International Journal of Environmental, Social and Economic Sustainability
www.ijeses.org

J. Monteiro and V. F. Pires, Vol. 1, No. 1, March, 2026 Research Article

Comparative Analysis of Self-Consumption and Energy Communities: A Transborder Study of Portugal and Spain

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Received: 11.03.2026 Accepted: 28.03.2026

Abstract-The energy transition in the European Union (EU) has prioritized self-consumption and energy communities (ECs) to foster decarbonization and energy democratization. This study provides a comparative analysis of the regulatory frameworks, implementation progress, and socio-economic impacts in Portugal and Spain. Both nations have transposed EU Directive 2018/2001, yet they demonstrate distinct approaches: Portugal excels in rapid legislative adaptation and high renewable integration (over 80% in 2024), while Spain shows greater dynamism in compensation mechanisms and regional decentralization. The research identifies barriers such as administrative complexity and geographic restrictions, alongside opportunities like vehicle-to-grid (V2G) technology and energy justice initiatives.

Keywords Energy communities, energy transition, regulatory frameworks.

1. Introduction

The establishment of energy communities represents a pivotal element in the broader European Union strategy for a green and inclusive energy transition, enabling active consumer participation in the energy market [1]. This transition is fundamentally driven by the imperative to reduce reliance on non-renewable resources and achieve net-zero greenhouse gas emissions by 2050, positioning energy communities as a promising solution within this ambitious framework [2]. These entities facilitate a decentralized energy production scheme, shifting from the traditional model of large, centrally located power plants to one where end-users are empowered to generate, consume, store, and even sell electricity [3]. This paradigm shift allows for greater energy independence and provides opportunities for economic benefits through reduced electricity bills and new revenue streams for participants [4]. These communities, comprising citizens, businesses, and other entities, engage in the localized production, consumption, and distribution of renewable energy, fostering a more decentralized and environmentally conscious energy system. Recognized under European legislation, both Renewable Energy Communities and Citizen Energy Communities are now considered non-commercial market actors, reflecting a concerted effort to decentralize energy governance and foster local ownership [5]. The growth of these communities is largely propelled by advancements in renewable energy technologies and an increasing awareness of the urgent need for sustainable energy solutions, leading to the emergence of innovative business models that facilitate

Cite this article as: J. Monteiro and V. Fernão Pires, " Comparative Analysis of Self-Consumption and Energy Communities: A Transborder Study of Portugal and Spain ", International Journal of Environmental, Social and Economic Sustainability, (IJESES), Vol.1, No. 1, pp. 73-83, March, 2026.

energy sharing and collaboration [5]. The European directive explicitly defines the concept of energy communities to promote the integration of renewable energy sources, thereby transforming the conventional electricity grid structure where end-users transition from passive actors to active participants capable of managing their consumption, sharing, storing, or selling energy. This evolution is firmly embedded within the EU's broader energy transition framework, initiated by the "Clean Energy for all European" package in 2016, which emphasizes the disintermediation of historically centralized energy functions [6]. This legislative package, alongside subsequent directives, mandates EU member states to establish frameworks that enable and support the formation of such communities, aiming for a significant reduction in greenhouse gas emissions by at least 40% by 2030 and a 50% share of renewables within the same timeframe [7]. These legislative acts, particularly the recast Electricity Market Directive and the Renewable Energy Directive, are critical in defining and promoting energy communities, envisioning them as key players in achieving a more localized, renewable, and participatory energy landscape [8].

2. Conceptual Foundations and Definitions

Energy communities encompass diverse organizational forms and activities related to collective renewable energy production, consumption, and management. The European Union's Clean Energy Package provides foundational definitions distinguishing between Renewable Energy Communities (RECs) under the Renewable Energy Directive (RED II) and Citizen Energy Communities (CECs) under the Electricity Market Directive [9], [10]. RECs focus specifically on renewable energy projects and can engage in generation, distribution, supply, consumption, aggregation, storage, and energy efficiency services, while CECs have broader scope including conventional energy sources but emphasize local participation and benefits [11], [12].

Research identifies several core characteristics that define energy communities across different contexts. First, energy communities are characterized by voluntary and open participation, allowing members to join or leave based on their interests and capacities [13], [14]. Second, they emphasize local ownership and control, with decision-making power residing primarily with community members rather than external investors or utilities [15], [16]. Third, energy communities prioritize local benefits, ensuring that economic, social, and environmental value generated remains within the community [17], [18]. Fourth, they typically operate on democratic governance principles, with members having equal voting rights regardless of investment size [19], [20].

