,00	0,2	0,050
B5	Biomass Boiler	4	85%	0	1,00	0,2	0,050
B6	Electric Resistance						
B7	Oil Boiler	10,7	85%	0,271	1,10	1,25	0,117
B8	Unknown	10,7	85%	0,271	1,10	1,25	0,117
B9	Oil Boiler	10,7	85%	0,271	1,10	1,25	0,117
B10	Oil Boiler	10,7	85%	0,271	1,10	1,25	0,117
B11	Unknown	10,7	85%	0,271	1,10	1,25	0,117
B12	Unknown	10,7	85%	0,271	1,10	1,25	0,117
B13	Biomass Boiler	4	85%	0	1,00	0,2	0,050
B14	Biomass Boiler	4	85%	0	1,00	0,2	0,050

*Data of thermal characteristics of heating system on each building from references (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021; WSP, 2024) based on known Heating Type. The grey box means the data was estimated due unavailable survey data (B1, B2, B8, B11, and B12 were treated as having oil-boiler as more common in Spain). The B3 and B6 are not applicable because it uses electric heater.

Appendix 9. Retrofit Cost Breakdown

No	Cost Item	B3 Total (€)	B5 Total (€)
1	External Wall Insulation (ETICS/XPS 55mm)	5.170,10 €	7.455,50 €
2	*Roof Insulation (XPS 60mm)*	2.012,50 €	3.494,00 €
3	Double-Glazed Windows (U≤1.4)	633,96 €	Not Applied
4	LED Interior Lighting (1.5 W/m²)	1.155,03 €	1.317,18 €
5	Combined Heat Pump (Space Heating + DHW)	9.000,00 €	9.000,00 €
	Subtotal - Construction (excl. VAT)	17.971,59 €	21.266,68 €
	Total - Construction (Inc. VAT)	**19.768,74** €	**23.393,34** €

*Cost is estimated from CYPE Website (CYPE Ingenieros, S.A., 2026).