Smart and Green Energy Systems Business Models

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Business Models for Smart and Green Energy Systems

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Compilation of selected
SMARTGYsum project public deliverables

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Preface

This book has been a result of the project SMARTGYsum, funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 955614, under Innovative Training Networks (ITN) call H2020-MSCA-ITN-2020).

The project has been run by a consortium coordinated by University of Extremadura (Spain) and conformed by Aalborg University (Denmark); Christian-Albrechts-Universitaet Zu Kiel (Germany); Tallinn University of Technology (Estonia); Universitá degli Studi di Salerno (Italy); CY Cergy Paris Université (France); Politechnika Gdanska; Politechnika Warszawska (Polan); Chernihiv National Technological University (Ukarine); Siemens Industry Software SAS France (France); Smart Energy Products and Services (Spain); Karlsruhe Institut für Technologie (Germany); Universitá Commerciale Luigi Bocconi (Italy); and Universidade Nova de Lisboa (Portugal).

Its general objective is to drive the evolution of European Electric Energy Systems by integrating the knowledge on Power Electronics, Electric Engineering and Information and Communication Technology as well as their socio-economical aspects with the creation of new Businesses Models to cover the green economy energy requirements (sustainability, efficiency, reliability and manageability). SMARTGYsum contributes to long-term structural challenges and also proposes an innovative program for training ESRs following a collaborative, transferable, inter and multidisciplinary approach, aimed at raising the employability and career opportunities of ESRs within the public and the private sectors, as well as their potential for conducting innovation, entrepreneurship and for impacting in European society at medium and long-term.

The overall objective of this ITN is to implement a multidisciplinary and innovative research and training programme, bringing together different scientific fields and industrial participation to enable a new generation of Early Stage Researchers (ESR) to foster a New Green Energy Economy in Europe. SMARTGYsum – Smart and Green Energy Systems and Business Models research and training programme will focus on providing the ESR with relevant knowledge, methods and skills across a wide range of disciplines around the Energy ecosystem and within the accelerating area of Renewable Electric Energy Systems (REES) to sustain the proliferation and consolidation of business models which will sustain the deployment of REES and technologies into the green energy system. Today, various barriers prevent an increased deployment of renewable electric energy systems including market and social barriers (as price distortion through externalities, low priority of energy issues, split incentive); financial barriers (investment, high up-front costs, lack of access to capital); Information failures (lack of awareness, knowledge and competence); and regulatory barriers (restrictive procurement rules). The business models in SMARTGYsum – will be developed as strategies to invest in renewable electric energy systems in which the financing and implementation of renewable electric energy systems contribute to overcome the deployment of REES. This goal will be achieved by a unique combination of direct research training, non-academic internships and courses and seminars/workshops on scientific and complementary so-called “transversal” or “soft” skills facilitated by a multidisciplinary, multisectoral and international consortium.

The objectives of the project are:

- The generation and storage of electric energy using Renewable Electric Energy Generation (REEG) sources and distributed energy resources (DER), and their integration in ESS. (Addressed in WP2)
- The distribution of electric energy from generator to consumers, ensuring the optimal efficiency of the system through collaborative models and radial networks.
- The analysis of the socioeconomic elements, among them the consumption patterns and behaviours, consumer engagement and other aspects that allow to understand and promote new business models to tackle with the customer 6resumption concept, as well as the market uptake of energy and ICT innovation.
- Coordination of all sectors of Electric Energy Systems fusing smart grids, combining IoT, sensor networks, Big Data, AI and together with societal/social and behavioural aspects.
- To perform knowledge networks and platforms to promote the required changes in academia, industry, policy and society.

This book is a compilation of SMARTGYsum public deliverables related with business models and identified barriers to boost the green energy transition, produced summarizing the main outcomes from the different individual research projects run during the project execution from September 2021 to September 2025, that are:

- D2.5. Innovative Business Models in Distributed Generation Systems
- D3.5. Innovative Business Models in Smart Energy Distribution Systems
- D4.4. Deliverable Innovation Business Models report
- D5.4. Identified enablers and barriers to foster the replicability and transfer of Green ES business models

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Chapter 1

Green and Renewable distributed electric energy generation and storing

Coordinator: WUT – Warsaw University of Technology

List of abbreviations used in this chapter

BEN	Beneficiary
Dn	Deliverable (number)
DoA	Description of Action
DS	Doctoral School
ESR	Early Stage Researcher
ETN	European Training Network
GA	Grant Agreement
IRP	Individual Research Project
ITN	Innovative Training Network
MSn	Milestone (number)
MSCA	Marie Sklodowska-Curie Actions
PC	Project Coordinator
REC	Research Ethics Committee
RSC	Recruitment and Secondment Committee
WPn	Work Package (number)

1. Executive summary

This section (related with the Work Package 2 (WP2) Green and Renewable distributed electric energy generation and storing of the SmartGYsum project) focuses on advancing green and renewable distributed energy generation, storage, and intelligent control solutions that address emerging challenges in flexibility, reliability, and cost-effective integration of distributed energy resources (DERs). Within this framework, four Individual Research Projects (IRPs) have developed complementary business models that reflect the technological innovation, market potential, and socio-economic impact of next-generation decentralized energy systems. Collectively, these IRPs form a set of solutions that address strategic domains: power electronics converter technology for microgrids, smart energy management for prosumers and small businesses, virtual power plant coordination, and predictive maintenance for large-scale PV assets. Together, they outline concrete steps toward more interoperable, reliable, and cost-effective distributed generation.

IRP01 introduces an advanced hybrid inverter concept that combines a three-level T-type inverter with a two-level VSI operating in parallel. This modular architecture provides enhanced redundancy, scalability, and superior power quality performance, tailored to commercial, industrial, and microgrid applications. The IRP provides a detailed bill-of-materials (BOM) assessment, competitive positioning within European inverter markets, and pricing strategies based on component-level cost modelling. With a prototype production cost of approximately €1,888, the system is positioned competitively against market offerings in the 5–10 kW hybrid segment. The revenue model explores profitability under various pricing scenarios, highlighting strong commercial potential supported by differentiated value propositions such as fault-tolerant operation, robust monitoring, and modular design.

IRP02 expands the focus to intelligent energy management within residential and small commercial buildings. It presents a vendor-agnostic modular platform composed of two complementary components: EconoBattery, a tariff-aware optimization and storage management system, and FlexiLoad, a flexible load scheduling tool. Unlike proprietary ecosystems that restrict interoperability, the proposed solution emphasizes openness, cross-compatibility, and transparent use of publicly available market price signals. This IRP includes a comprehensive benchmark of existing commercial offerings and demonstrates a clear market gap for customizable, hardware-independent control solutions. The financial model integrates hardware sales with recurring software revenues, forming a scalable hybrid business structure. With a target market of more than one million prosumers in Poland alone, this solution addresses the ongoing regulatory shift toward dynamic pricing and net-billing, strengthening prosumer empowerment and accelerating demand-side flexibility.

IRP03 addresses the coordination of distributed assets at the system level through the concept of a Virtual Power Plant for Cost Efficiency (VPPEC). The IRP proposes a software-centric platform enabling DER aggregation, market participation, and provision of ancillary services. Its business model builds upon a subscription-based structure reinforced by additional revenue streams from energy arbitrage, capacity markets, and service compensation. A detailed techno-economic analysis, including revenue, OPEX, EBITDA, and cash-flow projections, demonstrates strong financial viability with a payback period of approximately 1.5 years. The IRP highlights significant value in combining AI-based forecasting, real-time optimization, and user-friendly interface design to deliver up to 66% cost reductions for participating users under specific operating modes. The platform targets a wide range of stakeholders including prosumers, DSOs, aggregators, and commercial customers, showcasing broad applicability across evolving smart-grid environments.

IRP04 focuses on large-scale PV installations and introduces an innovative performance-driven predictive maintenance framework. Instead of traditional subscription pricing, the model adopts a risk-sharing approach in which service providers are compensated proportionally to verifiable reductions in downtime and maintenance costs. This aligns incentives, removes upfront investment barriers, and encourages continuous diagnostic improvements. The IRP integrates edge-based analytics, advanced condition-monitoring algorithms, and secure data-handling practices, enhancing reliability while minimizing cybersecurity risk. A structured assessment of operational workflows—from data acquisition to maintenance recommendation—demonstrates the practical feasibility of this approach. The model also includes a detailed risk analysis with mitigation strategies addressing technical, operational, and regulatory uncertainties. As predictive maintenance markets rapidly expand, this IRP positions itself as a next-generation service offering for improving PV fleet performance. ￼

Across all four IRPs, several unifying themes emerge:
- Interoperability and openness: IRP02 and IRP03 both prioritize vendor-agnostic, flexible architectures that enable cross-platform integration.
- Data-driven intelligence: IRP03 and IRP04 leverage advanced forecasting, optimization, and diagnostic algorithms to enhance economic and operational performance.
- Component-level techno-economics: IRP01 provides a rigorous BOM-based costing approach that strengthens commercial realism in product design.
- Value creation through digitalization: All IRPs embed digital tools—from cloud platforms to edge-computing—that reduce operational costs and improve resilience of distributed systems.

Together, these IRPs demonstrate how WP2 contributes to the broader goals of SmartGYsum by developing innovative, market-ready solutions that support greener, more resilient energy systems. The portfolio spans the entire value chain—from hardware development to system-level coordination and lifecycle asset management—reflecting the multidimensional nature of future distributed generation ecosystems.

2. IRP01 – Cooperative Smart Inverters for Green Generation Plants

2.1. Introduction

This report presents the business model for a hybrid parallel inverter system designed for commercial, industrial, and microgrid applications. The system utilizes a modular architecture combining a three-level (3L) T-type inverter and a two-level (2L) voltage source inverter (VSI) operating in parallel. This combination offers enhanced flexibility, fault tolerance, and superior power quality for modern distributed energy resources.

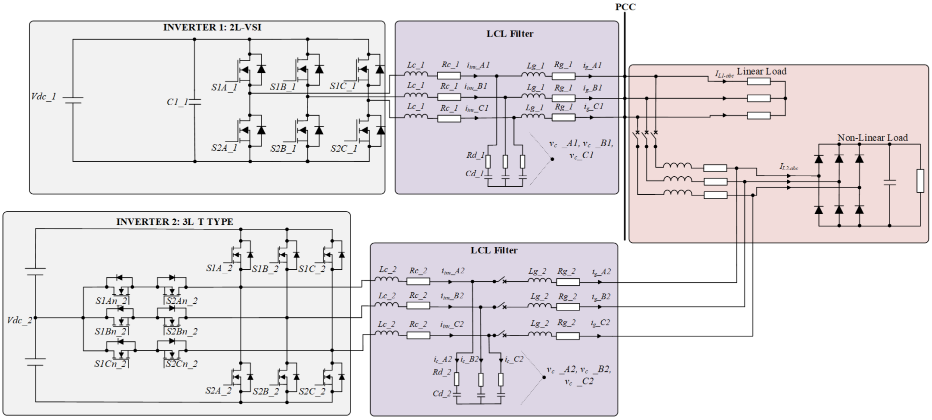


Figure 1 Schematic diagram of the AC nanogrid with parallel hybrid inverter system.

The model integrates detailed BOM costing, competitive pricing benchmarks from European markets, and comprehensive revenue modeling, providing a clear pathway for scalable commercialization with strong profit potential.

2.2. Project Overview

Product Architecture:

The inverter platform consists of two main units in parallel operation:

- 3L T-type inverter board: Provides high-efficiency three-level power conversion with enhanced voltage handling and reduced harmonic distortion.
- 2L VSI board: Offers a simpler two-level topology, enabling compatibility, cost-efficiency, and redundancy support in the parallel configuration.
- Measurement and Modulation Boards: Separate modules for accurate sensing, signal conditioning, protection, and modulation logic to enable robust and fault tolerant operation.

Target Market:

- Commercial and Industrial Microgrid operators
- Distributed Energy Resource aggregators
- Remote/off-grid installations in critical infrastructure (healthcare, education)
- Energy-as-a-service providers focusing on hybrid power solutions

2.3. Market Analysis and Benchmarking

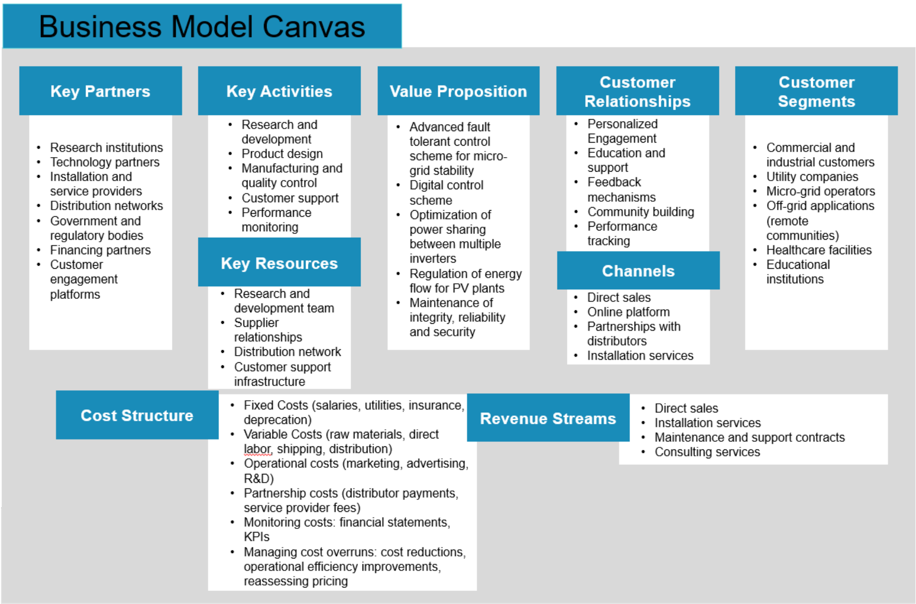
Recent European market studies show that competitive inverter prices for the 5–10 kW three-phase hybrid segment range from approximately €1,700 to €3,100 per unit depending on features and warranties. Leading providers include Deye, Sungrow, ABB/Fimer, Growatt, and Solplanet. Our prototype’s combined BOM cost for both 3L

T-type and 2L VSI units totals approximately €1,888, positioning it competitively within this range. This dual topology gives our system a technological edge through improved fault tolerance and load sharing being the key differentiators in grid-interactive microgrid applications.

Table 1 Market Pricing and Features Comparison for 5–10kW Three-Phase Hybrid Inverters (Europe, 2025).

Brand	**Model**	**Price Range (€)**	**Phase Type**	**Communication/Protection**	**Notable Features**
Deye	SUN-5K-SG04LP3-EU	1,900–2,200	3-phase	RS485, WiFi, surge protection	Full hybrid, EU compliant
Sungrow	SH10RT	2,300–2,900	3-phase	RS485, Ethernet, Type II SPD	High efficiency, warranty options
Solis	3P10K-4G	1,800–2,300	3-phase	WiFi, DC/AC Type II SPD	Easy monitoring
ABB/Fimer	UNO-DM-10.0-TL-PLUS-B	2,400–3,100	3-phase	RS485, Ethernet, integrated protection	Robust, industry recognised
Solplanet	ASW 6000H-S	1,500–2,100	3-phase	WiFi, surge protection	Reliable entry-level
Growatt	MIC 6000TL-X	1,600–2,250	3-phase	WiFi, DC protection	Compact, affordable

2.4. Business Model Canvas



Business Model Canvas

Key Partners
- Research institutions
- Technology partners
- Installation and service providers
- Distribution networks
- Government and regulatory bodies
- Financing partners
- Customer engagement platforms

Key Activities
- Research and development
- Product design
- Manufacturing and quality control
- Customer support
- Performance monitoring

Key Resources
- Research and development team
- Supplier relationships
- Distribution network
- Customer support infrastructure

Value Proposition
- Advanced fault tolerant control scheme for micro-grid stability
- Digital control scheme
- Optimization of power sharing between multiple inverters
- Regulation of energy flow for PV plants
- Maintenance of integrity, reliability and security

Customer Relationships
- Personalized Engagement
- Education and support
- Feedback mechanisms
- Community building
- Performance tracking

Channels
- Direct sales
- Online platform
- Partnerships with distributors
- Installation services

Customer Segments
- Commercial and industrial customers
- Utility companies
- Micro-grid operators
- Off-grid applications (remote communities)
- Healthcare facilities
- Educational institutions

Cost Structure
- Fixed Costs (salaries, utilities, insurance, deprecation)
- Variable Costs (raw materials, direct labor, shipping, distribution)
- Operational costs (marketing, advertising, R&D)
- Partnership costs (distributor payments, service provider fees)
- Monitoring costs: financial statements, KPIs
- Managing cost overruns: cost reductions, operational efficiency improvements, reassessing pricing

Revenue Streams
- Direct sales
- Installation services
- Maintenance and support contracts
- Consulting services

Figure 2 Business model canvas of the proposed system.

Key Partners:
Our primary partners include research institutions and technology providers who help develop and refine our advanced inverter control solutions. Reliable component suppliers ensure consistent access to high-quality MOSFETs, sensors, and PCBs. Certified installation and service providers enable proper deployment and maintenance on-site. Distribution partners expand sales reach across Europe. We also collaborate with government bodies for certification and regulatory compliance, while financing partners support flexible purchasing models. Lastly, customer engagement platforms facilitate ongoing feedback and community building.

Key Activities:
We conduct research and development to optimize parallel control algorithms and power electronics design. Product design and prototyping ensure manufacturability and compliance with grid codes. Manufacturing activities focus on maintaining quality and scale production. Customer support and service including training, performance monitoring, and remote diagnostics form vital ongoing functions.

Key Resources:
Our core resources include an expert R&D team experienced in inverter topology and control; strong supplier relationships securing high-quality components; robust manufacturing and testing infrastructure; and digital platforms supporting customer service and performance analytics.

Value Proposition:
We offer a modular parallel inverter combining a three-level T-type and two-level VSI for enhanced reliability, scalability, and power sharing capability. Advanced control schemes maintain grid stability with fault tolerance. Modular measurement and modulation boards facilitate maintenance and upgrades, lowering downtime. Our digital monitoring improves performance visibility and predictive maintenance.

Customer Relationships:
We foster personalized engagement through comprehensive training and support services, ensuring customer empowerment. Feedback mechanisms and community networks strengthen relationships and inform continuous product improvement. Proactive performance tracking and maintenance programs build trust and satisfaction.

Channels:
Sales channels include direct enterprise outreach to microgrid developers and industrial customers, supported by regional distributors. Certified installer networks deliver compliant onsite deployment. An online platform provides technical resources and customer service.

Customer Segments:
Target customers include commercial and industrial microgrid operators, utilities piloting distributed energy resources, off-grid critical infrastructure, and educational or healthcare institutions requiring resilient renewable energy solutions.