The literature distinguishes energy communities from other forms of distributed energy systems based on their organizational structure and motivations. Unlike purely commercial renewable energy projects driven primarily by profit maximization, energy communities integrate multiple objectives including environmental sustainability, energy autonomy, social cohesion, and local economic development [21], [22]. This multi-objective orientation shapes their governance structures, investment decisions, and operational strategies [23], [24].

Frieden et al. provide a comprehensive framework for understanding collective self-consumption and energy communities in the European context, emphasizing the importance of clear regulatory definitions and enabling frameworks [9]. Their analysis reveals significant variation in how member states interpret and implement EU directives, leading to diverse national models of energy communities. Ahmed et al. offer a systematic review of renewable energy community concepts, identifying common elements including community ownership, local resource utilization, participatory governance, and benefit sharing [15]. These conceptual foundations provide the basis for analyzing specific implementations in Portugal and Spain.

3. Regulatory and Policy Frameworks

3.1. European Union Directives

The regulatory landscape for energy communities in Europe has been fundamentally shaped by the Clean Energy for All Europeans Package, adopted between 2018 and 2019. This legislative package includes the Renewable Energy Directive (RED II, Directive 2018/2001) and the Electricity Market Directive (Directive 2019/944), which collectively establish the legal basis for energy communities across the European Union [9], [11]. These directives mandate member states to create enabling frameworks that remove unjustified barriers to energy community participation in energy markets while ensuring fair treatment and avoiding market distortions [10], [25].

The RED II directive specifically defines Renewable Energy Communities as legal entities based on open and voluntary participation, effectively controlled by shareholders or members located near renewable energy projects, with the primary purpose of providing environmental, economic, or social community benefits rather than financial profits [9]. Member states are required to ensure that RECs can produce, consume, store, and sell renewable energy, including through power purchase agreements, without facing discriminatory or disproportionately burdensome procedures [11], [12].

Research examining the implementation of these directives reveals significant heterogeneity in national approaches. Frieden et al. analyze collective self-consumption frameworks across EU member states, finding that countries differ substantially in their definitions of energy communities, eligible participants, geographic scope, and support mechanisms [9]. This regulatory diversity creates both opportunities for context-specific innovation and challenges for cross-border learning and replication [25], [26]. The Clean Energy Package represents a turning point for energy community development in Europe, providing legal recognition and mandating supportive frameworks, yet leaving substantial discretion to member states in implementation details [25]

3.2. National Frameworks in Portugal and Spain

Portugal and Spain have both transposed EU energy community directives into national legislation, but with distinct approaches reflecting their different energy governance traditions and policy priorities. Rocha et al. provide a comparative analysis of self-consumption and energy community regulations in the Iberian Peninsula, identifying both convergences and divergences in the two countries' frameworks [12]. Both countries have established legal definitions for energy communities and collective self-consumption, created simplified administrative procedures, and introduced economic incentives, yet they differ in specific eligibility criteria, geographic limitations, and support mechanisms [12], [21].

In Portugal, the regulatory framework for energy communities was established through Decree-Law 162/2019, which transposed the RED II directive and created the legal basis for Renewable Energy Communities [27], [28]. The Portuguese framework allows RECs to include citizens, local authorities, and small and medium enterprises, with the requirement that members be located within the same low-voltage grid [28], [29]. Portugal has also implemented specific support mechanisms including simplified grid connection procedures, exemptions from certain network charges, and access to funding programs for community energy projects [27], [12]. Research on Portuguese energy cooperatives, particularly Coopérnico, reveals the practical challenges of navigating regulatory requirements to become licensed electricity suppliers [27].

Spain's regulatory framework has evolved through several legislative instruments, including Royal Decree 244/2019 on self-consumption and subsequent regulations implementing energy community provisions [8], [10]. The Spanish framework distinguishes between individual and collective self-consumption, with specific provisions for energy communities that emphasize proximity requirements and shared infrastructure [14], [29]. Spanish regulations have been characterized as relatively progressive in enabling collective self-consumption but also complex in administrative requirements [30], [31]. Castro et al. compare energy community policies across Brazil, Germany, Portugal, and Spain, noting that Spain's framework provides relatively strong support for collective self-consumption but faces implementation challenges related to grid access and benefit distribution [21].

Comparative analysis reveals that both Portugal and Spain have made significant progress in establishing legal frameworks for energy communities following EU directives, yet both countries lag behind Northern European nations in terms of the number and scale of operational energy communities [29], [32]. Regulatory complexity, limited public awareness, and insufficient financial incentives have been identified as key barriers in both countries [30], [31], [32]. However, recent policy developments and growing civil society interest suggest increasing momentum for energy community development in the Iberian Peninsula [19], [33].

4. Regulatory Deep-Dive: A Comparative Legal Analysis Between Portugal and Spain

The implementation of the RED II Directive in the Iberian Peninsula is characterized by two distinct legal architectures: Portugal's integrated approach under the National Electric System (SEN) and Spain's decentralized model with a focus on surplus compensation. While both frameworks aim to accelerate renewable deployment and citizen participation in energy markets, their regulatory priorities differ significantly. Portugal prioritizes system integration and collective management structures, whereas Spain focuses on simplifying economic returns for individual and commercial producers through compensation schemes.

4.1. Portugal: The Unified Framework (Decree-Law 15/2022)

Portugal consolidated its energy transition laws into Decree-Law No. 15/2022, which governs the entire National Electric System. This legislation moved beyond individual production to establish a sophisticated ecosystem for collective sharing.

- Licensing and Tiers: The complexity of the licensing process is strictly proportional to the installed capacity of the Self-Consumption Unit (UPAC) :
  - < 700 W: Exempt from prior control, provided no energy is injected into the public grid (RESP).
  - 700 W – 30 kW: Subject to a Prior Communication (Comunicação Prévia), a simplified digital procedure.
  - 30 kW – 1 MW: Requires a Prior Registration and an Operating Certificate.
  - > 1 MW: Requires a full Production and Operating License.
- Energy Sharing Mechanisms: Regulation No. 2/2023 introduced dynamic and hierarchical sharing. This allows an Entity for the Management of Collective Self-Consumption (EGAC) to distribute energy among participants based on real-time demand, rather than fixed percentage coefficients.
- Fiscal and Grid Incentives: To boost adoption, Portugal implemented an exemption from CIEG (Costs of General Economic Interest) until December 31, 2025, for energy shared through the RESP. Fiscally, Decree-Law 85/2022 offers VAT self-assessment exemptions for specific entities until 2026.

By incorporating the new provisions, the Portuguese system is intended to alleviate administrative bottlenecks that had hindered the transition from single units to consolidated energy communities. Such a systematized manner will encourage local renewable production while democratizing the benefits of the energy shift, for all actors, including the most vulnerable families, at once and by building up the social resilience to address the root of energy poverty.

4.2. Spain: The Compensation Catalyst (RD 244/2019 & RD-L 23/2020)

Spain's regulatory landscape is defined by the removal of barriers and the introduction of regional dynamism.

- Modalities of Self-Consumption: Royal Decree 244/2019 established three primary pathways:
  - Without Surplus: Systems that technically prevent any energy from flowing back to the grid.
  - With Surplus & Simplified Compensation: For systems up to 100 kW, where the energy injected into the grid is deducted from the consumer's monthly bill at a regulated price (PVPC) or a market-negotiated rate.
  - With Surplus & Not Simplified: For systems > 100 kW, where the producer must act as a market agent and sell the energy.
- The 500-Meter Rule and Expansion: Initially, shared consumption was limited to a 500-meter radius between the production unit and the consumers. However, subsequent updates and regional pilot projects (particularly in Catalonia and the Basque Country) have pushed for an expansion of this limit to 2 km to accommodate industrial and rural communities.
- REER and Auctions: Royal Decree 960/2020 established the Renewable Energy Economic Regime (REER), utilizing competitive auctions based on a fixed price for energy, providing long-term stability for larger community projects.