Cost Structure:
Key costs include fixed expenses such as salaries, R&D, certifications, and utility charges. Variable costs encompass component procurement, assembly, shipping, and distribution fees. Operational expenses for marketing, customer support, and partnership management are also significant.

Revenue Streams:

Primary revenues derive from hardware sales. Additional income comes from installation and commissioning services, recurring maintenance and support contracts, and consulting for customized system integration.

Table 2 Production Cost Estimates and Unit Cost Variation of 2L VSI by Manufacturing Volume.

Component	**Price per unit at 1pc (€)**	**Price per unit at 5pc (€)**	**Price per unit at 10pc (€)**
3-phase 2L VSI prototype (Taraz technologies)	688	3440	6880
USM-3IV Isolated voltage current sensor (Taraz technologies)	600	3000	6000
Taraz shipping and tax estimate	73	73	73
LCL Filter inductors (6 units)	360	342	331.2
LCL Filter capacitors (3 units)	105	100.8	97.65
Cables, connectors, wiring (per meter)	4.5	4.41	4.32
Cables, connectors, wiring total (15-20 meters)	78.75	77.17	75.6
Mounting/enclosure	100	97	95

Table 2.1 Production Cost Estimates and Unit Cost Variation of 2L VSI by Manufacturing Volume.

Component	**25pc (€)**	**50pc (€)**	**100pc (€)**	**Quantity**	**Total cost at 1pc (€)**
3-phase 2L VSI prototype (Taraz technologies)	17200	34400	68800	1	688
USM-3IV Isolated voltage current sensor (Taraz technologies)	15000	30000	60000	1	600
Taraz shipping and tax estimate	73	73	73	1	73
LCL Filter inductors (6 units)	316.8	306	288	6	2160
LCL Filter capacitors (3 units)	93.45	91.35	87.15	3	315
Cables, connectors, wiring (per meter)	4.23	4.09	3.96	1	4.5
Cables, connectors, wiring total (15-20 meters)	74.03	71.58	69.3	1	78.75
Mounting/enclosure	92	90	87	1	100

2.5. Pricing and BOM Costing

Using detailed supplier data, the bill of materials encompasses component pricing for both inverter types and auxiliary boards, including:

- MOSFETs, gate drivers, amplifiers, sensors for each board
- PCB fabrication costs (2-layer and 4-layer variants)
- Passive components (capacitors, resistors, inductors), connectors, wiring, enclosure.

Pricing scales are modeled at unit quantities of 1, 5, 10, 25, 50, and 100, reflecting volume discounts. This tiered costing provides transparency on economies of scale and informs pricing strategies and cost reductions through supplier negotiation and alternate sourcing.

Table 3 Production Cost Estimates and Unit Cost Variation of 3L T-type (Power Board) by Manufacturing Volume.

Component	Price per unit at 1pc (€)	Price per unit at 5pc (€)	Price per unit at 10pc (€)
MOSFET switches	10.5	9.5	9.1
Gate Drivers	3.6	3.2	3
Isolation Amplifiers	5.2	4.8	4.5
Operational Amplifiers	4.5	4.3	4.1
Inductors	1.6	1.5	1.4
Resistors/Capacitors (Bulk Average)	0.25	0.22	0.2
Connectors/Headers	1.1	1	0.9
PCB Fabrication (4-layer)	90	85	80

Table 3.1 Production Cost Estimates and Unit Cost Variation of 3L T-type (Pobwer Board) by Manufacturing Volume.

Component	**25pc (€)**	**50pc (€)**	**100pc (€)**	**Quantity**	**Total cost at 1pc (€)**
MOSFET switches	8.5	8	7.5	14	147
Gate Drivers	2.8	2.5	2.3	14	50.4
Isolation Amplifiers	4.1	3.9	3.7	6	31.2
Operational Amplifiers	3.9	3.7	3.5	3	13.5
Inductors	1.3	1.2	1.1	20	32
Resistors/Capacitors (Bulk Average)	0.18	0.15	0.12	250	62.5
Connectors/Headers	0.8	0.75	0.7	15	16.5
PCB Fabrication (4-layer)	75	70	65	1	90

Table 4 Production Cost Estimates and Unit Cost Variation of 3L T-type (Measurement Board) by Manufacturing Volume.

Component	**Price per unit at 1pc (€)**	**Price per unit at 5pc (€)**	**Price per unit at 10pc (€)**
LA55-P Current Sensor	14.5	13.8	13
LV-25-P Voltage Sensor	13	12.2	11.5
Resistors (Bulk Average)	0.3	0.28	0.26
Capacitors (Bulk Average)	0.35	0.33	0.31
Operational Amplifiers	5	4.7	4.5
Connectors/Headers	1.2	1.08	1
PCB Fabrication (2-layer)	50	47	45

Table 4.1 Production Cost Estimates and Unit Cost Variation of 3L T-type (Measurement Board) by Manufacturing Volume.

Component	**25pc (€)**	**50pc (€)**	**100pc (€)**	**Quantity**	**Total cost at 1pc (€)**
LA55-P Current Sensor	12.3	11.7	11.3	7	101.5
LV-25-P Voltage Sensor	10.8	10.3	9.8	7	91
Resistors (Bulk Average)	0.25	0.23	0.2	30	9
Capacitors (Bulk Average)	0.28	0.26	0.23	30	10.5
Operational Amplifiers	4.2	3.9	3.8	5	25
Connectors/Headers	0.9	0.86	0.8	10	12
PCB Fabrication (2-layer)	42	40	36	1	50

2.6. Revenue Modeling

- Revenue models compute profit margins and sales volume targets conditioned on varying selling prices informed from market benchmarks:
- Base production cost (combined 3L T-type + 2L VSI) estimated at approx. €1,888 per unit for prototype-scale.
- Target price range from €2,000 to €3,100 to remain competitive but profitable.
- Profit per unit calculated as selling price minus production cost; units required to meet set revenue targets (e.g., €10k, €25k...) are derived accordingly.

Total system prototype production cost

- 2L VSI inverter: ~€688 per unit
- 3L T-type inverter: ~€1,200 per unit

Total system prototype production cost = €688 + €1,200 = €1,888

Revenue Calculation Table

Assumption: Production cost is €1,888 per inverter system

Table 5 Production Cost Estimates and Unit Cost Variation of 3L T-type (Modulation Board) by Manufacturing Volume.

Component	**Price per unit at 1pc (€)**	**Price per unit at 5pc (€)**	**Price per unit at 10pc (€)**
Logic gate IC (SN74LS32DG4)	1.5	1.4	1.35
Logic gate IC (SN74HCS08QDRQ1)	1.8	1.7	1.6
Voltage Regulator (LD1117V50)	1	0.95	0.9
Diodes (Zener MMSZ5251B-7-F)	0.2	0.18	0.16
Capacitors (Bulk Average)	0.35	0.33	0.31
Resistors (Bulk Average)	0.3	0.28	0.27
Connectors	1	0.9	0.85
PCB Fabrication (2-layer)	40	38	36

Table 5.1 Production Cost Estimates and Unit Cost Variation of 3L T-type (Modulation Board) by Manufacturing Volume.

Component	**25pc (€)**	**50pc (€)**	**100pc (€)**	**Quantity**	**Total cost at 1pc (€)**
Logic gate IC (SN74LS32DG4)	1.3	1.25	1.2	3	4.5
Logic gate IC (SN74HCS08QDRQ1)	1.5	1.4	1.3	5	9
Voltage Regulator (LD1117V50)	0.85	0.8	0.75	1	1
Diodes (Zener MMSZ5251B-7-F)	0.14	0.13	0.12	3	0.6
Capacitors (Bulk Average)	0.29	0.28	0.25	60	21
Resistors (Bulk Average)	0.25	0.23	0.2	80	24
Connectors	0.8	0.75	0.7	6	6
PCB Fabrication (2-layer)	35	33	30	1	40

Table 6 Revenue and Units-to-Sell Projections at Various Selling Prices and Revenue Targets.

Revenue Target (€)	Selling Price (€)	Profit/Unit (€)	Units to Sell for Revenue Target
10,000	2,000	112	90
10,000	2,500	612	17
10,000	3,100	1,212	9
25,000	2,000	112	223
25,000	2,500	612	41
25,000	3,100	1,212	21
50,000	2,000	112	446
50,000	2,500	612	82
50,000	3,100	1,212	41
100,000	2,000	112	893
100,000	2,500	612	164
100,000	3,100	1,212	83

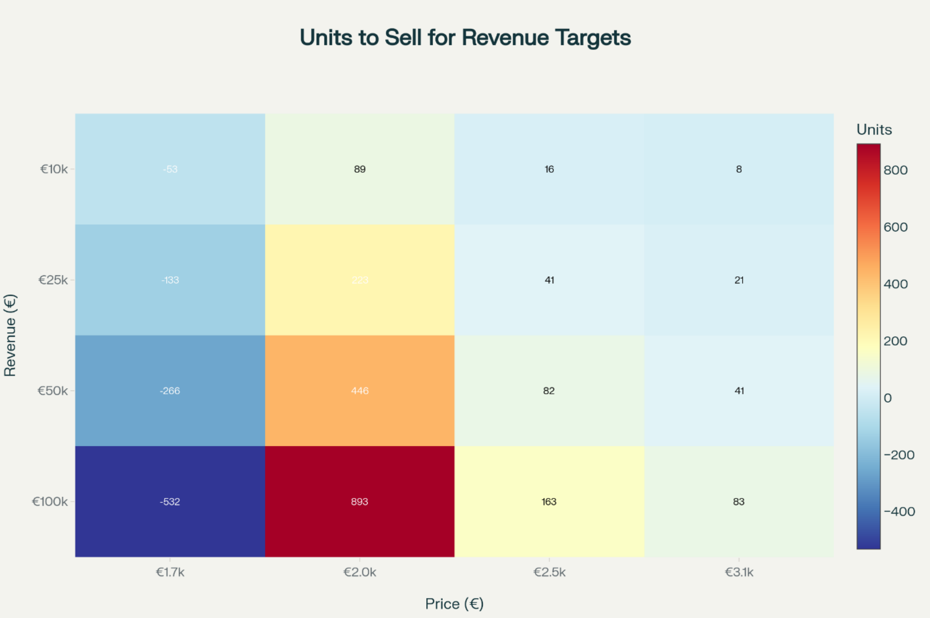


Figure 3 Units to Sell by Price & Revenue for Complete Inverter System (€1,888 Cost).

where:

- Profit/Unit = Selling Price – Production Cost (€1,888).
- Units to Sell = Revenue Target / Profit per Unit
- Production cost of €1,888 includes the full combined inverter system with both 2L VSI and 3L T-type inverters based on detailed BOM pricing and supplier quotes.
- Selling prices are chosen based on 2025 European market inverter prices between €2,000 and €3,100.

- Revenue targets vary (10k, 25k, 50k, 100k) to explore different business scale scenarios.
- Each cell shows the units to sell for its specific revenue target and selling price.
- Selling at higher prices greatly reduces the number of units needed to reach the same revenue.
- Results are calculated as: Units = Revenue Target / (Selling Price - Production Cost).

2.7. Business Model Pitch

Our hybrid parallel inverter system offers a uniquely balanced solution powered by the hybrid operation of advanced three-level T-type and reliable two-level VSI topologies. The combined inverter unit harnesses the strengths of both technologies, achieving superior power quality, fault resilience, and scalable capacity. Distributed energy resources and microgrids face increasing complexity due to variable renewable inputs and critical reliability needs; our solution mitigates these challenges with intelligent load sharing and real-time diagnostics enabled by modular measurement and modulation boards.

The product targets microgrid operators, utilities, and off-grid infrastructures demanding stability and modular reliability. Partnering with installers and leveraging a robust distribution network allows effective outreach. Comprehensive after-sales service, proactive maintenance, and data-driven performance monitoring secure long-term customer engagement and satisfaction.

Financially, the product is positioned within established European price points but enhanced with differentiated service contracts and performance guarantees to ensure sustainable profitability. The detailed cost model grounded in actual BOM pricing and scalable manufacturing practices underpins accurate margin forecasting and business scalability. Our go-to-market approach emphasizes pilot site validation, iterative product improvement, and strategic financing partnerships to accelerate adoption.

Compared to existing inverter business models that focus mainly on tariff structures or financing schemes, this work introduces a component-level, BOM-driven techno-economic framework tailored to hybrid AC nanogrids with parallel inverter topologies.

3. IRP02 – Development of Power Generators for Smart Buildings with Advanced Power Sharing Capabilities

3.1. Introduction

The present deliverable provides a report about the developed business model related to the Development of power generators for Smart Buildings with Advanced Shared Capabilities. The proposal consists in amodular platform for prosumers and small businesses and is described by two core modules. **EconoBattery** integrates a battery pack, bidirectional converter and optimization software to control charge and discharge in real time, while **FlexiLoad** schedules flexible appliances (EV charging, heating, dish-washer, etc.) so that the over all energy can be managed with the objective of electricity bills. Unlike many current offers that are tightly coupled to a single hardware vendor or depend on exclusive partnerships with specific aggregators, these devices are designed to provide cross-compatibility with other devices. Different to other solutions that expose only limited control, the proposed solution is vendor-agnostic and open-source, using publicly available spot and day-ahead price signals instead of proprietary tariffs. The diagram of the proposed product is shown in Figure 2.

3.2. Objectives of the business model

- Enable residential prosumers and small businesses to reduce their electricity bills and increase self-consumption by intelligently coordinating storage (EconoBattery) and flexible loads (FlexiLoad).
- Provide a vendor-agnostic, open-source platform that avoids lock-in to specific hardware or suppliers and supports rapid development of new applications, tariffs, and research experiments.
- Create sustainable, scalable revenues by combining upfront hardware sales with recurring software and service income, including integrations with aggregators, retailers, and technology partners.
- Build a flexibility-ready asset base that aggregators and energy service companies can use for demand response and grid services, leveraging transparent, public price signals rather than exclusive bilateral agreements.

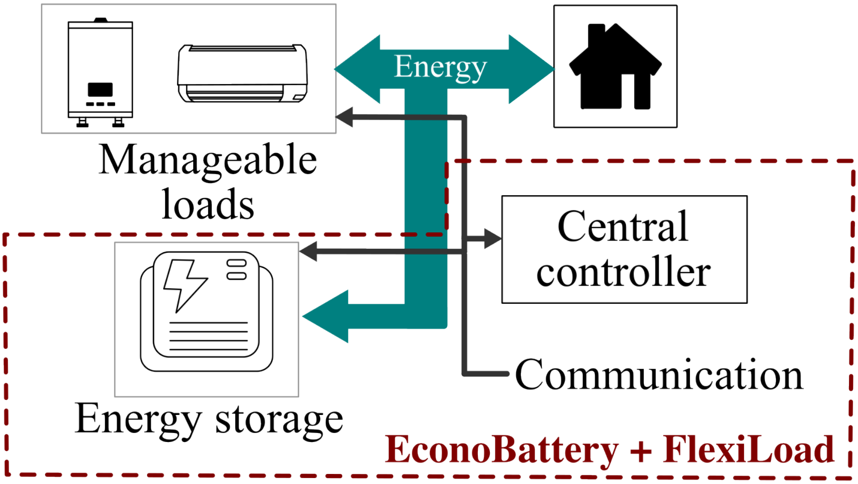


Figure 2.Diagram of the product for the business model

3.3. Project Overview

Product description

The platform consists of two parts that can be acquired together or separately. The first one is a bundle consisting of a battery and its corresponding power converter, together with decision-making software that determines the optimal operating condition of the battery to minimize the electricity bill and satisfy operational constraints. This system will be referred to as **EconoBattery**. The second part of the platform, named **FlexiLoad,** is a load management system that schedules appliances to contribute to the electricity bill minimization target, provided that the user makes them available for this purpose. A detailed description of the two modules is provided in Table I.

Table I. Detailed product description of EconoBattery and FlexiLoad modules.

Module	**Software**	**Hardware**
EconoBattery	- Real-time tariff-aware optimization: - Constraint-aware operation: respects user comfort, power limits, grid constraints and contractual limits automatically. - Cloud connectivity & analytics: remote monitoring, dashboards, and history. - Open-source code: allows for third party improvements and close collaboration with academia.	Modular battery pack: scalable capacity for different customer segments (home, small business). - Bidirectional power converter – high-efficiency inverter/charger that supports grid-tie, and islanded modes. - Advanced metering interfaces: integration with smart meters/CT clamps for accurate consumption and export measurement. - Communications gateway: built-in connectivity.
FlexiLoad	- Automated appliance scheduling: optimally shifts loads within user-defined availability windows. - User preference engine: configurable comfort and priority settings so automation is acceptable and low-friction for end-users. - Dynamic price response: adapts appliance operation to real-time prices.	- Retrofit control of existing appliances: lowering adoption barriers and upfront cost. - Embedded metering in devices: per-appliance measurement for granular optimization. - Private data: statistics are only accessible to the end user. - Interoperable interfaces – support for standard protocols (e.g., Modbus) to integrate diverse assets.

Justification and added value

Existing battery optimization solutions often depend on exclusive partnerships between hardware vendors and specific aggregators or retailers. For example, the tight integration of Tesla Powerwall with Octopus Energy's Kraken platform and smart tariffs in the UK and Spain, as well as the collaboration between Enphase and Frank Energie in the Netherlands [1, 2].

Although third-party open-source solutions are available, they do not enable direct control of the battery system, but rather interaction with vendor-specific software [3].

At the same time, many third-party and even open-source solutions only expose limited communication interfaces and do not allow direct, continuous control of the battery management, restricting truly optimal operation. In contrast, the proposed EconoBattery + FlexiLoad platform is vendor-free and open-source, designed to interface with various storage and load technologies while providing full control over charge/discharge and flexible loads.

The initial target market comprises residential prosumers in detached houses and small commercial customers who already operate rooftop photovoltaic (PV) systems in Poland, under any pricing scheme. This is possible thanks to the open availability of day-ahead and spot market prices in Poland [4], which is crucial for the optimization engine. Compared to other solutions, this approach removes the need for commercial agreements between equipment vendors and electricity suppliers.

Table II. Available products related to battery installation.

Brand	**Model / Platform**	**Price range for 10 kWh battery (€)**	**Features**
Tesla	Powerwall 2 / 3	6,000–8,500	• Time-based control and TOU optimization via Tesla app.Tesla ecosystem. • Deep integration with selected agregattors.
sonnen	sonnenBatterie Evo	6,000–8,000	• Energy manager with self-learning charge/discharge algorithm. • Closed ecosystem with proprietary cloud software
Huawei	LUNA2000	3,400-4,000	• Modular battery •Tight integration with Huawei inverters and FusionSolar cloud platform
BYD	Battery-Box	~3,700	• Paired with 3rd-party hybrid inverters (Fronius, SMA, etc.), where the inverter performs the energy management. • Monitoring interfaces exist via compatible inverters.