The Spanish model decentralized energy generation to a great extent by placing a strong focus on simplified compensation for smaller installations and broadening the area covered by shared projects. Such is tailored toward urban and industrial agglomerations in particular, as it provides a more dynamic and flexible market situation. But the 'Efficiency Gap' still exists; in 2024, approximately 19% of self-produced energy was wasted, so even though the legal barrier of production has eased, the next regulatory frontiers must be focused on 'Smart Self-Consumption', and that means integrated storage and demand-side management to unlock the full potential of these decentralized assets. These findings, including the context of the 19% gap, are derived from a synthesis of recent specialized academic studies and the monitoring of regional pilot projects in Spain. Specifically, the percentage and related economic data are drawn from research papers analyzed in this work, such as [4] and [34]. The estimates are based on a comparison between the potential self-consumption rate—representing the energy that could be utilized locally through optimal allocation or storage—and the actual economic benefit realized under current 'simplified compensation' (Compensación Simplificada) schemes. While the work references national-level regulations like Real Decreto 244/2019, the specific efficiency percentages are linked to modeled scenarios and monitored pilot projects, such as the Pallars Jussà Energy Community, which test these market flexibilities. In summary, the 19% figure represents energy that is produced but either "lost" to the grid at low compensation rates or unable to be shared locally due to administrative and geographic barriers, highlighting a gap between technical potential and regulatory reality.

4.3. Comparative Regulatory Frameworks: Proximity Criteria and Tariff Structures

The divergence in how each country handles the "public grid" is a critical factor for project ROI. As synthesized in Table 1, while Portugal incentivizes the use of the grid through cost exemptions to foster community growth, Spain leverages geographical proximity and simplified billing to accelerate individual and industrial payback periods.

Table 1. Regulatory comparison: Portugal (DL 15/2022) versus Spain (RD 244/2019)

Aspect	Portugal (DL 15/2022)	Spain (RD 244/2019)
Proximity Definition	Defined by electrical topology; proximity is determined by voltage levels and grid topology.	Strictly geographic; based on a strict radius (initially 500m, expanding to 2km, for certain installations).
Grid Fees (TAR)	Temporary exemption from CIEG (Costs of General Economic Interest) until end of 2025.	Application of simplified compensation mechanisms for the energy component.
Sharing Logic	Presentes a hierarchical and Dynamic sharing model via EGAC, allowing real-time optimization.	Utilizes either fixed or dynamic allocation coefficients defined by the participants.
Surplus Treatment	Focus on maximizing self-consumption within the community, to avoid grid injection.	Implements a strong mechanism for "net-billing" (simplified compensation) for surpluses injected into the grid.

These regulatory differences create distinct financial pathways. In Portugal, the EGAC's ability to manage dynamic sharing allows for a higher Self-Consumption Ratio (SCR), which protects the Internal Rate of Return (IRR) by reducing the amount of energy wasted. On the other hand, the Spanish model's strength lies in its "Simplified Compensation." By allowing users to deduct injected surplus directly from their PVPC, Spain offers more predictable and immediate liquidity for residential and small commercial investors, leading to shorter PBP as observed in the case studies. However, the geographic "500m/2km rule" in Spain remains a limiting factor for the scalability of rural energy communities compared to Portugal's topology-based approach.

The general competitiveness of the collective model relative to large-scale individual commercial projects under current Spanish regulations is illustrated in Table 2. Based on this analysis, it can be concluded that large-scale individual commercial projects in Spain remain more competitive in terms of immediate financial ROI and administrative simplicity. In contrast, the competitiveness of the collective model remains 'fragile' due to low surplus compensation rates and geographic constraints, despite offering superior social value—such as addressing energy poverty—which individual commercial projects do not target.

Table 2. General competitiveness of the collective model compared to large-scale individual commercial projects under Spain's current rules

Feature	Large-Scale Individual Commercial	Collective/Energy Community
Payback Period	Highly competitive (~2.1 to 9 years)	Slightly longer due to management overhead
Regulatory Path	Clearer for high-power (>100 kW) assets.	High bureaucratic complexity.
Scale Potential	Unlimited by proximity rules.	Limited by 500m/2km radius
Primary Incentive	Direct LCOE savings and market sales.	Simplified compensation for small consumers.

4.4. Regulatory Barriers: The "Efficiency Gap"

The "Efficiency Gap" remains a significant cross-border issue. In Spain, despite the favorable compensation laws, approximately 2.094 GWh (19% of self-consumption production) was wasted in 2024 because the systems were not optimized for the grid's capacity or the compensation limits were exceeded. This reveals a paradox: while the Spanish model leverages investment via simpler billing, the absence of storage incentives and strict sharing limits has caused significant waste of clean energy. In Portugal, the barrier is less about energy waste and more about administrative lead times, where the transition from a pilot to a commercial community can be hindered by the lack of digitalization in grid access requests. While the 2022 legislation put a strong legal framework in place, there was still an operational 'bottleneck'. The Distribution System Operator (DSO) and the regulator (ERSE) often have slow approvals for sharing coefficients needed for RECs. To bridge this gap, both countries need to shift from their 'Simple' approach to 'Smart' Self-Consumption. For Spain, this means introducing Demand Side Management (DSM), and expanding the 2-km limit to prevent waste from having an impact on energy. Specifically in Portugal the system needs to be configured for the automated linkage of the EGAC to the grid operator. The challenges faced must be managed not only technically, but also so that the economic gains generated by the energy transition aren't diminished by lack of system efficiency. To mention that the 19% of self-produced energy wasted is primarily an economic devaluation and a regulatory misalignment, rather than a purely physical curtailment due to grid constraints. In fact, the following factors can be highlighted from this study:

- Low Remuneration for Surpluses: The research concluded that there is a "fragility in the incentive system," whereby payments for surplus energy injected into the grid make investment in storage (batteries) economically unfavorable;
- Regulatory Disincentive: Under current Spanish conditions, consumers have a higher incentive to inject surpluses directly into the grid for minimal compensation rather than storing them for later use. This results in an efficiency gap where produced energy is not utilized optimally within the community or by the producer;
- Geographic Restrictions: The "Efficiency Gap" is further exacerbated by the 500-meter proximity limit for collective self-consumption, which prevents the sharing of energy with potential consumers just outside this radius, effectively "wasting" the potential for local balancing.

5. Methodology and Economic Framework

The study employs a quantitative comparative analysis based on high-resolution consumption and production data. To ensure comparability between the Portuguese and Spanish contexts, the methodology is divided into three tiers: Technical Sizing, Financial Performance Metrics, and Scenario Modeling.

5.1. Technical Sizing and Solar Resource Assessment

The production potential for each case study was determined using the Photovoltaic Geographical Information System (PVGIS), utilizing the SARAH-2 solar radiation database to ensure high temporal resolution.

- Portugal (Lisbon/Telheiras): Average annual global horizontal irradiation of ~1.750 kWh/m².
- Spain (Alicante/Murcia): Average annual global horizontal irradiation of ~1.900 kWh/m².

The systems were sized based on the Self-Consumption Ratio (SCR), which measures the proportion of local renewable generation that is consumed on-site rather than exported to the grid. The SCR is defined as:

$$SCR = \frac{E_C}{E_P} \quad (1)$$

where E_C represents the locally consumed energy (kWh) and E_P represents the total energy produced by the photovoltaic system (kWh).

This ratio is critical in the Iberian market because the retail price of electricity, including network access tariffs (regulated by ERSE in Portugal and CNMC in Spain) is significantly higher than the remuneration for grid injection. Thus, the maximum SCR is the primary driver for technical design, hence it directly leads to the substitution of expensive grid-purchased energy. The direct consequence is that engineering and technical design are primarily driven by the SCR. It affects the displacement of expensive grid-purchased energy.

5.2. Financial Performance Metrics

The economic viability is assessed through a 25-year lifecycle analysis (corresponding to the standard warrantied life of modern PV modules). To evaluate the profitability and feasibility across the three profiles, the following formulas are applied:

- Net Present Value (NPV / VAL):

$$NPV = \sum_{t=1}^{25} \frac{C_t}{(1+r)^t} - CAPEX \quad (2)$$

where C_t represents the net cash flow (energy savings + surplus compensation) in year *t*, *CAPEX* and *r* is the discount rate. For this study, *r* is adjusted at 4% to reflect current Iberian inflation and interest rates.

- Payback Period (PBP):

$$PBP = \frac{CAPEX}{ACI} \quad (3)$$

where *ACI* represents the average annual cash inflow derived from avoided grid costs and remunerated surplus.

- Internal Rate of Return (IRR). The discount rate (*r*) that makes the NPV of all cash flows from equal to zero. This is used to compare the energy project against other investment vehicles, such as government bonds or traditional financial products:

$$0 = \sum_{t=1}^{25} \frac{C_t}{(1+IRR)^t} - CAPEX \quad (4)$$

- Levelized Cost of Energy (LCOE):

$$LCOE == \frac{Total\ Life\ Cycle}{Total\ Lifetime\ Energy\ Production} \quad (5)$$

This allows a direct comparison between the cost of "producing your own kWh" versus "buying a kWh from the grid."