3.4. Market Analysis and Benchmarking

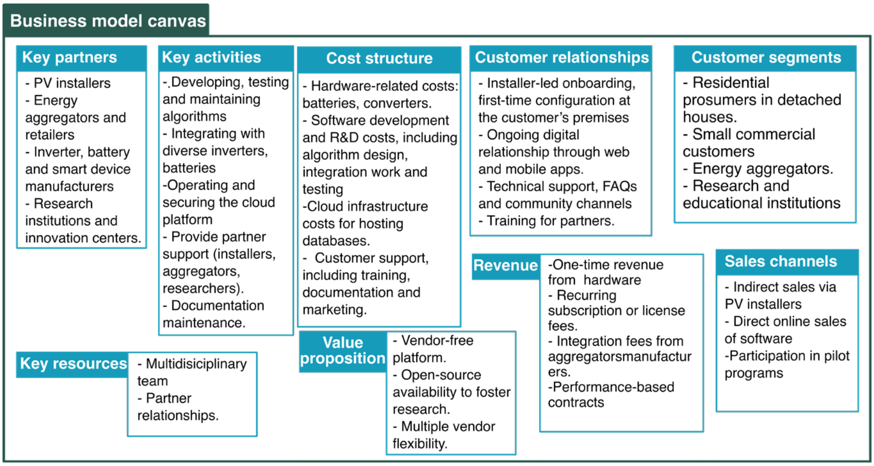
At the end of 2024, there were approximately 1.5 million renewable photovoltaic micro-installations in Poland, with a total capacity of around 12.7 GW, and 98% of these were primarily residential [5]. Moreover, there is a regultaroy shift from old net-metering to net-billing, meaning that new prosumers sell surplus energy at the market price, which increases the interest in electricity bill minimization solutions that account for different price ratings. The existing solutions are tightly integrated ecosystems where software is proprietary and tied to specific hardware. A comparison of products available in the market related to battery units and load management is described in Table II and Table III, respectively.

Table III. Available products related to load management.

Brand	**Product / Service**	**Price (€)**	**Features**
Fronius	Ohmpilot	~800	• Optimizes self-consumption rather than explicit market price.
Tibber	Tibber app + dynamic electricity tariff & smart charging	Dynamic supply contract with monthly base fee around €5.99	• Shifts EV charging and electric heating to cheap, green hours.
Homey / LG	Homey Pro	~350	• Integrates a wide range of devices via Zigbee • Whole-home consumption, solar generation tracking. • Very flexible ecosystem, but requires user configuration

3.5. Business Canvas

The business canvas of the proposal is summarized in next figure:



Business model canvas

Key partners
- PV installers
- Energy aggregators and retailers
- Inverter, battery and smart device manufacturers
- Research institutions and innovation centers.

Key activities
-.Developing, testing and maintaining algorithms
- Integrating with diverse inverters, batteries
-Operating and securing the cloud platform
- Provide partner support (installers, aggregators, researchers).
- Documentation maintenance.

Cost structure
- Hardware-related costs: batteries, converters.
- Software development and R&D costs, including algorithm design, integration work and testing
-Cloud infrastructure costs for hosting databases.
- Customer support, including training, documentation and marketing.

Customer relationships
- Installer-led onboarding, first-time configuration at the customer's premises
- Ongoing digital relationship through web and mobile apps.
- Technical support, FAQs and community channels
- Training for partners.

Customer segments
- Residential prosumers in detached houses.
- Small commercial customers
- Energy aggregators.
- Research and educational institutions

Key resources
- Multidisiciplinary team
- Partner relationships.

Value proposition
- Vendor-free platform.
- Open-source availability to foster research.
- Multiple vendor flexibility.

Revenue
-One-time revenue from hardware
- Recurring subscription or license fees.
- Integration fees from aggregatorsmanufacturers.
-Performance-based contracts

Sales channels
- Indirect sales via PV installers
- Direct online sales of software
-Participation in pilot programs

Figure 3. Business model canvas of the proposal.

- **Key partners:**
  PV installers and companies that provide access to end customers and handle on-site integration, while energy aggregators and retailers use EconoBattery + FlexiLoad as a flexibility asset. Power electronics converter manufacturers can include EconoBattery software in their own devices.
- **Key activities:**
  Maintenance and development of optimization algorithms and an open-source platform. Customer support and service to ensure up-to-date monitoring and functionality of the interface between the pricing information platform.
- **Key resources:**
  Multidisciplinary team that, among other tasks, is in charge of: development of novel algorithms, communication software at the edge level, and cloud-based interfacing maintenance, development of competitive power converter proposals.
- **Value proposition:**
  A vendor-free, open-source platform that gives complete, real-time control of batteries and flexible loads, enabling advanced research, innovative tariffs, and new applications without lock-in or exclusive partnership.
- **Customer relationships:**
  Created through installer onboarding, self-service web or app interfaces, and ongoing digital support with transparency on savings and performance.
- **Sales Channels:**
  Primary customers are residential prosumers in detached houses and small businesses with existing PV installations
- **Customer segments:**
  Residential prosumers in detached houses and small businesses, which may or may not have a photovoltaic system. The concept of payback time is the driving factor. PV installers and energy aggregators that will include the product into their existing offers.
- **Cost structure:**
  Significant costs arise from hardware components and manufacturing, cloud infrastructure, R&D and software development, technical support, and partner acquisition and training.
- **Revenue streams:**
  Revenues are generated from the sales of EconoBattery hardware, a single payment for one year of software without support, and subscription-based fees for enhanced optimization algorithms and continuous support.

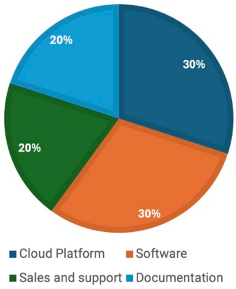
3.6. Economic and Financial Plan

In order to analyse the profitability and the financial structure of the project, it is necessary to describe the information on the cost breakdown and revenue plan, which together will determine the cash flow and balance of the proposal.

Cost Breakdown

The suggested cost structure is organized into three sections. Two sections correspond to the costs related to the core products, EconoBattery and FlexiLoad, and the remaining section corresponds to shared costs for both products. The percentages of each concept to the respective cost section are summarized in Figure 4(a), Figure 4(b), and Figure

4(c), for the EconoBattery bundle, the FlexLoad including four smart plugs, and the shared costs, respectively.



(a) (b) (c)

Figure 4. Cost breakdown of the proposal. (a)EconoBattery. (b) FlexiLoad. (c) Shared costs.

Pricing scheme

The pricing scheme and revenue model consider three sales cases. One is for only selling the EconoBattery device and software, the second is for only delivering the FlexiLoad module, and lastly, a bundle offer in which both products can be purchased. Indicative prices for each case are summarized in Table IV.

Table IV. Pricing scheme for three different cases.

Product	**Unit cost (€)**	**Selling price (€)**	**Recurring software fee (€ / month)**	**Notes**
EconoBattery	4000	5500	12 (EconoBattery Optimization)	10 kWh battery + converter + commissioning + Year 1 SW included, subscription starts in Year 2.
FlexiLoad	400	700 (gateway + 4 controllers)	8 (FlexiLoad Scheduling & App)	Can be sold as independent add on.
Bundle: EconoBattery + FlexiLoad	4300	5950 (combined hardware, discounted)	15 (Combined EconoBattery + FlexiLoad SW)	Bundle discount and single subscription covers both modules.

Revenue plan.

From the pricing scheme, it can be noted that the revenue streams come from the following:

1. **Hardware Sales (Upfront)**

- EconoBattery hardware revenue per standalone customer: €5500.
- FlexiLoad hardware revenue per standalone customer: €700.
- Bundle hardware revenue per customer: €5950.

2. **Recurring Software / SaaS Revenue**

- EconoBattery-only customer: €12 / month (€144 / year).
- FlexiLoad-only customer: €8 / month (€96 / year).
- Bundle customer: €15 / month (180 € / year) covering both modules.
- With an average customer lifetime of 8–10 years, the revenue can reach € 1400–€ 1800.

Cash Flow

The expected sales for the first four years and the corresponding cash inflow and outflow are summarized in Table V. It can be noted that despite the differences in profit margin for each product the expected overall profit for sales of the three options is approximately 40% without considering the license fees, or additional revenues obtained from partnering with suppliers.

Table V. Cash flow

Year	**Sold units**			**Cash (€)**	
	EconoBattery	**FlexiLoad**	**Bundle**	**Outflow**	**Inflow**
1	40	80	30	321000	454500
2	50	150	40	432000	618000
3	60	350	50	595000	872500
4	60	300	50	575000	837500

3.7. Business Pitch

We offer a pair of smart energy helpers for homes and small businesses that may already have solar panels, but feel they are not getting the full benefit**.** **EconoBattery** stores extra solar energy in a battery and decides when to charge and when to use it, so that you rely less on expensive electricity from the grid. **FlexiLoad** considers the appliances you choose to connect, such as water heaters, car chargers, or other plug-in devices, and adjusts their use to times when electricity from the grid is cheaper, without compromising your comfort. Together, they work in the background so that more of the energy you produce stays with you.

The product is aimed at detached houses and owners of small businesses who already have solar panels and want lower bills, more independence, and better use of their own clean energy. We work closely with local solar installers and energy service companies, who can offer the system as part of new installations or as an upgrade to existing ones, making it easy for customers to get a complete solution from a trusted local partner. Clear guidance, simple mobile and web access, and friendly support help customers understand what is happening and stay in control at all times. The offer combines a one-time purchase of the battery and control devices with a modest monthly service fee that keeps the software up to date and the cloud service running. Prices are designed to fit within the usual range of European home battery and smart home systems, while giving customers extra value by coordinating both storage and appliances in one place.

Compared to many existing solutions that lock you into a single brand, depend on special deals with one electricity retailer, or hide their decision-making behind complex settings, this business model puts openness and flexibility first. The system is designed to work with different brands of batteries and devices, it uses publicly available information about electricity prices, and it gives clear, direct control over how the battery and connected appliances behave. This creates a simple way for customers to share the benefits of utilizing smarter solar energy.

3.8. References

[1] *"Octopus Energy integrates with Tesla Powerwall, enabling lower bills for customers"*. [Online]. Available: https://octopus.energy/Octopus-Energy-integrates-Tesla-Powerwall/
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[3] *"Netzero - Dynamic Electricity Pricing"*. [Online]. Available: https://docs.netzero.energy/docs/tariffs/Dynamic-Electricity-Pricing.html
[4] *"Dynamic electricity price"*. [Online]. Available: https://www.tge.pl/dynamic_electricity
[5] *"The number of RES micro-installations in Poland exceeds 1.4 million"*. [Online]. Available: https://www.ure.gov.pl/en/communication/news/378%2CThe-number-of-RES-micro-installations-in-Poland-exceeds-14-million.html

4. IRP03 – Virtual Power Plant for operation, both isolated and connected

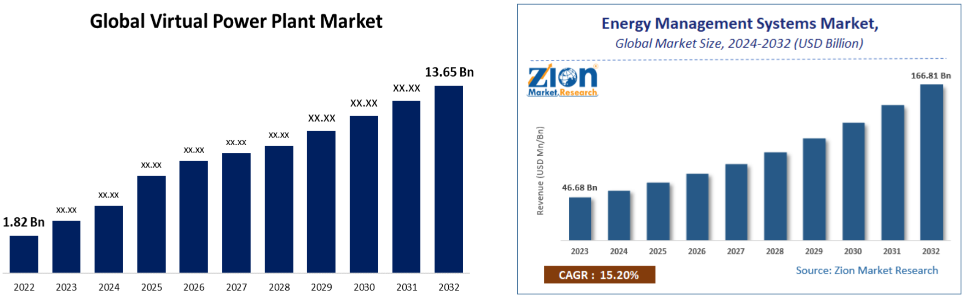
4.1. Introduction

The name of the application is chosen as VPPEC (Virtual Power Plant for Cost Efficiency) in which the motto is chosen as "Providing Economican Energy for All". Some of the main features of the application are given below:

- Price Minimization of up to 15%
- Price Minimization of up to 44.1% (Peak Shaving Constraint)
- Price Minimization of up to 66.92% (Providing Ancillary Services)
- User friendly interface
- Personalized services
- Eco-Friendly Solution
- Social Awareness

4.2. Market and Impact on Society

VPPs enable market participation for smaller producers, offering ancillary services, peak shaving, demand response, and grid stabilization. In diversified markets, VPPs improve resilience, flexibility, and cost efficiency by dynamically coordinating varied resources. The current VPP Market is USD 48 Million in Spain and USD 1951.2 million globally in which the main customers are commercial VPP users, DSOs and aggregators. The current EMS Market is USD 143.1 Million in Spain and USD 57.33 Billion globally mostly for the EMS Users.



Global Virtual Power Plant Market

Energy Management Systems Market,
Global Market Size, 2024-2032 (USD Billion)

Source: Zion Market Research

Global VPP and EMS Market

The main business plan is based on the following:

- Subscription model: 15 Euro/Month
- To collaborate with industries for reducing price and take a percentage of the reduction in exchange
- 1st year forecast: 500 Customers with a Net profit of €758K
- 2nd year forecast: 650 Customers with a Net profit of €1.6M
- 3rd year forecast: 800 Customers with a Net profit of €2.5M
- Providing ancillary services as well as capacity.

4.3. Financial Model Analysis

Technical		**Market**	
Parameter	**Value**	**Parameter**	**Value**
Total aggregated capacity	20 MW	Energy selling price (average)	€60/MWh (Spain)
Battery storage capacity	12 MWh	Ancillary services revenue	€35/MWh
PV generation	20,000 MWh/year	Capacity market price	€60/kW-year
Customers aggregated	800 prosumers by Year 3	VPP platform fee per user	€15/month

Cost Inputs		**Financial**	
Cost Item	**Value**	**Parameter**	**Value**
Capex (control hardware, metering, servers)	€1,000,000	Discount rate	10%
Software platform license	€200,000/year	Inflation	N/A
O&M + staff	€250,000/year	Tax rate	21%
IT cloud + communication	€100,000/year		
Customer acquisition cost	€300/prosumer		

Year	DER Availability	Effective Capacity
Year 1	50%	10 MW
Year 2	75%	15 MW
Year 3	100%	20 MW

Total VPP revenue comes from several streams:

A. **Energy Market Arbitrage Revenue**

R_{energy}= MWh_{sold} × Price

Assume VPP dispatches 7,000 MWh/year in year 1, 10,000 MWh/year in year 2 and 14,000 MWh/year in year 3 keeping the price constant:

Year 1: R_{energy}=7,000×60=€420,000
Year 2: R_{energy}=10,000 ×60=€600,000

Year 3: R_{energy}=14,000 ×60=€840,000

B. **Ancillary Services Revenue**

Frequency regulation, reserve, ramping:
R_{anc}= $Capacity_{MW}$ × Hours × Price

Assume 10 MW in year 1, 15MW in year 2 and 20MW in year 3 participating 3000 h/year:

Year 1: R_{anc}=10×3000×35/1000 = €1,050,000
Year 2: R_{anc}=15×3000×35/1000 = €1,575,000
Year 3: R_{anc}=20×3000×35/1000 = €2,100,000

C. **Capacity Market Revenue**

R_{cap}=$Capacity_{kW}$ × Price
Year 1 for 10kW: R_{cap}=10,000×60=€600,000
Year 2 for 15kW: R_{cap}=10,000×60=€900,000
Year 3 for 20kW: R_{cap}=10,000×60=€1,200,000

D. **VPP Platform Subscription Fees**

R_{sub} = N_{users} × Fee ×12
Year 1 for 500 prosumers: R_{sub} = 500×15×12 = €90,000
Year 2 for 650 prosumers: R_{sub} = 650×15×12 = €117,000
Year 3 for 800 prosumers: R_{sub} = 800×15×12 = €144,000

Total Annual Revenue

Year 1: R_{total}=420000+1050000+600000+90000 = €2,160,000
Year 2: R_{total}=600000+1575000+900000+117000 = €3,192,000
Year 3: R_{total}=840000+2100000+1200000+144000 = €4,284,000

Annual Operating Costs

Fixed OPEX

- Software license: €200,000

- O&M and personnel: €250,000
- IT cloud + comms: €100,000

Variable OPEX
Customer Acquisition Cost C AC:
Year 1: 500 × €300 = €150,000
Year 2: 150 × €300 = €45,000
Year 3: 150 × €300 = €45,000

Total Annual OPEX
Year 1: OPEX=200000+250000+100000+150000=€700,000
Year 2: OPEX=200000+250000+100000+45,000=€650,000
Year 3: OPEX=200000+250000+100000+45,000=€650,000

EBITDA
EBITDA = Revenue−OPEX

Year	Revenue (€)	OPEX (€)	EBITDA (€)
Year 1	2,160,000	700,000	1,460,000
Year 2	3,192,000	650,000	2,542,000
Year 3	4,284,000	650,000	3,634,000

Depreciation
Assuming 5-year straight-line with a CAPEX of €2,500,000:
Dep=2,500,000/5 = €500,000

EBIT
EBIT=EBITDA−Dep
Year 1, EBIT=1,460,000−500,000 = €960,000
Year 2, EBIT=2,542,000−500,000 = €2,042,000
Year 3, EBIT=3,634,000−500,000 = €3,134,000

Taxes
Tax=EBIT×0.21
Year 1, Tax =960,000×-0.21 = €201,600
Year 2, Tax = 2,042,000×-0.21 = €428,820
Year 3, Tax = 3,134,000×-0.21 = €658,140

Net Income
Net Income = EBIT−Tax
Year 1, Net Income = 960,000 − 201,600 = €758,400
Year 2, Net Income = 2,042,000 − 428,820 = €1,613,180
Year 3, Net Income = 3,134,000 − 658,140 = €2,475,860

Cash Flow
Cash_Flow = Net + Depreciation
Year 1, Cash_Flow = 758,400 + 500,000 = €1,258,400
Year 2, Cash_Flow = 1,613,180 + 500,000 = €2,113,180
Year 3, Cash_Flow = 2,475,860 + 500,000 = €2,975,860

3-Year Projection

Year	Revenue (€)	OPEX (€)	EBITDA (€)	Net Income (€)	Cash Flow (€)
Year 1	2,160,000	700,000	1,460,000	758,400	1,258,400
Year 2	3,192,000	650,000	2,542,000	1,613,180	2,113,180
Year 3	4,284,000	650,000	3,634,000	2,475,860	2,975,860

Net Present Value (NPV), Payback

NPV (3 years)
$NPV = \sum CF_t/(1+r)^t - \text{Capex}$
Using $r = 10\%$:

Year 1, $1{,}258{,}400/(1.1)^1 = €1{,}144{,}000$
Year 2, $2{,}113{,}180/(1.1)^2 = €1{,}746{,}430$
Year 3, $2{,}975{,}860/(1.1)^3 = €2{,}237{,}770$

NPV = 1,144,000+1,746,430+2,237,770 = €5.1282M

Payback Period

Year	Cash Flow (€)	Cumulative (€)
0	–2,500,000	–2,500,000
1	+1,258,400	–1,241,600
2	+2,113,180	+871,580
3	+2,975,860	+3,847,440

Payback Period Calculation
After Year 1, cumulative cash flow = –1,241,600

- Remaining to recover: 1,241,600
- Cash flow in Year 2 = 2,113,180

Fraction of Year 2 needed:
Fraction=1,241,600/2,113,180≈0.587 years
Converting into months:
$0.587 \times 12 \approx 7.05$
So, Payback Period = 1 year 7 months.