5.3. Scenario Definitions

The paper analyzes three distinct "Investment Profiles" that represent the current market landscape in the Iberian Peninsula, drawing upon data derived from the original work:

- Individual Residential (PT): A 9 kWp system focused on a household with high daytime loads (e.g., remote work and swimming pool pumps), representing the "top" of residential investment.
- Collective Community (PT): The Telheiras CER, in Lisbon, Portugal, focusing on shared infrastructure and diverse consumption profiles to smooth out demand peaks.
- Industrial/Commercial (ES): A 100 kWp system in Spain utilizing the "Simplified Compensation" mechanism to offset high operational OPEX (Operating Expenditure).

5.4. OPEX and Maintenance Assumptions

Operation Expenditure and Maintenance (OPEX) costs are factored at 1% of the initial CAPEX per annum. This estimation accounts includes:

- Inverter replacement between years 12 and 15.
- Annual panel cleaning and electrical safety inspections.
- Management fees for the Entity for the Management of Collective Self-Consumption (EGAC) in the Portuguese case.

5.5. Data Sources and Sensitivity Analysis

The primary data was gathered through direct monitoring of the Telheiras pilot and billing analysis of Spanish residential units. Due to the volatility in the Iberian energy market (MIBEL), a Sensitivity Analysis was performed by varying electricity prices by ±20%. This is especially important in two to account for market volatility and potential changes in the "CIEG" (Costs of General Economic Interest) exemptions could expire post-2025, providing robust results under changing regulatory and market conditions. It should be noted that average electricity prices for non-domestic consumers in Spain have remained similar and relatively stable in recent years, as illustrated in Fig. 1. Furthermore, it is evident that these prices are similar to those of the Euro Area and the EU 27. Recently, they have even fallen below the Euro Area and EU 27 averages, a trend that can be attributed to the rapid expansion of renewable energy sources.

The primary data involved direct observations of the Telheiras pilot and past billing analysis from Spanish commercial units. Due to the volatility in the Iberian energy market (MIBEL), a Sensitivity Analysis was used by changing electricity prices by ±20%. This is especially important in the two Portuguese scenarios where "CIEG" (Costs of General Economic Interest) exemptions could expire post-2025, providing robust results under changing regulatory and market conditions.

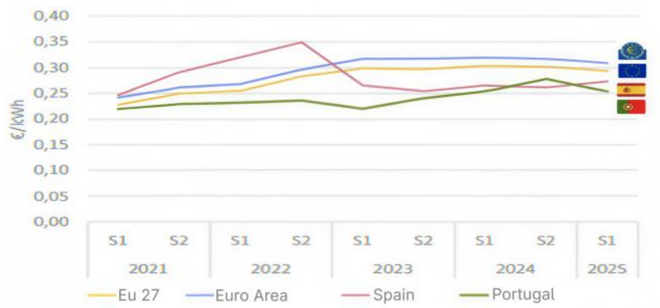

Fig. 1. Average electricity prices for non-domestic consumers in EU countries.

6. Results and Comparative Analysis

The results are categorized into three domains: Economic Performance (ROI/Payback), Technical Efficiency (SCR), and the Social-Environmental impact observed in the pilot projects. The study highlights how 'diversity of demand' (load complementarity) acts as the primary engine for improving the economic performance of collective models compared to individual ones. The work acknowledges that the success of the collective model is not guaranteed if patterns are too similar. It emphasizes that a "balanced mix" of consumers (e.g., combining residential users who consume more at night/weekends with commercial/services users who consume during the day) is what maximizes the Self-Consumption Ratio (SCR).

6.1. Comparative Economic Performance

Based on the financial modeling of the three distinct investment profiles, a clear hierarchy of profitability emerges.

- Individual Residential Unit (Portugal - 9 kWp): With a total CAPEX of approximately €17.665 and annual savings of €1.950, this project yields a Payback Period (PBP) of 9.1 years. While the IRR of 10.02% is attractive compared to traditional savings accounts, the length of the PBP reflects the high initial cost per kWp for residential-scale systems in Portugal.
- Collective Self-Consumption / CER (Portugal - Telheiras): The Telheiras project demonstrates the power of "aggregation." By sharing the investment among 17 participants, the per-capita cost drops. The study shows that the collective model reduces energy bills by an average of 30% to 35% for participating members, achieving a more favorable PBP of 7.8 years.
- Commercial/Industrial (Spain - 100 kWp): This case study represents the most economically efficient model. Benefiting from economies of scale, the CAPEX drops to €1.200/kWp. Combined with Spain's simplified compensation, the project achieves an IRR of 15.28% and a PBP of only 6.25 years.

It must be noted that the success of the collective model is not guaranteed if consumption patterns are too similar. The study emphasizes that a 'balanced mix' of consumers—for instance, combining residential users (who consume more at night and on weekends) with commercial or service users (who consume during the day)—is essential to maximizing the Self-Consumption Ratio (SCR).

6.2. Technical Efficiency and the "Efficiency Gap"

The Self-Consumption Ratio (SCR) is the primary technical KPI utilized to evaluate grid independence.

- In the Telheiras (PT) case, the CER achieved an SCR of over 70%. This high efficiency is attributed to the "diversity of demand", different families consume energy at different times, ensuring that very little solar production is "wasted" or injected into the grid at low prices.
- In the Spanish residential cases, a significant technical bottleneck was identified. Due to a lack of storage systems and a mismatch between solar peak (12:00–14:00) and residential peak (19:00–21:00), approximately 19% of produced energy was injected into the grid without compensation in 2024. This represents the "Efficiency Gap" where regulatory or technological intervention (such as batteries) is required.

6.3. Social and Environmental Impact

The results transcend financial metrics, focusing on the reduction of energy vulnerability:

- Energy Poverty Mitigation: In the Telheiras CER, the inclusion of 3 vulnerable families allowed them to access clean energy at a cost 40% lower than the standard grid tariff, highlighting the social resilience of the Portuguese model.
- Carbon Footprint: On average, the projects analyzed resulted in an avoided emission of 2.2 to 2.4 tonnes of CO_2 per year for residential systems and over 24.5 tonnes of CO_2 per year for the commercial Spanish collective community pilots.

6.4. Summary of Case Study Results

Financial modeling shows a distinct hierarchy of profitability influenced by both scale and local regulatory mechanisms. Table 3 summarizes the key financial and environmental performance indicators for the three analyzed investment profiles. These results highlight the divergence between individual residential investments, collective community models, and large-scale commercial installations in the Iberian context.

The quantitative data confirms that while the Commercial (ES) profile remains the most profitable for private investors, driven by lower unit costs (€/kWp) and efficient compensation, the CER Telheiras (PT) model proves that collective action can bridge the profitability gap for residential users. By reducing the Payback Period from 9.1 to 7.8 years through shared demand, the CER framework validates Portugal's regulatory focus on social resilience.

Table 3. Economic and environmental performance ındicators across ıberian ınvestment profiles

Case Study	Capacity	PBP (Years)	IRR (25y)	Annual CO2 Avoided
Residential (PT)	9 kWp	9.1	10.02%	2.2 tons
CER Telheiras (PT)	7.36 kWp	7.8	12.5%	1.8 tons
Commercial (ES)	100 kWp	6.25	15.28%	24.5 tons

7. Discussion (Analysis of Findings)

The data suggests that while the Spanish model is currently more "profitable" for investors due to compensation mechanisms and scale, the Portuguese model is increasingly focusing on "social resilience" through the CER framework.

A critical finding is that Collective Self-Consumption consistently outperforms Individual Self-Consumption in terms of both SCR and PBP. This is because a community of users can "balance" the grid internally. For example, a resident working from home consumes energy when a commuting neighbor's solar panels are producing a surplus. This internal load-balancing maximizes the utilization of produced energy before it ever reaches the public network, effectively lowering the LCOE for all participants.

However, the "Efficiency Gap" in Spain highlights a crucial need: the transition from "Simple Self-Consumption" to "Smart Self-Consumption" (incorporating batteries and Demand Side Management). Without these tools, nearly 1/5th of the green energy produced by citizens is lost to the grid's inefficiencies or wasted due to compensation caps.

8. Barriers and Recommendations

Despite the robust regulatory progress in both nations, the gap between legislative intent and practical implementation remains wide. This section categorizes the remaining obstacles and proposes targeted interventions to minimize this divide.