4.4. Summary of VPP Financial Viability

- Highly profitable
- Payback < 2 years
- High recurring revenue from markets and subscriptions
- Costs remain stable while revenue scales with energy markets and number of aggregated users

4.5. Business Model Canvas

Key partners:

Universities and Research Centres

- Access to technical expertise
- Collaboration on R&D
- Ability to support ongoing development of the application

Software Firm / R&D Partner
(Equity share or one-time payment model)

- Development of Android / iOS application
- Long-term maintenance and updates
- Technical scalability support

Expertise and Experience Providers

- Subject-matter experts (energy, IoT, AI, forecasting, optimization)
- Advisory roles for validating algorithms and system design
- **Motivations for Partnerships**
- **Acquisition of key resources** (technical, academic, financial)
- **Access to specialized activities** such as advanced R&D, software development, testing
- **Acceleration of product development and innovation**
- **Shared risk and reduced development cost**

Key activities:

Energy optimization
This is the core technical activity of the virtual power plant (VPP) or energy management platform. It includes:

- **Forecasting energy demand and generation** using AI/ML models.
- **Optimizing consumption schedules** for households or businesses (e.g., shifting loads to off-peak hours).
- **Managing distributed energy resources (DERs)** such as solar panels, batteries, EV chargers.
- **Reducing overall energy cost** for users by making real-time adjustments.
- **Coordinating flexibility services** for the grid (e.g., demand response). This activity ensures both economic savings and improved grid stability.

User-friendly interface
A smooth and intuitive interface is essential for customer adoption. Activities include:

- Designing **mobile and web app interfaces** that are visually simple and easy to navigate.
- Offering **dashboard analytics** for energy usage, cost savings, carbon footprint, and system performance.
- Ensuring accessibility and usability for non-technical users through clear icons, tips, and real-time feedback.

- Continuous UI/UX improvements based on user test results and feedback. This activity makes the technology approachable and increases engagement and retention.

Personalized services
Providing tailored solutions enhances customer experience. This involves:

- Recommending **individual energy-saving strategies** based on the user's consumption patterns.
- Custom notifications such as:
    - "Best time to run appliances"
    - "Your battery reached optimal charge"
    - "High energy price alert"
- Offering **smart automations** depending on user lifestyle (e.g., work schedules, occupancy).
- Providing user-specific financial insights (ROI, payback period, projected savings).

  These tailored features increase customer value and differentiate our solution from generic energy apps.

Eco-friendly solution
The product aligns with environmental sustainability. Key activities:

- Promoting the use of **renewable energy sources** through optimal scheduling and integration.
- Reducing **carbon emissions** by shifting energy usage to cleaner periods of the grid.
- Encouraging energy-efficient behavior through tips, goals, and progress indicators.
- Supporting the circular economy by integrating storage sharing, community energy, and peer-to-peer trading.

  This aligns the business with the global push for sustainable development and green energy.

Value propositions:

Price minimization of up to 15%
This refers to the **baseline cost savings** users can achieve simply by optimizing their daily energy usage. The system uses:

- Smart scheduling of appliances
- Load forecasting
- Time-of-use (TOU) price optimization

Even without advanced constraints or market participation, users can save **up to 15%** on their electricity bills through efficient consumption patterns.

Price minimization of up to 44.1% (Peak Shaving Constraint)
Peak shaving reduces electricity usage during the hours when demand — and prices — are highest.
By implementing a **peak shaving strategy**, the system:

- Lowers consumption during expensive peak hours
- Utilizes stored energy (batteries, EVs)

- Reschedules flexible loads

This results in significantly larger savings, achieving **up to 44.1%**, because customers avoid the highest tariff periods.

Price minimization of up to 66.92% (Providing Ancillary Services)
This represents the highest level of savings because the system not only optimizes internal consumption but also **earns revenue** by participating in external services such as:

- Frequency regulation
- Voltage support
- Demand response programs
- Capacity markets

By providing these ancillary services, the user (or the virtual power plant operator) receives compensation from the grid or the utility. This additional revenue can reduce the net electricity cost by **up to 66.92%**, making it a powerful value proposition for prosumers and microgrid participants.

Social awareness
The platform promotes energy education and community engagement through:

- Awareness campaigns on sustainable living
- Insights about how user choices affect the environment
- Shared community goals (e.g., “Save 10% Month”)
- Encouraging participation in local energy programs

This transforms users from passive consumers into active contributors to energy sustainability.
Customer relationships:

Daily customer support and engagement
The business maintains **continuous interaction** with customers to ensure smooth usage of the energy management or virtual power plant platform. This includes:

- Responding to customer questions and issues **every day**
- Offering **technical support** for app usage, device integration, or energy settings
- Providing **real-time notifications** about energy prices, consumption, and system alerts
- Ensuring customers always feel supported, informed, and connected to the service

Daily engagement helps build trust, reduce churn, and ensure long-term satisfaction.

Personalized services (Core relationship model)
The customer relationship strategy is strongly based on **personalization**, meaning each user gets a tailored experience driven by their own behavior, needs, and preferences. This includes:

- Customized energy use recommendations
- Individual savings reports
- Personalized alerts (high price, peak hours, battery status, solar forecasts)
- Tailored interface and usage insights
- Automated optimization configured to each user’s lifestyle

This high level of personalization strengthens the relationship by making the customer feel seen, understood, and valued—creating long-lasting loyalty and differentiation from competitors.

Customer segments:

Commercial VPP users

These are businesses or industrial clients who participate in a **Virtual Power Plant (VPP)** model that may operate:

- Large commercial buildings
- Factories or warehouses
- Shopping centers
- Data centers

These benefit from:

- Energy cost reductions
- Peak shaving
- Revenue from ancillary services
- Grid flexibility participation

These are typically high-energy users looking for **optimization and financial performance**.

Distribution System Operators (DSOs)

DSOs manage and operate the electricity distribution grid. They are a key segment because they need:

- Better grid balancing
- Demand response resources
- Real-time data on local consumption
- Distributed energy resource (DER) coordination
- Voltage and frequency regulation

The system can support DSOs with:

- Aggregated flexibility
- Predictive analytics
- Enhanced grid reliability

They represent a **high-value B2B customer segment**.

Aggregators

Aggregators combine multiple small energy resources (homes, buildings, DERs) and act as a single unit in the market. They require:

- Optimization tools
- Real-time control
- Market bidding automation
- Asset coordination (batteries, EVs, solar, flexible loads)

The product helps them maximize:

- Market revenue
- Operational efficiency
- Customer participation levels

They are essential players in **modern electricity markets**

Energy Management System (EMS) users

This segment includes:

- Homeowners
- Small businesses
- Residential solar users
- Smart home users
- Energy-conscious consumers

These users want:

- Cost savings
- Insights into consumption
- Automated control of devices
- Personalized recommendations

These represent the **retail market and mass adoption potential**.

Diversified market

This refers to the extended audience beyond the core segments, including:

- Municipalities
- Renewable energy communities
- Universities and campuses
- Housing cooperatives
- Smart city projects
- EV fleet operators
- Industrial clusters

Key resources:

Human Resources (Technical & Business Teams)

These are the most critical assets for operating the Virtual Power Plant (VPP) that include:

Technical team

- Software developers (mobile app, backend, optimization algorithms)
- Data scientists and AI/ML experts
- Energy engineers (VPP design, DER integration, energy markets)
- Cybersecurity specialists
- System integration experts (IoT, smart meters, batteries, EV chargers)

Business team

- Project managers
- Marketing and sales professionals
- Customer support representatives
- Financial analysts
- Partnership managers

These teams work together to build, maintain, and scale the solution.

Online Channels (Website & Digital Platform)

The website and online interfaces act as key operational resources by enabling:

- Customer acquisition (information, sign-up, marketing funnel)
- User access to the platform
- Distribution of updates, services, and community engagement

- Support/helpdesk communication

They support both daily operations and long-term brand visibility.

Personalized Features

Personalization is a **core intellectual and functional resource** that differentiates our solution.

These features include:

- Customized energy recommendations
- AI-driven consumption patterns
- Tailored dashboard analytics
- Alerts based on user behavior and goal tracking
- Smart automation rules

These capabilities increase user value and improve retention.

Intellectual Resources

These are strategic assets that give our business a competitive edge:

- **Patents** (e.g., optimization algorithm, VPP coordination method, or EMS logic)
- **Copyrights** (software, UI design, documentation)
- **Brand identity** (logo, trademarks, corporate reputation)
- **Proprietary datasets**
- **Operational know-how & algorithms**

A patent for our algorithm or application strengthens unique market position and protects our innovation.

Physical Resources

While our solution is mostly digital, some physical resources may include:

- Office space
- Testing hardware (controllers, IoT devices, sensors, smart meters)
- Servers (if not fully cloud-based)
- Laptops and IT infrastructure for staff

These support development, testing, and daily operations.

Financial Resources

Financial capital is crucial for:

- R&D and prototyping
- Patent filing and legal protection
- Software development
- Marketing and customer acquisition
- Cloud hosting and operational costs
- Hiring and talent retention

Funding sources may include investors, grants, and revenue from early adopters.

Channels:

The channels describe the solution that reaches customers, delivers value, and provides support. Each channel serves a different customer need and strengthens the overall customer experience.

Online platform

This is the **primary delivery channel** for the Virtual Power Plant service. It includes:

- Mobile app (Android/iOS)
- Website dashboard
- Customer portal

The online platform enables users to:

- Monitor energy consumption
- View savings and analytics
- Control devices and settings
- Receive alerts, recommendations, and personalized insights
- Perform account management and payments

It is the most scalable and cost-effective channel, allowing global reach and 24/7 interaction.

Telephone service

A telephone support line provides a **direct and human-centered communication channel** for customers. It is used for:

- Customer service inquiries
- Technical support and troubleshooting
- Onboarding assistance
- Emergency or urgent energy-related issues
- Sales or upgrade support

This channel builds customer trust and ensures users receive immediate help when needed.

In-Person technician

Some services require **on-site technical support**, especially when dealing with:

- Installation of hardware (controllers, sensors, meters)
- Integration of solar panels, batteries, EV chargers, or IoT devices
- Diagnostic visits to resolve complex issues
- Maintenance and system checks
- Physical upgrades or replacements

This channel ensures reliability and strengthens customer relationships by providing hands-on professional support.

Cost Structure:

The business operates under a **value-driven model**, meaning it prioritizes offering high-quality features, personalized services, and strong user experience—rather than competing only on low cost. As a result, the cost structure includes both significant fixed investments and variable operational costs.

Fixed Costs

These are the costs that remain constant regardless of the number of customers. They are essential to run the service reliably.

a. Human Resources

A core fixed cost, including:

- Software developers
- Data scientists & AI/ML engineers
- Energy engineers
- Cybersecurity specialists
- Sales, marketing, and administrative staff

These salaries represent the primary long-term expenses in a tech-driven energy business.

b. Application Development

One-time or recurring costs related to:

- Mobile app (Android/iOS) development
- Backend, APIs, optimization engines
- UI/UX design
- Continuous updates, bug fixes, and improvements
- QA testing and version releases

This investment ensures that the platform provides advanced features and excellent performance.

c. Server Maintenance Costs

Recurring technical infrastructure expenses:

- Cloud hosting (AWS, Azure, Google Cloud)
- Data storage
- Cybersecurity measures
- Server administration
- API and third-party integration fees

This ensures high availability, real-time performance, and data safety.

Variable Costs

These costs fluctuate based on the number of users or level of service usage.

a. Personalized Services

Personalization requires:

- Additional computation resources
- AI processing and model inference
- Customer support needs
- Increased data storage and recommendation engine usage

As more users join, the cost scales with the volume of personalized analytics and support.

Other variable costs can include:

- In-person technician visits
- Customer acquisition (marketing spend per user)
- Payment transaction fees

Economies of Scale

As the number of users grows:

- The average cost per user decreases
- Server and tech infrastructure become more efficient
- Development costs are spread across more customers
- Profit margins improve

This is typical for software-based businesses: **high initial investment, low marginal cost**.

Economies of Scope

Because the platform can serve multiple customer segments (EMS users, aggregators, DSOs, commercial VPP clients), the business benefits from:

- Shared technology and algorithms
- Reusable data models
- Cross-segment synergies
- Reduced cost of entering adjacent markets

For example, the same optimization engine can serve both residential users and commercial VPP clients with minor adaptations.

Value-Driven Structure

The business is **value-driven** rather than cost-driven. This means:

- High emphasis on personalization
- Investment in a premium user interface
- High-quality service delivery
- Reliable technical performance
- Innovation and continuous development

Users receive **better savings, sustainability benefits, and a superior experience**, justifying the investment in high-value capabilities.

Revenue streams:

The business generates revenue through a combination of **upfront licensing** and **recurring subscription income**. This mixed model is ideal for software-driven energy management systems (EMS) and Virtual Power Plant (VPP) platforms because it provides both **initial capital** and **long-term financial sustainability**.

Initial Application License Fee

This is a **one-time payment** charged at the beginning of the customer relationship. It covers access to the core application and initial setup.

The license fee may include:

- Access to the platform’s main features
- Activation of user accounts
- Integration with hardware (smart meters, controllers, IoT devices)
- Configuration of optimization algorithms
- Initial training or onboarding
- Basic support during the installation phase

Benefits of this revenue stream:

- Immediate cash inflow
- Helps recover development and setup costs
- Attractive for B2B customers (commercial VPP users, aggregators, DSOs)
- Supports early-stage scaling and market entry

This model also signals a **premium, high-value product**.

Subscription Model (Recurring Revenue)

This is a **monthly or annual subscription fee** paid by users to continue accessing the service. It creates a stable, predictable revenue stream (MRR/ARR).

Subscriptions can be structured based on:

- Number of users or devices
- Level of personalization

- Access to advanced analytics
- Participation in ancillary services
- Cloud data storage
- Premium features (e.g., AI-driven automation, peak shaving optimization)

Advantages:

- Continuous revenue over the customer lifetime
- Predictable cash flow
- Encourages long-term customer relationships
- Scales easily as the user base grows
- Allows tiered pricing (basic, premium, enterprise)

4.6. Conclusions

The prototype of the VPP Control is composed of 2 sections. The first part consisted of optimizing the energy interchange between the VPP and the MG to reduce electricity bill by creating new set points of operation of the elements included in the MGs such as Energy Storage Systems and EVs. The second part consisted of designing a GUI based digital twin of the VPP in which the number of MGs and VPPs along with the elements can be modified according to the needs of the user. This digital twin can optimize the results based on the algorithm of the first part and display the results in a very user-friendly manner so that it is easy to understand. The future work will include creating an infinite number of MGs that can be modified according to the user's input and be able to optimize the results instantaneously. This will be particularly helpful in setting up a new factory or a residential house in the existing grid and observe the effects of the new establishment. Also, selecting the right capacity of EMS for the new establishment can be also identified from the results.

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5. IRP04 – Condition Monitoring for Smart Power Electronic Converter Systems for Distributed Generation

5.1. Introduction

Predictive maintenance is emerging as a key enabler for improving reliability and reducing the operational expenditure of large-scale photovoltaic (PV) assets. However, traditional adoption is often constrained by high upfront investment, limited data accessibility, and unclear returns on predictive analytics. This work proposes a performance-driven, risk-sharing business model that integrates advanced condition monitoring, digital diagnostics, and edge-computing capabilities to deliver measurable improvements in system availability and maintenance efficiency. Instead of conventional subscription-based pricing, the model aligns economic incentives by directly linking compensation to verified reductions in downtime and maintenance costs, thereby lowering the financial and operational barriers for operation and maintenance (O&M) contractors. The proposed framework includes structured data acquisition, on-site diagnostics, health-indicator classification, and targeted maintenance recommendation workflows, all while ensuring secure data handling through local computation and controlled data flows. A comprehensive assessment of key activities, stakeholder relationships, cost–revenue mechanisms, and potential risks demonstrates that this model offers a scalable and mutually beneficial pathway for accelerating the adoption of predictive maintenance in modern solar power plants.

The objective of this work is to develop and evaluate a performance-driven predictive maintenance framework for large-scale PV installations, integrating advanced condition monitoring, edge-based diagnostics, and a risk-sharing business model that aligns financial incentives with measurable improvements in system reliability and O&M cost reduction.

5.2. Background

The global maintenance market for large-scale solar power plants is experiencing significant expansion, driven by the rapid deployment of photovoltaic (PV) installations worldwide. Recent market analyses indicate that the value of this sector reached 1141 GW in 2023, and is projected to grow substantially, potentially attaining 5457 GW by 2030 as solar power penetration continues to increase [1]. This trend underscores a growing demand for more efficient and cost-effective maintenance strategies capable of maintaining high system availability amid aging assets and expanding operational portfolios.

At present, maintenance activities in large-scale solar power assets rely predominantly on corrective maintenance and preventive maintenance approaches [2]. These two methods are illustrated in Fig. 1. Corrective maintenance follows a “run-to-failure” strategy, which results in extended downtime, higher risk of cascading failures, and increased operational losses [3]. Preventive maintenance, while reducing catastrophic failures, often adopts rigid, time-based replacement schedules, leading to material waste and elevated O&M expenditure due to the premature replacement of components in a healthy statue [3].

To balance reliability and cost, predictive maintenance has emerged as a promising strategy that dynamically schedules interventions based on equipment condition rather than fixed intervals [2][3]. According to industrial market reports, predictive maintenance remains in an early but rapidly evolving stage, supported by advancements in sensing technology and data analytics [5]. The predictive maintenance market is expected to grow to USD 60 billion by 2030, demonstrating strong commercial interest and technological momentum [6], [7].

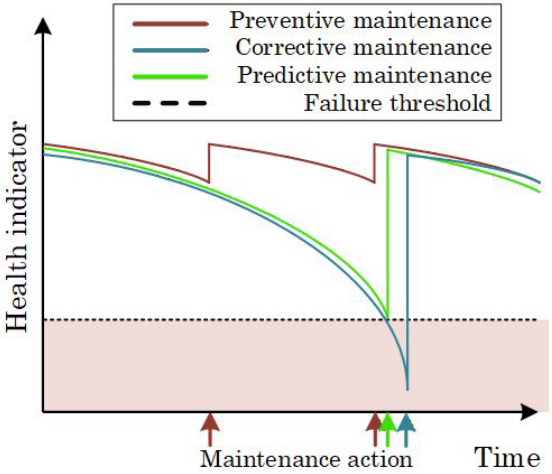

Fig. 1: Comparison between preventive-, corrective-, and predictive maintenance [4]. The health indicator reduces gradually with time, and it fails once the health indicator is below the threshold. Preventing maintenance requires more action, while corrective maintenance needs to work till failure. The predictive maintenance provides a balanced option between maintenance actions and system reliability.

More recently, commercial vendors have introduced subscription-based predictive maintenance services, where operators pay a fixed recurring fee for diagnostic capabilities and remote monitoring tools. Although this model simplifies budgeting, it often lacks alignment between costs and actual performance outcomes and may still require substantial upfront investment in sensing or digital infrastructure. As a result, subscription-based pricing has not fully resolved barriers related to uncertain return on investment (ROI) or limited incentives for continuous reliability improvement.

Despite its potential, the widespread adoption of predictive maintenance faces challenges related to high upfront investment, data accessibility, and unclear return on investment (ROI). To address these barriers, a new business model has been developed to align economic incentives across stakeholders, particularly between operation and maintenance (O&M) contractors and predictive maintenance solution providers. This model aims to reduce adoption reluctance, expand coverage, and enable scalable deployment across large solar power portfolios.

5.3. Key Activity of the Predictive Maintenance Service

The core activities of the proposed business model focus on the secure acquisition, processing, and interpretation of operational data to enable accurate and timely predictive maintenance decisions, as illustrated in Fig. 2.

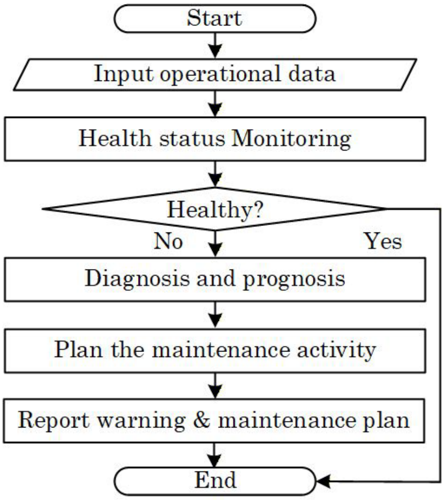

Fig. 2: PdM service workflow of processing the operational data to estimate the health status and plan health-condition-based maintenance.

First, operational and environmental data are collected from power plant components, including PV inverters and associated critical devices that affect system operation and reliability [8]. To enhance diagnostic accuracy, additional sensors are deployed when existing operational sensors do not provide sufficient granularity to detect early-stage degradation or failure precursors. These sensors feed data to edge-computing devices equipped with advanced diagnostic algorithms.

The edge-computing platform operates a software toolset capable of extracting health indicators, classifying degradation patterns, and generating failure predictions based on historical data and embedded failure mechanism models. The device also incorporates a local database, allowing the system to reference known degradation signatures and continuously refine its assessments. By performing on-site computation, the solution ensures low-latency detection and addresses cybersecurity concerns associated with remote data transmission.

Once degradation or elevated failure risk is identified, the system translates these findings into maintenance recommendations, balancing component health status with expected impacts on operational continuity and maintenance cost. Recommendations are communicated to the O&M contractor through a structured notification system, enabling proactive and cost-efficient maintenance scheduling. This workflow strengthens coordination between the predictive maintenance service provider and the O&M team, supporting timely interventions that minimize downtime and reduce unnecessary material replacement.

5.4. Customer Relationship

The success of this business model relies on establishing long-term, collaborative, and performance-oriented relationships with operation and maintenance contractors. These relationships are inherently bidirectional (as seen in Fig. 3): O&M contractors provide access to solar power generation assets, operational data streams, and historical maintenance records, all of which serve as essential inputs for accurate health assessment and predictive diagnostics [8]. In return, the predictive maintenance provider delivers data-driven insights that enhance system availability, increase energy yield, and reduce maintenance costs, creating tangible operational value for the contractors.

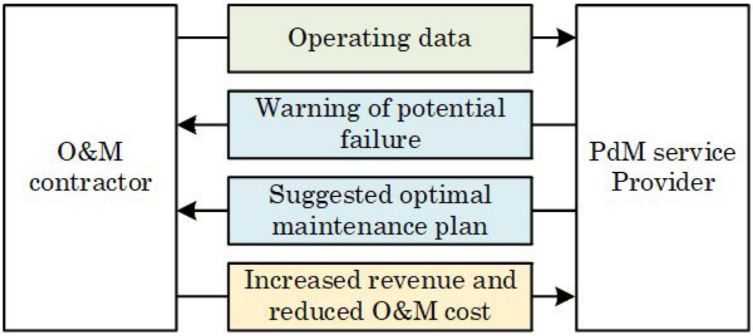

Fig. 3: The O&M provides data, and then the predictive maintenance (PdM) service provider gives health monitoring results, including potential failures and optimal maintenance plan. At the end, PdM service provider gains revenue from enhanced system performance.

Unlike conventional vendor–client arrangements, the proposed business model adopts a risk-sharing framework, eliminating the need for upfront investment or subscription fees. Instead, compensation is tied to the verified reduction in downtime and maintenance expenditures, which fosters trust and strengthens alignment between stakeholders. This structure not only lowers the adoption barrier for O&M contractors but also motivates the predictive maintenance service provider to continuously refine diagnostic tools and maintain high solution performance.

Through this collaborative approach, stakeholders form a unified ecosystem that supports accurate fault detection, informed maintenance planning, and dependable field execution. By integrating predictive insights directly into the operational workflow of O&M contractors, the model enhances reliability management practices and establishes a scalable foundation for long-term partnership and shared operational benefits.

5.5. Cost and Revenue

The cost structure of the proposed business model comprises both development-stage expenditures and operational-stage expenditures, including both hardware and software usage in predictive maintenance solutions. During the development stage, costs arise from the procurement of additional sensing hardware, edge-computing platforms, and communication modules required to support failure prediction alarm. Parallel to this, significant investment is required in software development, including diagnostic algorithms, failure mechanism analysis models, and maintenance decision-planning tools. These activities rely heavily on skilled human resources, such as hardware engineers, software developers, and data scientists, to ensure accurate model construction and seamless system integration.

In the operational stage, both hardware and software components require continuous calibration, verification, and updates to maintain high diagnostic accuracy and enable timely identification of potential failures. Edge devices and sensors must be periodically tested, while analytics models require continuous refinement based on newly observed degradation patterns. These ongoing requirements contribute to operating expenditure (OPEX), together forming the full lifecycle cost profile of the business model.

Revenue is generated through a shared-savings mechanism, in which the O&M contractor pays a proportion of the financial gains realized from reduced downtime, optimized maintenance activities, and lowered material replacement costs. This structure transforms predictive maintenance into a performance-driven service, ensuring that the financial burden on the contractor is proportional to measurable and verified benefits. In addition to the shared-savings model, optional revenue streams include premium service tiers, such as advanced diagnostic subscriptions or enhanced operational dashboards that offer deeper asset insights and further reduce maintenance time. The pricing structure can also scale with the size and operational complexity of the power plant portfolio, enabling flexible deployment across diverse customer segments.

5.6. Risk assessment

The implementation of the proposed predictive maintenance business model involves several technical, operational, and commercial risks. To ensure long-term viability, these risks must be systematically evaluated and addressed through appropriate mitigation strategies. Table 1 summarizes the major risks and corresponding solutions.

5.7. Conclusion

The proposed business model introduces a performance-driven predictive maintenance framework designed to enhance reliability and reduce operation and maintenance (O&M) costs for large-scale solar power assets. By leveraging advanced diagnostic analytics, condition monitoring, and edge-computing technologies, the model provides O&M contractors with data-driven insights that enable timely, targeted maintenance actions, thereby minimizing downtime and preventing unnecessary component replacements.

Unlike traditional maintenance service structures, the model adopts a risk-sharing and value-aligned revenue mechanism, in which compensation is tied directly to verified improvements in system performance. This approach not only reduces the financial barrier for O&M contractors, who are not required to make upfront investments, but also creates strong incentives for continuous algorithm enhancement and high-quality service delivery.

By combining technological innovation with an economically aligned contractual framework, the proposed model establishes a scalable and mutually beneficial foundation for modernizing maintenance practices in large-scale PV installations. This integration of reliability improvement, cost reduction, and shared financial benefits positions the model as a promising pathway for accelerating the adoption of predictive maintenance across the solar power sector.

Table 1. Key Risks and Mitigation Strategies

Risk	Description of Risk	Mitigation Strategy
Insufficient maintenance cost reduction	The improvement achieved through predictive maintenance may not be sufficient to justify operational expenses or support the financial sustainability of the business model [9].	• Continuously refine diagnostic algorithms using real-world data [10]. • Deploy targeted sensing to increase detection accuracy. • Start with pilot projects to validate ROI before scaling.
Data security concerns	O&M contractors may be reluctant to share operational data due to cybersecurity risks or data ownership considerations.	• Provide edge-only deployment with local data storage. • Implement strong encryption and access control policies. • Employ dedicated cybersecurity engineers and perform regular penetration testing.
Resistance from O&M contractors	Contractors may fear workflow disruptions or increased operational complexity.	• Offer training sessions and intuitive dashboards. • Ensure integration with existing maintenance processes. • Highlight zero-upfront-cost and shared-savings benefits.
Hardware reliability issues	Additional sensors or edge devices may fail or degrade, reducing system performance.	• Use industrial-grade, certified hardware. • Implement periodic device diagnostics and redundancy where needed. • Provide rapid replacement and support service.
Model performance Degradation over time	Predictive models may become less accurate due to changing operational conditions or new failure modes.	• Schedule periodic model retraining with updated field data. • Use adaptive and self-learning algorithms. • Maintain historical libraries of failure signatures for continuous improvement.
Integration challenges with existing SCADA/EMS	Legacy systems may limit data availability, compatibility, or communication bandwidth.	• Develop modular APIs and communication interfaces. • Provide on-site integration support. • Utilize lightweight edge analytics to minimize dependence on SCADA throughput.
Regulatory or compliance constraints	National or regional regulations may restrict data handling or remote diagnostics.	• Comply with IEC 62443, GDPR, and local grid codes [11]. • Keep all sensitive data on local servers when required. • Maintain transparent documentation for audits.

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6. General Conclusions

The four Individual Research Projects developed within Work Package 2 collectively demonstrate the technical maturity and market relevance of next-generation distributed energy solutions. Each IRP addresses a different but complementary element of the distributed energy value chain: advanced inverter hardware for resilient microgrids, open and vendor-neutral energy management for prosumers, coordinated control of aggregated assets through virtual power plant technologies, and performance-driven predictive maintenance for large-scale PV installations. Together, they form a coherent set of tools that can improve the flexibility, reliability, and economic performance of renewable energy systems.

The results highlight that hardware innovation alone is no longer sufficient; meaningful progress requires the integration of digital intelligence, modular architectures, and data-driven decision-making. The business models proposed in the IRPs emphasize affordability, interoperability, and transparent value creation—key factors for the widespread adoption of distributed energy technologies across residential, commercial, and utility-scale sectors. Moreover, the techno-economic analyses included in the IRPs confirm that these approaches can be financially viable, scalable, and aligned with evolving energy policies.

Overall, WP2 contributes a robust foundation for future research and innovation in distributed renewable energy systems. The work supports the broader goals of

SmartGYsum by connecting technical advancements with practical, market-oriented solutions that can accelerate the transition toward a more flexible, efficient, and resilient energy ecosystem.

Chapter 2

Innovative Business Models in Smart Energy Distribution Systems

Coordinator: USA – University of Salerno

List of abbreviations used in this Chapter

BEN	Beneficiary
Dn	Deliverable (number)
DoA	Description of Action
DS	Doctoral School
ESR	Early Stage Researcher
ETN	European Training Network
GA	Grant Agreement
IRP	Individual Research Project
ITN	Innovative Training Network
MSn	Milestone (number)
MSCA	Marie Sklodowska-Curie Actions
PC	Project Coordinator
REC	Research Ethics Committee
RSC	Recruitment and Secondment Committee
WPn	Work Package (number)

1. Executive summary

The present deliverable provides the report about the developed business models, related with the implementation of IRPs in WP3 Smart Energy Distribution, Microgrids and Grid of Microgrids of the SMARTGYSUM project. This chapter aims to explore the possibilities of microgrids for energy management to address the challenges of secure energy routing and power quality control, as well as advanced distribution grid management and the use of radial grids. In particular, the objectives of WP3 are to identify and demonstrate new ways of collaborative distributing electric energy and new operation strategies as well as operating in connected and islanding modes; to design converters and strategies to control microgrids (as optimal operational parts of distribution grids) to manage energy flows and minimize transportation losses; to coordinate the production of different generators with the consumption of different consumers to match generation and consumption in a safety and optimize way; finally to analyse the new opportunities of storage system in microgrids and conventional grids. This research is addressed by IRPs identified by 5 to 8.

The ESRs involved in this WP3 are indicated below with a brief description of the initial targets of their IRPs:

- ESR05 (**Mohammadreza Azizi**), recruited and coordinated by Chernihiv Polytechnic National University (CNTU). The individual research project is entitled "Energy Router for Hybrid Microgrids for efficient and robust energy and power management". The IRP objectives are linked to research on the communication performance requirements in wireless networks, as well as to advance in the grid intelligence to understand the energy distribution in the grid and allow real-time decision-making.
- ESR06 (**Mykola Lukianov**), recruited and coordinated by Politechnika Gdanska (GUT). The individual research project is entitled "EV chargers, developing an active bidirectional charger able to provide anciallary services". The IRP objectives are linked to develop new power electronics facilities for energy transfer system with improved efficiency and power density and analyse future energy system including wireless charge system for electric vehicles.
- ESR07 (**Mahyar Hassanifar**), recruited and coordinated by Christian-Albrechts-Universitaet Zu Kiel (CAU). The individual research project is entitled "Reliability and availability of Smart Transformers for cost effective and high quality of services in the grid". The IRP objectives are linked to create smart devices in the grid, aimed at enabling autonomous grid management increasing the reliability and the availability of grid services.
- ESR08 (**Gabriele Arena,** followed by **Danilo Di Bernardino**), recruited and coordinated by Karlsruhe Institut für Technologie (KIT). The individual research project is entitled "Real-time modelling and validation of Distributed Energy Storage Systems and Integration strategies". The IRP objectives are linked to generate and analyse real-time models of Distributed Energy Sustems, to optimize distributed REES through the integration of actual and simulated components, controls and networks, under a wide variety of scenarios, to optimize the computation efforts for the obtention of the models.

The contents of this deliverable are based on the reports made by ESRs. The objective is to collect the proposals of business models provided by each ESR for making profitable the research work they conducted in the SMARTGYSUM project for achieving the WP3 objectives. To develop such business models ESRs exploited competencies acquired during the courses of the doctoral schools delivered in the frame of the SMARTGYSUM project.

The parts carried out by ESRs are reported in the following sections and identified with these topics:

- IRP05 – Energy Router for Hybrid Microgrids for efficient and robust energy and power management
- IRP06 – EV chargers, developing an active bidirectional charger able to provide anciallary services
- IRP07 – Reliability and availability of Smart Transformers for cost effective and high quality of services in the grid
- IRP08 – Real-time modelling and validation of Distributed Energy Storage Systems and Integration strategies

The developed business models, one for each activity, are reported in section 3 and detailed in the subsections indicated with BM.1, BM.2 BM.3 and BM.4 respectively.

In this section the scientific work and the context where the activities of each ESR have been carried out are described briefly.

IRP05 – Energy Router for Hybrid Microgrids for efficient and robust energy and power management

This research work has been conducted from August 2022 to July 2025, under general supervision of Chernihiv Polytechnic National University (CNTU) at premises of University of Extremadura (Spain) as the host institution and a research secondment at Gdańsk University of Technology (Poland). The overall objective was the research and development of power electronics facilities to enable efficient and robust energy and power management in microgrid environments, focusing on the realization of an Energy Router (ER) suitable for residential and small-scale applications.

The energy router prototype has been designed, assembled, and experimentally validated. It integrates all key functionalities, including single-phase AC input/output, PV and battery interfaces, and DC grid terminals, forming a 5-kW multiport converter suitable for residential or small-scale microgrid applications. The implemented topology adopts a common-ground inverter structure, ensuring safety and eliminating leakage current paths without the need for isolation, which also reduces cost and complexity.

The control system has been developed based on Flatness-Based Control (FBC) theory for the DC-link voltage, combined with a Proportional Resonant (PR) controller for the grid current regulation. The FBC approach ensures a highly stable DC-link under dynamic load variations, as demonstrated through experimental testing. Tests under grid-forming and grid-following conditions, including dynamic load steps (e.g., 59 Ω), confirmed the robustness and rapid response of the proposed control scheme. Additionally, reliability and protection aspects were addressed through analysis of grounding configurations and leakage current mitigation, in accordance with the research objectives. The use of common-ground topology has proven effective in enhancing system safety and simplifying protection design. Regarding communication capabilities, the system architecture and control framework were designed to be compatible with wireless communication interfaces for future integration into smart microgrids. While a complete implementation of the wireless communication layer was outside the primary hardware validation phase, its structure and interface points have been defined for future work.

The work progressed through three main phases:

- Preliminary phase (University of Extremadura):
- During the initial stage, the research focused on reviewing and analyzing the state-of-the-art in Energy Routers, grounding techniques, and dc-ac interlink topologies. This phase provided a comprehensive understanding of integration challenges between dc systems and the ac grid, including issues of leakage current, isolation, and safety.
- Design and simulation phase (University of Extremadura and Gdańsk University of Technology):
  The theoretical findings were followed by detailed modeling and simulation in PLECS software. The author developed and compared various converter structures, proposed a common-ground three-phase ER topology, and designed its control strategy based on flatness-based control (FBC) theory to ensure a fast and robust response under dynamic conditions.

The author visited Gdańsk University of Technology three times to perform specialized research activities:

- First visit (November–December 2023): Simulation and analysis of leakage currents, grounding configurations, and protection mechanisms at the dc–ac interface.
- Second visit (May 10 – July 10, 2024): Development and implementation of the control system using FBC theory for dynamic condition improvement.
- Third visit (April – July 2025): Assembly and experimental testing of the 5 kW ER prototype, including verification under multiple operating modes and dynamic load transitions.