8.1. Identified Barriers

- Administrative Inertia (Portugal): The transition from individual self-consumption (UPAC) to collective communities (CER) involves complex interactions with the DGEG. The lack of a fully digitalized, "one-stop-shop" platform often leads to approval delays exceeding 12 months, discouraging small-scale community initiatives.
- The "Double-Charging" Paradox: In some collective models using the public grid (RESP), participants still face network access tariffs that do not fully account for the reduced strain they place on the high-voltage transmission system. This creates a financial disincentive where consumers feel they are paying twice for the infrastructure despite producing and consuming locally.
- Energy Literacy and Social Trust: The transition to a CER requires a high degree of communal trust and shared responsibility. In both Portugal and Spain, a lack of public understanding regarding energy sharing coefficients and the role of the Management Entity (EGAC) acts as a non-technical barrier to adoption. Without clear communication, potential members remain wary of the complex billing structures.
- Grid Capacity Constraints: In high-density urban areas of Spain, the local distribution grid occasionally lacks the "hosting capacity" to integrate large-scale industrial self-consumption units without significant (and expensive) infrastructure upgrades. This often forces projects to scale down or face prohibitive connection costs.

9. Strategic Recommendations

To move beyond the current barriers and fully realize the potential of the Iberian energy market, the following strategic interventions are recommended for policy-makers and grid operators:

- Standardization of Sharing Coefficients: Implementing dynamic, AI-driven sharing coefficients across the Iberia market would allow communities to optimize energy distribution in real-time, significantly reducing the 19% "Efficiency Gap" noted in Spain and increasing the overall profitability of collective projects.
- Cross-Border Energy Communities: Leveraging the MIBEL framework to allow "Transborder CERs." A community in a border town (e.g., Elvas and Badajoz) should be legally permitted to share energy across the national frontier, treating the Iberian grid as a single entity. This would harmonize the 'social resilience' of the Portuguese model with the 'market dynamism' of the Spanish model.
- Fiscal Harmonization: Extending the VAT self-assessment exemptions and CIEG reductions beyond 2026 to provide long-term "investment visibility" for institutional investors in energy communities. Harmonizing these tax benefits across both nations would create a unified investment climate, attracting the capital necessary for large-scale urban energy transformations.
- Incentivizing Residential Storage: Shifting subsidies from solar panels (which are now market-mature) to battery storage and Vehicle-to-Grid (V2G) technology to ensure that surplus energy is stored rather than wasted. This pivot is essential to ensure that surplus energy is stored or utilized by the mobility sector rather than being wasted, effectively transforming the 'Efficiency Gap' into a strategic reserve for the grid.

10. Conclusion

The comparative analysis of Portugal and Spain reveals two nations at the forefront of the European energy transition, yet facing distinct implementation challenges. Portugal's strength lies in its early adoption of a comprehensive legal framework (DL 15/2022) and its success in integrating renewable sources into the national mix. Spain, conversely, offers a highly dynamic market driven by competitive compensation and significant economies of scale in the industrial sector, which has accelerated private investment.

The research confirms that Collective Self-Consumption is the most viable path toward achieving the EU's 2030 targets. By aggregating diverse demand profiles, communities can achieve an internal consumption efficiency (SCR) of over 70%, far outperforming individual residential units. Furthermore, the "Telheiras Model" serves as a definitive proof-of-concept for Energy Justice, demonstrating that decentralized energy can provide a tangible safety net for families in energy poverty, reducing their costs by up to 40% compared to standard grid tariffs.

However, for the Iberian Peninsula to transition from an "Energy Island" to a "Green Energy Hub," the identified efficiency gaps and administrative bottlenecks must be resolved. The future of energy in Iberia is not just about production, but about the intelligent, democratic, and shared management of every kilowatt-hour produced under the sun. The 19% energy waste observed in the Spanish residential sector and the 12-month licensing delays in Portugal represent the final hurdles to a truly optimized system.

Finally, the future of energy in Iberia is not just about production, but about the intelligent, democratic, and shared management of every kilowatt-hour produced under the sun. By balancing the 'Social Resilience' of the Portuguese framework with the 'Market Dynamism' of the Spanish approach, the Iberian Peninsula can establish a global benchmark for the democratization of renewable energy.

Author Contributions

J.M. performed the data analysis; drafted the manuscript; V.F.P. drafted the manuscript, conceptualized and supervised the study; all authors reviewed and approved the final version.

Acknowledgements

This work was supported by national funds through Fundação para a Ciência e a Tecnologia, I.P. (FCT) under projects.

UID/50021/2025

(DOI: https://doi.org/10.54499/UID/50021/2025)

and UID/PRR/50021/2025

(DOI: https://doi.org/10.54499/UID/PRR/50021/2025)

Conflict of Interest:

The authors declare no conflict of interest.

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