Experimental validation phase (Gdańsk University of Technology):

The assembled prototype was tested under dc-mode, grid-forming, and grid-following scenarios. Extensive dynamic tests were conducted to validate the robustness of the proposed topology and control method.

Throughout the project, four conference papers and two journal articles were published, with an additional journal paper submitted, including the final experimental results. All publications acknowledge funding from the Horizon Europe programme.

The business model was initially conceived during the 5th Doctoral School event in Pärnu, Estonia, and later refined through collaboration with academic and industrial partners. The model focuses on the commercial production of a compact residential Energy Router, emphasizing cost-effective integration of renewable energy sources, dc microgrids, and conventional ac household systems.

IRP06 – EV chargers, developing an active bidirectional charger able to provide anciallary services

The research was primarily conducted at the facilities of Gdańsk University of Technology (GUT), Poland, within the research team led by Prof. Ryszard Strzelecki.

At GUT, the complete research workflow was executed — from conceptual development to the realization of a small-scale hardware prototype of the bidirectional multi-terminal EV charging station.

Parts of the work were also carried out during secondments at the University of Extremadura (UEX) in Spain, under the co-supervision of Prof. Enrique Romero-Cadaval and his research group. At UEX, the charging station simulation model was developed in PLECS and subsequently validated through hardware-in-the-loop testing using RT BOX 1.

The results of this research form the foundation of the business model, demonstrating the system's functionality, application suitability and competitiveness in the current market. Key references related to the developed system are listed in the References section.

IRP07 – Reliability and availability of Smart Transformers for cost effective and high quality of services in the grid

The work was performed between August 2022 and July 2025 under the supervision of the Chair of Power Electronics at Christian-Albrechts-Universität zu Kiel (CAU), Germany, with additional input from secondments and collaborations with both academic and industrial partners within the SMARTGYSUM project. The research was developed under the Individual Research Project (IRP) entitled "*Reliability and Availability of Smart Transformers for Cost-Effective and High-Quality Services in the Grid.*"

The core of this work focuses on the development of a Real-Time Model-Assisted Modular Multilevel Converter (MMC) Emulator. This test bench integrates an actual MMC submodule (SM) with a fully detailed real-time model of the MMC running on a real-time simulator. The hybrid setup enables safe, accurate, and flexible investigation of complex test cases such as AC/DC faults, overcurrent conditions, and submodule failures, which are difficult, expensive, or dangerous to reproduce in full-scale or even scaled-down laboratory prototypes. Moreover, the presence of real hardware in the loop makes this setup particularly valuable, as it allows the evaluation of the converter real world behaviour under conditions that closely replicate practical operating scenarios, ensuring highly realistic and reliable hardware-validation results.

The scientific background supporting this work builds upon previous and ongoing research at the Chair of Power Electronics and within the SMARTGYSUM. These studies explore converter control strategies, submodule hardware validation, and real-time simulation methods for advanced power electronic systems. The Power Electronics Laboratory at CAU, equipped with OPAL-RT real-time simulator and small-scale MMC prototype hardware, provided the experimental infrastructure necessary to validate the concept and gather representative results.

In parallel with the technical development, the business and commercialization aspects of the research were refined through a series of Horizon Results Booster (HRB) initiatives conducted between 2023 and 2025. These included Business Plan Development, Go-to-Market coaching, and Exploitation Options workshops facilitated by the META Group. Over the course of approximately 12 months, continuous technical refinement and expert feedback guided the formulation of this business model. The final outcomes and recommendations are intended to be reviewed and further developed in collaboration with CAU's Technology Transfer Office (TTO) to support future exploitation and implementation strategies.

IRP08 – Real-time modelling and validation of Distributed Energy Storage Systems and Integration strategies

The business model has been developed through the individual research work of the ESR, focusing specifically on the feasibility assessment of hydrogen applications. This scientific work was conducted over a period of six months, drawing primarily on scientific literature, technical reports and publicly available data from relevant companies and industrial stakeholders.

The research approach began with a broad investigation of potential hydrogen-use scenarios, aiming to identify the most feasible applications from a commercial perspective. This included a review of potential competitors, allowing for a clear understanding of current market possibilities and prevailing limitations within the sector. Following the technological and competitive assessment, the revenue model was developed in alignment with the identified limitations and market conditions

2. Business models

2.1. IRP05 – Energy Router for Hybrid Microgrids for efficient and robust energy and power management

Executive Summary

The proposed business model is centered on the development and potential commercialization of a residential single-cell three-phase (SC-TP) Energy Router (ER), a compact, safe, and cost-efficient hardware platform designed for next-generation smart and sustainable homes. The prototype enables direct integration of photovoltaic panels, battery storage, and AC/DC loads through a common-ground inverter structure, eliminating the need for galvanic isolation and significantly reducing both system complexity and cost. The mission of this business model is to make advanced energy routing technology accessible for residential and small-scale microgrid applications, contributing to the realization of net-zero energy buildings (NZEBs). The vision is to create a universal and modular energy hub capable of hosting any intelligent energy management algorithm in the future, thus bridging the gap between hardware innovation and digital energy services.

The key goals include:

- Advancing the prototype toward a commercially viable TRL level, ensuring compliance with safety and reliability standards.
- Demonstrating high efficiency and robustness of the ER in real dynamic operating conditions.
- Establishing the foundation for future integration with IoT-based monitoring and control systems.

Main success metrics are defined by experimental performance indicators (voltage stability, power balance, and dynamic response), scalability toward industrial design, and cost competitiveness compared to existing inverter-based systems. The strategic priorities of the business model are focused on technology validation, prototype optimization, and the exploration of commercialization pathways through academic–industrial collaboration under the Horizon Europe framework.

Value Proposition & Competitive Advantage

The proposed business model is centered on the development and commercialization of an experimentally validated prototype of a Single-Cell Three-Phase (SC-TP) Energy Router (ER). This hardware platform provides an efficient, safe, and cost-effective interlink between residential dc and ac systems, representing a breakthrough in the power electronics domain for microgrid and smart home applications.

The key value proposition lies in the unique single-cell three-phase structure, which enables access to all grid phases and phase balancing without the need for multiple conversion cells, thereby significantly reducing cost, weight, and system complexity. Additionally, the common-ground inverter topology ensures inherent safety by mitigating leakage currents and eliminating galvanic isolation, addressing one of the most critical technical challenges in dc–ac integration.

From a control perspective, the system incorporates an innovative Flatness-Based Control (FBC) method to enhance dynamic performance under transient operating conditions. Experimental results, published in peer-reviewed journals and international conference papers, have confirmed that the proposed control strategy provides fast response, high reliability, and robustness, outperforming conventional methods such as PI, PR, or sliding-mode controllers in dynamic conditions.

Beyond the hardware advantages, the prototype has been designed with a modular and communication-ready architecture, allowing future integration of intelligent energy management algorithms and wireless monitoring systems. This flexibility positions the system as a scalable and future-proof solution compatible with evolving smart-grid standards and energy community infrastructures.

In summary, the competitive advantage of the proposed solution includes:

- Simplified and cost-effective topology (single-cell three-phase configuration).
- Enhanced safety via common-ground structure and reduced leakage currents.
- Superior control dynamics based on FBC theory.
- Experimental validation confirming efficiency and reliability.
- Compatibility with future digital and communication-based EMS solutions.

The current prototype has achieved Technology Readiness Level (TRL) 5, having been successfully validated in relevant laboratory environments under various operating and dynamic conditions. The next development stage will focus on extending the system toward TRL 6–7, enabling semi-industrial demonstration and preparation for pilot commercialization in collaboration with industrial partners.

Market & Customer Segments

The primary market focus of the developed Energy Router (ER) technology lies in the renewable energy and power electronics industry, particularly targeting companies involved in solar energy systems, battery storage solutions, and power converter manufacturing. These industrial partners represent the key customers capable of integrating the ER hardware into their own product lines, enabling large-scale production and commercialization.

In the medium term, the product is also aimed at residential and small-scale microgrid applications, where the ER can operate as a compact and intelligent interlink device managing energy flows among PV panels, storage systems, and local ac/dc loads. This semi-commercial version is designed to contribute to the growing demand for efficient, safe, and flexible energy management solutions in Zero-Energy Buildings (ZEBs) and smart homes.

From a geographic perspective, the initial market entry is planned within Spain, leveraging the research infrastructure and industrial connections around the University of Extremadura, before scaling to the broader European market. Europe provides a favorable regulatory and technological environment, driven by the EU Green Deal, the rapid growth of distributed renewable generation, and the rising number of prosumers adopting dc microgrid technologies.

The prototype, validated experimentally under different operating conditions, demonstrates the potential for real-world implementation. Furthermore, given the flexible hardware architecture and integrated communication capabilities, the developed ER can in the future, support innovative energy management and digital optimization layers, aligning with the ongoing transition toward intelligent, grid-interactive energy systems.

Market Segment	Description & Target Customers	Current Pain Points / Needs	ER Competitive Advantage
Solar Energy Integrators	Companies developing residential or commercial PV systems with storage	Complexity and high cost of managing multiple energy sources	Single-Cell Three-Phase design reduces conversion stages and cost while improving efficiency
Power Electronics Manufacturers	Producers of inverters, converters, and hybrid controllers	Need for flexible hardware adaptable to ac/dc environments	Modular and scalable hardware, compatible with various EMS platforms
Residential & Microgrid Installers	Installers of hybrid ac/dc microgrids and smart homes	Lack of compact, safe, and interoperable energy routers	Experimentally validated, common-ground structure ensures safety and dc/ac interconnection
Energy Research & Development Centers	Universities, research labs, and pilot projects	Need for testbeds supporting innovative control and management algorithms	Open hardware and control platform, ready for integration with advanced EMS solutions
European Smart Grid Market	National utilities and grid operators in the EU	Integration of distributed generation and real-time grid balancing	Future-ready design allowing SEMA integration and real-time phase balancing

Channels & Customer Relationships

The commercialization strategy of the Energy Router (ER) prototype relies on a dual approach that combines academic–industrial dissemination with direct collaboration channels toward commercialization.

Channels

1. **Research and Innovation Networks**
   The ER was developed within a Horizon Europe project framework, providing direct visibility through European research networks. Participation in EU research clusters, doctoral schools, and conferences serves as the first step toward building recognition and credibility in both academic and industrial domains.

2. **Industry Collaboration and Technology Transfer Offices**
   Cooperation with solar energy companies, inverter manufacturers, and grid-technology developers is planned through joint R&D projects and technology transfer agreements.
   The University of Extremadura and Gdańsk University of Technology will act as facilitators for collaboration, prototyping, and patenting processes.
3. **Professional Exhibitions and Technical Workshops**
   Presentation of the experimentally validated prototype at **energy and smart grid exhibitions** (e.g., Intersolar Europe, Smart Energy Expo) will enable direct contact with potential adopters and investors.
   Technical workshops and demonstration sessions will be organized to showcase the system's **flexibility**, **control performance**, and **modular structure**.
4. **Digital and Academic Dissemination**
   Publications in high-impact journals and open-access repositories serve as a continuous visibility channel.
   The system's modular control infrastructure allows the creation of demo videos and simulation platforms that can be shared with R&D centers and companies through institutional websites and LinkedIn networks.

Customer Relationships

1. **Collaborative and Long-Term Partnerships**
   Early customers (mainly universities, R&D centers, and innovative SMEs) will be engaged through joint pilot programs and customized prototype adaptations.
   These relationships are based on knowledge exchange, technical support, and co-development rather than standard sales.
2. **Technical Support and Co-Design Services**
   The ER team will provide technical documentation, training, and integration support for customers who aim to embed the hardware into larger hybrid energy systems.
   Feedback loops from early adopters will directly contribute to the next design iterations.
3. **Future Customer Retention Strategy**
   Once TRL ≥ 6 is achieved, customer retention will rely on offering:
   - Firmware and software updates for advanced energy management integration.
   - Optional consultancy for system optimization and compliance with grid codes.
   - Continuous access to the ER research community for innovation sharing.

Revenue Model & Cost Structure

Revenue Model

At the current stage (TRL 5), the Energy Router (ER) functions primarily as a research-driven prototype. However, its modular design and validated experimental performance establish a strong foundation for future commercialization.
The revenue generation pathway is envisioned in three main phases:

Phase	**Stage Description**	**Revenue Sources**	**Target Clients / Partners**
Phase 1 – Research & Prototyping (2022–2025)	Horizon Europe–funded R&D phase; design, assembly, and experimental validation of the prototype	- EU project funding - Research collaborations - Conference presentations and workshops	Universities, research groups, public R&D projects
Phase 2 – Semi-commercial & Pilot Deployment (2025–2026)	Limited pilot production for residential and microgrid demonstrators	- Prototype sales - Technical consultancy - Licensing of control algorithms and topology	Solar and storage companies, inverter manufacturers
Phase 3 – Full Commercial Expansion (Post-2026)	Mass production and deployment in the EU market	- Direct hardware sales - Licensing agreements - Subscription services for smart control - Training programs	Renewable energy providers, residential installers, SMEs in power electronics

Pricing Strategy

While the current prototype is research-oriented, cost analysis shows that the proposed ER can achieve lower system costs compared to conventional multi-stage inverters. This is primarily due to:

- The SC-TP topology, which reduces hardware complexity by eliminatingtwo extra conversion stages.
- The common-ground structure, removing isolation components and simplifying protection.

In future commercialization, a value-based pricing strategy will be applied - emphasizing efficiency, compactness, and system reliability as key differentiators.

The project’s funding through Horizon Europe ensured the financial feasibility of the research and prototype development phase. As the experimentally validated prototype demonstrates robust operation and scalability, the business model naturally transitions from grant-supported research to commercially viable hardware production**,** with future potential for integration of intelligent energy management services.

This structured evolution ensures a sustainable transition from a publicly funded R&D project to a self-sustaining commercial venture. The experimentally validated prototype (TRL 5) serves as a tangible bridge between the scientific phase and market-oriented development, supported by published research results and proven control performance under dynamic conditions.

Cost Structure

Category	Description	Current Cost Drivers	Optimization Approach
Hardware components	Semiconductors, magnetics, sensors, control board, mechanical parts	High – due to limited prototype scale	Bulk purchasing, design standardization
Testing & validation	Experimental verification, measurement equipment, TRL progression	Moderate	Shared use of university labs and joint facilities
Software & control development	Flatness-based control design, firmware, wireless interface	Moderate	Modular software and reusability across systems
Assembly & logistics	Prototype assembly, wiring, thermal design	Low–Moderate	Outsourcing assembly to specialized SMEs
Certification & compliance	CE/IEC standards for grid connection	High (in commercialization phase)	Early-stage compliance planning and simulation-based pre-certification

Financial Flow Overview

Phase	Estimated TRL	Main Funding Source	Revenue Type	Cost Intensity
Phase 1	TRL 4–5	Horizon Europe Grant	Research-based	Medium
Phase 2	TRL 6–7	Institutional and Industrial Partnerships	Prototype sales & Licensing	High
Phase 3	TRL 8–9	Commercial Partners & Investors	Product sales & Subscriptions	Moderate

Key Resources & Activities

The development of the proposed energy router prototype has been carried out under the supervision of the project’s academic supervisors and the researcher. The work utilized the laboratory facilities of the University of Extremadura (Spain) and the Gdańsk University of Technology (Poland). Experimental validation was performed using advanced laboratory equipment, including bidirectional power supplies used as battery and PV emulators, precision power analyzers, programmable loads, and data acquisition systems.

Key resources supporting this development include:

- **Human resources:** The PhD researcher and academic supervisors specializing in power electronics and energy management systems.
- **Physical resources:** Laboratory setups in both universities, equipped with converters, control platforms, and real-time testing infrastructure.

- **Intellectual resources:** Simulation models developed in PLECS and MATLAB/Simulink, along with the experimental prototype validated under real operating conditions.

The core activities of the project comprise:

1. Design and development of a 5 kW single-cell three-phase (SC-TP) energy router, integrating PV, BSS, ac/dc loads, and grid interfaces.
2. Assembly and testing of the prototype using both open-loop and closed-loop configurations, including grid-forming and grid-following operation modes.
3. Implementation and evaluation of the flatness-based control (FBC) to ensure robust dc-link performance in dynamic conditions.
4. Validation using existing energy management platforms, demonstrating interoperability and readiness for integration with digital EMS solutions.

In future commercialization stages, small and medium-sized enterprises (SMEs) are expected to participate in hardware production and pilot deployment phases, leveraging the existing prototype design and control framework developed within this project.

Key Partnerships

The development of the proposed energy router was supported through collaborative research within the Horizon Europe framework, involving strong partnerships between academia and industry. The main academic partners include:

- University of Extremadura (Spain): Lead host institution, responsible for the system design, preliminary assembly, and initial prototype validation.
- Gdańsk University of Technology (Poland): Focused on advanced simulations, grounding and protection analysis, and final-stage experimental testing under various operating and dynamic conditions.

These collaborations allowed for a seamless transition from simulation and modeling to hardware implementation, leveraging the complementary laboratory infrastructures of both institutions. Bidirectional power supplies were used as battery and PV emulators, ensuring realistic testing scenarios for multi-port energy management.

In the next development phases, the project envisions active collaboration with small and medium-sized enterprises (SMEs) specializing in power electronics manufacturing, energy storage systems, and converter production. These industrial partners will be essential for:

- Scaling up hardware production and improving manufacturability.
- Standardizing modules for residential and microgrid applications.
- Ensuring cost-effective and high-efficiency designs suitable for mass production.

Furthermore, future partnerships are expected with companies and research groups developing Energy Management Systems (EMS) and smart home automation platforms. Given that the hardware infrastructure is already compatible with advanced digital interfaces, integrating innovative EMS solutions will enable smart energy scheduling, wireless monitoring, and predictive control in residential and microgrid environments.

This partnership structure ensures a balanced ecosystem combining academic innovation, industrial expertise, and digital intelligence, paving the way from a validated prototype (TRL 5) to a scalable, commercially viable energy router platform.

Sustainability & Scalability

The proposed Single-Cell Three-Phase Energy Router (SC-TP ER) was designed with long-term scalability and sustainability in mind. Its modular architecture allows straightforward adaptation for different power levels, making it suitable for residential, microgrid, and small industrial applications.

From a sustainability perspective, the solution directly supports the transition toward Zero-Energy Buildings (ZEBs) and renewable-based smart grids, aligning with the European Green Deal and Horizon Europe objectives. By efficiently integrating renewable sources such as photovoltaic panels and battery storage, the system minimizes conversion losses and reduces dependency on fossil-based energy. The common-ground topology further contributes to environmental sustainability by lowering material usage through the elimination of bulky isolation transformers and reducing system weight and cost.

In terms of scalability, the design is inherently adaptable:

- The hardware platform can be scaled up by paralleling converter modules for higher power levels.
- The embedded control structure is flexible and can incorporate advanced energy management algorithms and wireless communication protocols without hardware modification.
- The validated prototype (TRL 5) serves as a foundation for moving toward semi-commercial pilot production (TRL 6–7) through collaboration with SMEs.

Additionally, the system provides a solid base for future integration with cloud-based energy management, IoT connectivity, and smart home ecosystems. This adaptability ensures relevance in evolving energy markets that demand intelligent, distributed, and user-interactive power management solutions.

By emphasizing modularity, renewable integration, and software compatibility, the proposed ER ensures long-term sustainability not only in energy efficiency but also in its potential for technological evolution and market scalability.

Financial Overview (Optional)

At the current stage (TRL 5), the Single-Cell Three-Phase Energy Router (SC-TP ER) remains a research-oriented prototype developed under the Horizon Europe funding framework, which fully supported the R&D phase, laboratory testing, and mobility activities between the University of Extremadura (Spain) and Gdańsk University of Technology (Poland)**.**

Funding and Cost Structure

The project’s financial resources have primarily covered:

- Hardware development and laboratory materials, including power converters, control boards, and safety components.
- Testing equipment and facilities, utilizing existing university laboratories and shared resources.
- Researcher mobility and collaboration costs, through the Horizon program.

Future cost structures will depend on the transition to semi-commercialization, which includes:

- Manufacturing and assembly of small pilot batches (with SMEs).
- Integration of embedded wireless communication and software-based energy management systems.

- Certification and compliance testing according to EU electrical safety and EMC standards.

Revenue and Market Potential

The initial revenue model is based on direct hardware sales of modular ER units for residential and microgrid applications. Additional revenue streams are envisioned in:

- Licensing of the design and control algorithms to inverter and power-electronics manufacturers.
- Collaborative projects with renewable energy system integrators for pilot deployments.
- Future subscription-based services for cloud and energy management platforms once the communication layer is fully developed.

Funding Requirements and Future Outlook

To advance from TRL 5 to TRL 7, an estimated €200,000–€300,000 would be required for pilot-scale production, certification, and extended field validation. Funding is expected to be sought through European innovation grants, public-private partnerships, and potential collaborations with SMEs in renewable technology manufacturing.

The long-term financial vision aims for sustainable growth through low-cost, scalable production, leveraging the system's modular design and alignment with EU green energy policies to attract both public funding and industrial partners.

2.2. IRP06 – EV chargers, developing an active bidirectional charger able to provide ancillary services

Executive Summary

This business model targets the deployment of multiterminal fast EV charging stations using a Current-Fed Multi-Active Bridge (CF-MAB) converter connected to low-voltage DC (LV DC) traction grids (trams/trolleybuses). The solution is designed for high efficiency (>96%), scalable architecture and reduced installation costs by utilizing existing DC traction infrastructure.

- **Mission:** Accelerate urban EV adoption by providing cost-effective, high-power, scalable fast-charging solutions.
- **Vision:** Enable large-scale integration of EV chargers into urban traction networks while providing ancillary services such as voltage stabilization and reactive power compensation for the LV DC grids.
- **Goals:** Deploy multi-port stations (3×50 kW EV ports + 250 kW BES), achieve energy efficiency >96%, reduce installation costs by ~25% compared to conventional MV AC-connected chargers and scale to major European cities by 2030.
- **Success Metrics:** Number of deployed stations, average utilization rate, reduction in installation cost, efficiency, regulatory approvals obtained.

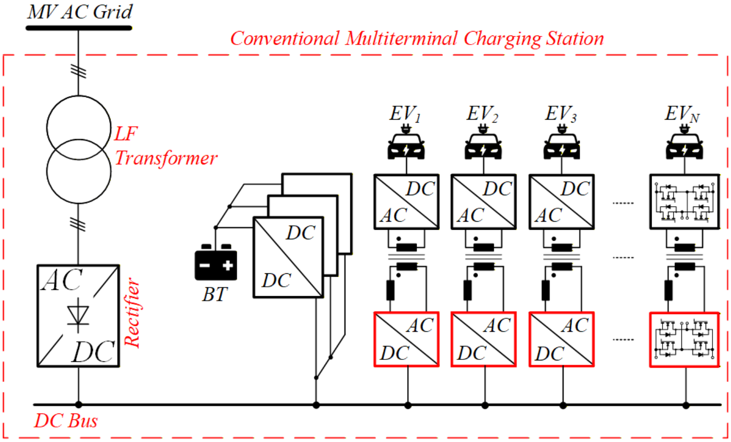


Fig. 1 Existing solution

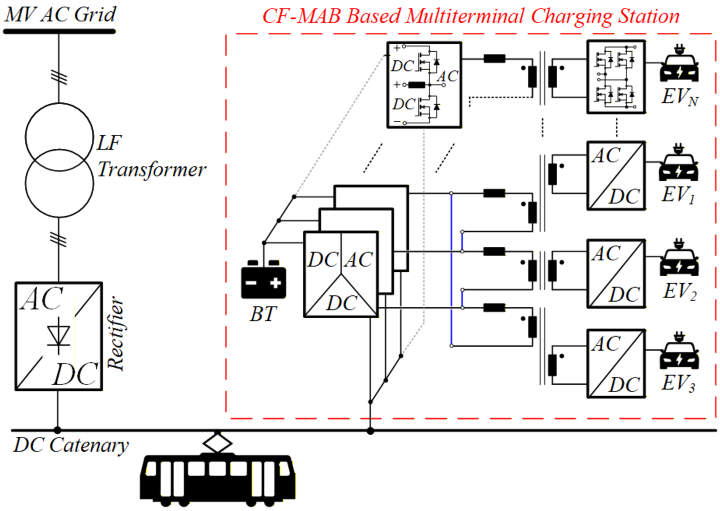
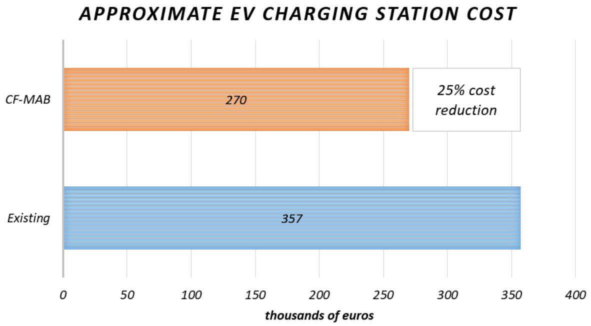


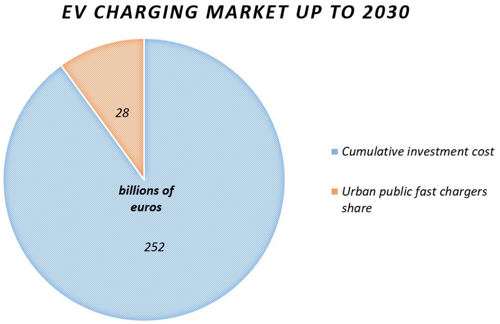
Fig. 2 Proposed Solution

Value Proposition & Competitive Advantage

- **Problem Addressed:** Rapid EV adoption demands high-power fast chargers. Existing solutions require independent converters per EV and costly MV AC infrastructure. LV DC traction grids remain underutilized for EV charging.
- **Proposed Solution:** Multiport CF-MAB converter connects multiple EVs and BES to LV DC traction grid, allowing independent charging. Uses SiC devices, high-frequency isolation and scalable port count.
- **Differentiation:**
    - ~25% reduction in silicon area due to shared switches.
    - Eliminates AC-DC rectifier and low-frequency transformer.
    - Enables bidirectional V2G operation.

- **Customer Advantage:** Reduced CAPEX (~€270k for 3 EV ports + BES in comparison to existing solution with ~€357k), scalable deployment and compatibility with existing urban infrastructure
-





Market & Customer Segments

- **Target Customers:** Utilities, public transport authorities, government agencies, private integrators responding to tenders.
- **Customer Needs:** Cost-efficient high-power fast chargers, modular deployment, V2G capability, compliance with standards (IEC 61851-23, ISO 15118-20), reduced permitting hurdles.
- **Market Overview:** European EV fast-charging infrastructure is growing rapidly; >1.3 million new points in 2024 globally, ~60% are slow chargers. Studies estimate that cumulative investment cost necessary to install charging points, enhance power grid and expand renewable energy capacity for EV charging is 280 billion euros by 2030 year in Europe and UK. Estimating 10% of that infrastructure is urban fast chargers, located close to traction grids, market size is 28 billion euros
- **Competitors:** ABB, Siemens, Schneider Electric, Ingeteam, Heliox.
- **Our technical edge:** multiport CF-MAB with lower installation cost, high efficiency and ancillary service potential.

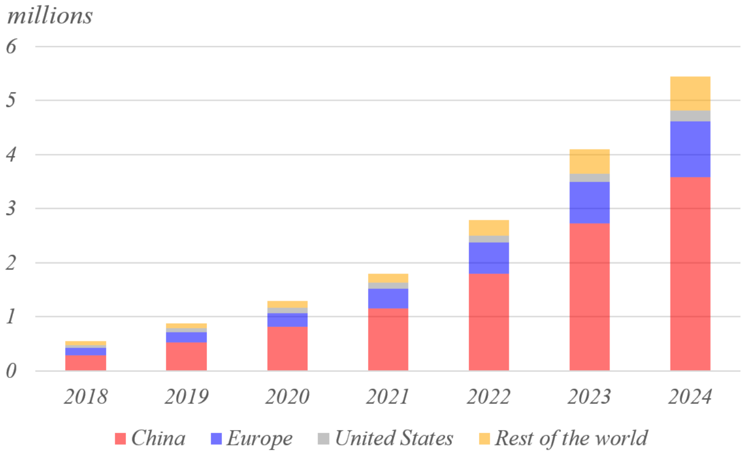


Fig. 3 Global stock of public charging points by region

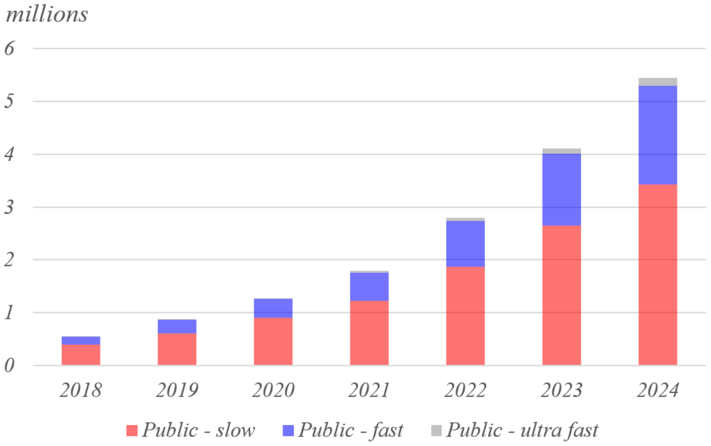


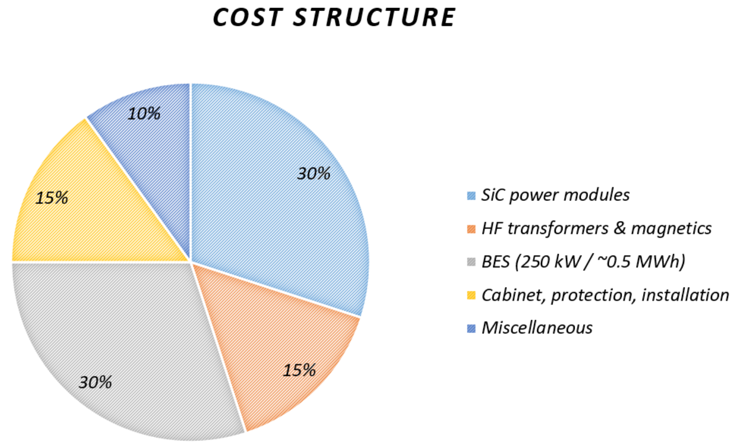
Fig. 4 Share of public fast chargers

Channels & Customer Relationships

- **Channels:** Direct tender responses to municipalities and utilities; strategic partnerships with transport authorities; technical workshops and demonstrations.
- **Customer Relationships:**
  - Technical consulting and co-design support.
  - Automated monitoring and remote management platform.
  - On-site installation support and after-sales service.
- **Retention Strategy:** Performance guarantees, regular firmware updates for CF-MAB converters, predictive maintenance and optional BES upgrade modules.

Revenue Model & Cost Structure

- **Revenue Source:** Direct sale of multiterminal EV fast-charging stations; additional revenue from maintenance contracts.
- **Pricing Strategy:** Competitive tender pricing (~€270k per 3 EV + BES system).
- **Cost Structure:**
    - SiC power modules & drivers: ~30% of BOM.
    - HF transformer & magnetics: ~15% of BOM.
    - BES (250 kW / ~0.5 MWh): ~30%.
    - Cabinet, protection, installation: ~15%.
    - Miscellaneous: ~10%.
    - Expected efficiency losses <4%, resulting in <16 kW for a 400 kW station.



Resources & Activities

- **Resources:**
    - Human: Power electronics engineers, control software developers, installation/commissioning teams.
    - Physical: Production facilities, testing labs, urban deployment sites.
    - Intellectual: CF-MAB topology patents, control algorithms, design documentation.
    - Financial: Working capital for prototypes, initial production batch.
- **Activities:** Converter design, system integration, HV/LV testing, tender management, deployment, operation monitoring.

Key Partnerships

- Strategic partnerships with city transport authorities and utilities.
- Component suppliers for SiC modules, inductors, transformers, and BES cells.

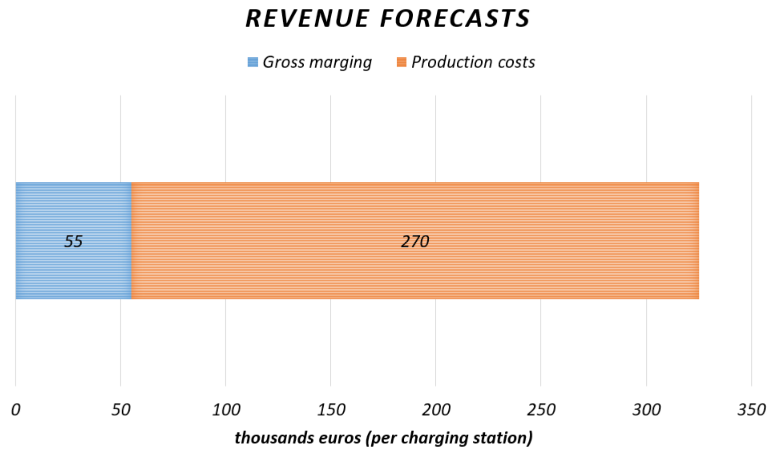
- Research institutions for optimization of control algorithms and grid interaction studies.
- Outsourcing options: manufacturing of cabinets, assembly of magnetics or modular BES integration.

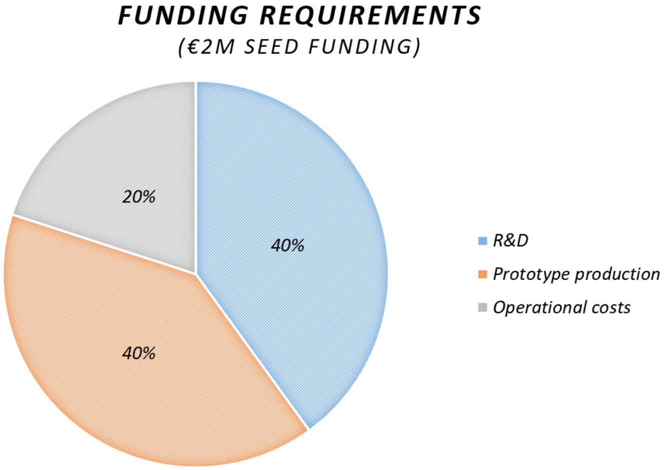
Sustainability & Scalability

- **Growth Plan:** Start with urban centers in Poland, scale to European cities with dense tram/trolleybus networks. Modular CF-MAB allows easy scaling from 3 to 5 EV ports.
- **Environmental Responsibility:** Supports renewable integration via DC traction grids; reduces need for new AC transformers and substations.
- **Scalability:** Converter architecture allows additional ports with minimal incremental cost (~€25k per 50 kW EV port). Efficiency remains >96% with increased ports and HF magnetics scale ~0.8× per new port.

Financial Overview (Optional)

- **Revenue Forecasts:** For initial deployment of 20 stations (3×50 kW + 250 kW BES each):
    - Revenue: 20 × €325k ~ €6.5M.
    - Gross margin ~15–20%.
- **Key Expense Assumptions:** BOM, installation, R&D amortization.
- **Funding Requirements:** €2M seed funding to cover initial prototypes and development, testing and tender participation. Use of funds: 40% R&D, 40% prototype production, 20% operational costs.





2.3. Business model (BM.3) presentation

IRP07 – Reliability and availability of Smart Transformers for cost effective and high quality of services in the grid

Executive Summary

- ***Business Idea:***
  Develop and commercialize a real-time model-assisted test bench for modular multilevel converters (MMCs), which can be used in Smart Transformer applications. This platform allows safe, cost-effective, full-dynamic testing of converter submodules under realistic operating and fault conditions without requiring a complete high-power prototype.
- ***Mission:***
  To enhance the safety, reliability, and performance of future Smart Transformers and renewables-based power grids through innovative hybrid testing methodologies that bridge the gap between simulation and hardware validation.
- ***Vision:***
  To become a leading provider of integrated real-time testing and validation solutions for power conversion systems, serving universities, R&D centers, and manufacturers worldwide.
- ***Strategic Goals:***
  - Validate and standardize the hybrid MMC test bench by 2026.
  - Establish initial collaborations with research institutions and converter manufacturers (2025–2026).
  - If possible, secure EU or national funding to bring the technology from proof-of-concept (TRL 5–6) to market-ready system (TRL 8–9).
- ***Key Success Metrics:***
  - Number of contracts or collaborations with early adopters.
  - Reduction in test costs and risks for clients.
  - IP licensing revenues or product sales.

  - Recognition as a reference platform for hybrid real-time converter testing.

Value Proposition & Competitive Advantage

- ***Problem:***
  Full-scale converter testing is expensive, risky, and time-consuming. Simulation-only studies fail to capture all physical behaviours (electromagnetic, electrothermal, and failure dynamics) and therefore cannot reliably reproduce the complexity of real operating scenarios, especially under disturbed or faulty conditions.
- ***Solution:***
- A hybrid test bench combining real-time simulation and real submodule hardware, enabling detailed converter behaviour analysis, including fault and transient conditions, without endangering full systems.
- ***Unique Selling Proposition (USP):***
  - Risk-free failure scenario testing (AC/DC faults, over currents, internal SM failures).
  - Real-time integration of hardware and simulated environment.
  - Reduced cost and time compared to full-scale high-voltage prototypes.
  - Scalability: easily adaptable to different converter topologies or voltage levels.
- ***Differentiation:***
- Existing real-time simulator providers (e.g., OPAL-RT) do not offer integrated physical submodule interfacing. This hybrid physical-virtual setup offers a unique competitive edge bridging industrial validation and academic research.

Market & Customer Segments

- **Primary Markets:**
  Converter and Solid State Transformer manufacturers, research labs, universities, and real-time simulator providers.
- **Early Adopters:**
  Research institutes working on MMC (joint testing or contract services).
- **Trends:**
  Expansion of hybrid AC/DC grids; growth in hardware-in-the-loop (HIL) demand; global shift to high-efficiency converter testing.
- **Customer Needs:**
  Greater safety, reduced costs, faster prototyping, access to realistic case testing.

Channels & Customer Relationships

- **Channels:**
  Direct B2B outreach, joint research projects, technical conferences (ECCE, ISIE), academic publications, licensing to simulator firms.
- **Relationship Type:**
  Initially collaborative (R&D partnerships); evolving to structured B2B sales/support.

- **Retention & Support:**
  Software updates, modular hardware upgrades, ongoing service agreements.

Revenue Model & Cost Structure

- **Revenue Sources** ➔ Contract-based testing services, modular test-bench sales, IP licensing.
- **Pricing** ➔ Manufacturing ≈ €7000 / unit → sale ≈ €10 000 / unit (≈ 30 % margin).
- **Costs** ➔ Hardware components, simulator units, R&D personnel, IP/legal, maintenance.
- **Optimization** ➔ Modular design, co-funded grants, lean production chain.

Key Resources & Activities

- **Resources:**
  - Skilled researchers and engineers (CAU ESRs).
  - Real-time simulators & MMC hardware.
  - Grants and institutional funding.
- **Core Activities:**
  Design & validation of prototype, market testing, IP management, dissemination, and training.

Key Partnerships

- Technology Transfer Office (IP strategy and licensing).
- Real-Time Simulator Companies (product integration partners).
- Research Institutes / Universities (co-development and benchmarking).
- Industrial Stakeholders (field validation and feedback).

Sustainability & Scalability

- **Growth Plan:**
  Extend hybrid methodology to DC-DC and EV-drive converters.
- **Sustainability:**
  Reduces energy and material waste, aligns with EU Green goals.
- **Scalability:**
  Modular platform replicable across laboratories; compatible with commercial real-time systems.

Financial Overview (Optional)

Unit cost	€7 000	Materials + labour
Sale price	€10 000	Target retail
Target sales (3 yrs)	10–20 units	Research institutions
Revenue (3 yrs)	€100 000 – €200 000	Conservative
Funding needs	€150 000 – €250 000	For scale-up & IP
Main sources	Horizon Europe / Nat. grants / private investors	

2.4. IRP08 – Real-time modelling and validation of Distributed Energy Storage Systems and Integration strategies

Executive Summary

- **Brief overview of the business idea.**
  The business idea is a company that designs and delivers customized energy solutions for off-grid communities, combining renewable energy generation with hydrogen-based storage to reduce electricity costs and minimize emissions.
- **Mission, vision, and key goals.**
  The company's mission is to provide off-grid communities with sustainable, cost-effective, and reliable energy solutions. Its vision is to become a leading provider of innovative energy systems for off-grid and remote communities worldwide, supporting a global transition to clean and resilient energy networks. To achieve this, the company aims to build a robust network of partnerships worldwide and to develop its own design tools and modular solutions to optimize the process.
- **Main success metrics and strategic priorities.**
  Key performance indicators include revenue growth and profit margins, number of installed systems, reduction in electricity costs and emissions for client communities and customer satisfaction. Operational efficiency, such as time and cost required for design and installation, will also be monitored. Strategic priorities focus on expanding the company's presence in off-grid communities and building strong local and international partnerships.

Value Proposition & Competitive Advantage

- **What problem solve the proposed solution**
  An off-grid microgrid, which relies exclusively on renewables, must be able to store for long time the energy produced during high-energy-production season. Batteries are not suitable for this purpose due to self-discharge and degradation phenomena. Conversely, the use of traditional generators based on fossil fuels entails a high environmental impact, so it is no longer sustainable.
- **Unique solution or offering**
  For long-term storage applications in off-grid systems, hydrogen offers an effective way to store large amounts of energy from renewable sources, whose production is intermittent. Its adoption reduces emissions compared to traditional fossil fuel generators and requires fewer critical materials than battery-only solutions. Hydrogen-based storage ensures that renewable energy is available year-round with minimal environmental impact, representing a superior economic and ecological investment compared to conventional fossil fuel-based generation.
- **Why customers will choose this solution — differentiation, innovation, or entry barriers**
  Hydrogen storage systems have proven to be a reliable and cost-effective alternative to traditional energy generators; however, their adoption to store energy is still limited. The proposed technology is innovative, so on one hand it entails several benefits in terms of performances, offering enhanced efficiency, scalability and environmental sustainability. On the other hand,

some skepticism may arise by due to the limited familiarity with hydrogen-based storage, especially concerning safety issues. This, in particular, may constitute the main barrier to market adoption.

Market & Customer Segments

- **Target markets and customer profiles**
  The target market consists of all the off-grid communities worldwide, which are geographically located in areas where connection to the main grid is either technically unfeasible or not economically convenient, for example for islands or in remote rural regions. The proposed solution specifically targets the existing communities which currently rely on fossil fuels to produce electricity. The potential customer, the community authority, should have interest in addressing environmental problems.
- **Customer needs, behaviours, and pain points**
  The typical community authority customer needs to reduce the cost of electricity in the community and the emissions associated with energy generation. Ideally, it already utilizes the renewable sources for energy production and aims to rely only in clean energy. The community should have enough financial capacity, as upfront capital investment for hydrogen-based systems can be significant.
- **Industry overview, market trends, and competitive positioning**
  The hydrogen-based off-grid storage market is still emerging, with a few companies offering solutions for remote communities and industrial sites. Current trends indicate growing interest in renewable-based microgrids, particularly in regions where connection to the main grid is challenging. Many existing companies focus primarily on supplying equipment. For example, HPS Home Power Solutions’ Picea system is a hydrogen-based, all-season electricity storage unit for buildings: it integrates a battery, an electrolyser, a hydrogen storage tank, and a fuel cell to reliably supply electricity and heat year-round. Some other companies provide full design and installation of the energy system. A notable case is Symbase Hydrogen Energy, which offers fully equipped, modular off-grid hydrogen fuel cell installations in containerized form. However, many of these providers still primarily target medium-to-large installations or industrial clients, leaving smaller off-grid communities underserved. The proposed solution differentiates itself by focusing specifically on these smaller communities, offering a modular and scalable plant design. Additionally, it fosters close collaboration with customers to ensure they acquire the right knowledge to operate, maintain, and monitor the system independently.

Channels & Customer Relationships

- **How you reach and deliver value to customers (sales and marketing channels)**
  The primary channel for reaching customers is direct engagement with government and community authorities, initiating contact with potential communities personally. Moreover, a dedicated website provides information for other prospective customers, showcasing case studies and completed projects. Marketing efforts emphasize the environmental, economic and

technical benefits of the hydrogen storage system, as well as the tailored design and support.

- **Type of customer relationships (personal, automated, self-service)**
  Customer relationships are personal and consultative, combining direct interactions for key discussions with online channels for ongoing communication. Some digital monitoring tools are available too, to enable remote system management and provide continuous support, ensuring quick response to any operational issues.
- **Retention, loyalty, and customer support strategies**
  Retention and loyalty are fostered by continuous technical support and training programs for local operators, ensuring sustainable use of the system. However, given the long-term investment and the specialized nature of the technology, in this kind of business customer retention is less critical and once a community has chosen the operator and installed the system, it is unlikely to switch providers.

Revenue Model & Cost Structure

- **Revenue sources and monetization model (sales, subscriptions, commissions, etc.)**
  The main sources of revenue can be categorized into short-term payments and long-term payments. Short-term payments cover the construction and equipment costs, which are incurred at the beginning of the project and can be structured into multiple instalments according to the customer's financial capacity and needs. Long-term payments correspond to system design and operations and maintenance (O&M) costs, which are distributed over the lifetime of the plant, with pricing that may vary over time depending on service requirements and system state.
- **Pricing strategy**
  The capital investment for this type of plant can be significant, so short-term payments are set at the minimum feasible level to cover the first costs, with a small profit margin. Subsequent payments related to system design and operations and maintenance (O&M) are structured as follows:
  - Fixed component to cover basic expenses.
  - Variable component proportional to the savings generated, to enhance economic attractiveness.
  - Small variable component covering extraordinary activities, if they occur.
- **Major cost drivers and cost optimization approach**
  The main cost drivers are construction and equipment costs, system design and O&M. Construction and equipment can be optimized thanks to strategic partnerships with devices suppliers of hydrogen system components as well as through special agreements with local providers for renewable energy technologies. Cost efficiency in system design is achieved by applying standardized approaches based on modular configurations, which allow for scalable and replicable solutions across different communities. O&M costs are minimized through training programs for local operators, enabling them to manage and maintain the systems effectively and reducing reliance on external technical support.

Key Resources & Activities

- **Core resources (human, physical, intellectual, financial)**

  The core resources required are:
  - The human resources comprise several teams, according to their expertise. The main teams are the design and technic team, the construction team and administration team. In addition, complementary teams, such as the training team and the R&D team, can be established at a later stage
  - Physical resources include office spaces for design and coordination activities, along with dedicated areas to build and test specific system configurations when required and to eventually train new personnel.
  - Intellectual resources involve expertise in energy and electrical engineering, plant design and legal and administrative knowledge for contract development and regulatory compliance. Strong project management and coordination skills are also essential to manage complex installations in remote areas.
  - Financial resources must be sufficient to cover startup, personnel and working spaces. The initial revenues are reinvested to scale up operations and expand service capabilities.
- **Main business operations that create and deliver value (production, marketing, R&D, service)**

  Value is created and delivered through the design, construction and maintenance of off-grid hydrogen storage systems tailored to each community's needs. Core operations include system engineering, system construction and R&D, aimed at developing structured procedures and digital tools to simplify and accelerate the design process. Marketing focuses on demonstrating the environmental and economic benefits of the technology, while ongoing technical support, training programs and remote monitoring.

Key Partnerships

- **Strategic partners, suppliers, or distributors**

  Strategic partners include providers of renewable energy generation technologies, particularly local suppliers, to optimize costs and facilitate installation. Suppliers of hydrogen technologies are also crucial, as these solutions are relatively new and maintaining competitive pricing is essential. Additionally, partnerships with software providers are important for designing and monitoring tools of the plants.
- **Outsourcing or alliances that reduce risk or cost**

  Equipment manufacturing, components supply and software tools are outsourced to specialized companies, ensuring devices availability without the need for in-house production facilities. Software tools for system design, monitoring, and predictive maintenance are also provided through partnerships with specialized providers, eliminating the need to develop them internally. Alliances with local renewable energy developers and producers, research institutions allow the company to share technical expertise and lower installation and logistics costs.

Sustainability & Scalability

- **Long-term growth and expansion plans**

The company's growth strategy is gradual. It will begin by offering consulting and design services to build expertise and customer trust. As capabilities expand, activities will expand to include the full construction and commissioning of off-grid hydrogen storage plants, as well as R&D and dedicated training programs initiatives. it could develop proprietary software tools for design, control, and monitoring, which could eventually be offered commercially. Over time, key production activities, such as the manufacturing of components or devices, may be progressively integrated into the company to reduce dependence on external suppliers.

- **Environmental or social responsibility initiatives (if relevant)**
  The company is committed to minimizing its environmental impact and promoting sustainable development. Although the hydrogen-based systems are designed to operate with zero emissions during use, residual emissions related to plant construction and logistics can be offset through targeted initiatives. In particular, the company plans to collaborate with specialized environmental organizations to effectively neutralize the carbon impact associated with each installation. In addition, training programs will promote knowledge transfer within the community and partnerships with local suppliers will foster local economy.
- **How the model adapts as the business scales**
  As the business scales and internal and device costs decline, the model will extend its solutions to other microgrid configurations, including grid-connected systems, and can be expanded to industrial applications, enabling fully integrated hydrogen-based energy systems in factories that already utilize hydrogen for industrial processes. Over time, the gained knowledge may also be applied to systems that do not involve hydrogen use.

3. Conclusions

Overall, the proposed business models are in line with what was expected and large part of activities have been done. Also accounting that some of ESRs already concluded their three years of fellowship.
In the following a summary for the four specific topics.

IRP05 – Energy Router for Hybrid Microgrids for efficient and robust energy and power management

The conducted research and development activities have led to the successful design, modeling, and experimental validation of a novel Single-Cell Three-Phase Energy Router (SC-TP ER) — an advanced power-electronic interface enabling efficient and safe energy exchange between residential DC networks and the AC grid. Through a systematic approach, the project has progressed from conceptual studies to a validated hardware prototype (TRL 5), tested under various static and dynamic operating conditions.

The scientific contributions include the introduction of a new ER topology that reduces system complexity and cost by eliminating redundant conversion cells, as well as novel insights into grounding, leakage current behavior, and safe connection schemes between isolated DC systems and the AC grid. Moreover, the application of Flatness-Based

Control (FBC) demonstrated significant improvement in dynamic response **and** robustness compared to conventional methods.

The project's experimental validation confirmed the practicality and reliability of the proposed architecture, using shared laboratory facilities in the University of Extremadura (Spain) and Gdańsk University of Technology (Poland).

The collaboration between the two institutions enabled complementary expertise, from initial assembly and open-loop testing to final implementation and performance evaluation under real-world scenarios.

From the business perspective, the developed prototype represents a promising foundation for a scalable and sustainable product aimed at solar energy companies, energy storage providers, and power electronics manufacturers. The hardware-centric design allows future integration of innovative software-based energy management systems, enabling the Energy Router to evolve into a multifunctional, intelligent interface for residential and microgrid applications.

Overall, the project outcomes contribute both to the academic advancement of power electronic interface technologies and to the European vision of smart, sustainable, and decentralized energy systems. The next phase will focus on advancing the TRL level through pilot production with SME partners, system certification, and the exploration of commercialization pathways supported by EU innovation frameworks.

IRP06 – EV chargers, developing an active bidirectional charger able to provide anciallary services

The CF-MAB based fast-charging architecture offers a decisive technical and economic advantage in the rapidly expanding EV infrastructure sector. By consolidating multiple EV outputs and a high-power BES port into a single current-fed multi-active-bridge converter, the system achieves substantial reductions in silicon area (~25%), magnetics volume (~20–25%) and total installation cost (~20–35%) relative to conventional multi-converter designs. These gains are enabled by the inherent strengths of the CF-MAB topology—shared power paths, high-frequency isolation, efficient current regulation and scalable multiport operation, while maintaining excellent performance, with system efficiency expected to exceed 96% in real-world operating conditions.

The business plan accompanying this technology is equally strong. It aligns precisely with market needs in urban environments: lower CAPEX, compatibility with existing LV DC traction grids and integrated BES support for peak shaving, continuity of service and future V2G functionality. The financial model is supported by realistic BOM assumptions, competitive tender pricing and healthy target margins demonstrates a commercially sustainable path to early deployments and subsequent scale-up across European cities.

In summary, the CF-MAB solution represents far more than an incremental improvement in converter design. It is a platform that enables a new generation of modular, high-efficiency, cost-optimized fast-charging stations. The strategy laid out in this plan provides a clear, actionable roadmap for transitioning the concept from validated research into a market-ready product with strong long-term growth potential.

IRP07 – Reliability and availability of Smart Transformers for cost effective and high quality of services in the grid

The conducted research and development activities have led to the development of a real-time model-assisted test bench for modular multilevel converters (MMCs), which can be used in Smart Transformer applications. This platform allows safe, cost-effective, full-dynamic testing of converter submodules under realistic operating and fault conditions without requiring a complete high-power prototype. A possible commercialization of this platform allows to enhance the safety, reliability, and performance of future Smart Transformers and renewables-based power grids through innovative hybrid testing methodologies that bridge the gap between simulation and hardware validation. The proposed business model is focused on using the research results to become a leading provider of integrated real-time testing and validation solutions for power conversion systems, serving universities, R&D centers, and manufacturers worldwide.

IRP08 – Real-time modelling and validation of Distributed Energy Storage Systems and Integration strategies

The proposed business offers an innovative solution to the energy challenges faced by off-grid communities worldwide. By integrating renewable energy generation with hydrogen-based storage, the company provides an approach that is both environmentally sustainable and economically viable, ensuring year-round energy availability while minimizing emissions and reducing dependence on fossil fuels. This dual focus on clean generation and efficient long-term storage directly addresses one of the most critical limitations of renewable-based microgrids: the need for clean, reliable, long-duration energy storage.

Unlike traditional battery systems, hydrogen-based storage offers superior scalability and long-term efficiency. Although the technology is still emerging and may face initial scepticism due to limited familiarity, the company’s consultative approach and emphasis on direct engagement with community authorities help foster trust among target customers. By prioritizing collaboration and training, the company empowers local stakeholders to operate and maintain their systems independently, strengthening long-term relationships and ensuring sustainable project outcomes.

The business model effectively combines short-term and long-term revenue streams, balancing upfront capital costs with ongoing fees that are structured to promote cost savings and maximize value creation for clients. Strategic partnerships with local suppliers, modular system designs and comprehensive training programs for community operators further optimize costs and enhance operational efficiency.

Sustainability and scalability are fundamental elements of the company’s long-term vision. The initial focus on consulting and system design will gradually evolve into full construction, commissioning and the development of proprietary software tools for system control and monitoring. Complementing this growth, the company is committed to offsetting residual emissions and supporting local economic development through collaborations with environmental organizations and local suppliers. As operations expand and expertise deepens, the business model can be adapted to serve industrial applications and other microgrid configurations, extending the benefits of hydrogen-based energy systems to broader markets.

Overall, this venture integrates an approach to off-grid energy provision, through innovative technology, a well-structured operational model and social responsibility. It has the potential to contribute significantly to the global transition toward clean and resilient energy systems.

4. References

List of publications related to BM.1 for ESR05 – Energy Router for Hybrid Microgrids for efficient and robust energy and power management

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Chapter 3

Innovative Business Models in Smart Buildings and Prosumer Communities

Coordinator: Nova University Lisbon

List of abbreviations used in this chapter

API	Application programming interface
BEN	Beneficiary
CCP	Cloud Computing Platform
COTS	commercial off-the-shelf
Dn	Deliverable (number)
DoA	Description of Action
DS	Doctoral School
ECP	Edge Computing Platform
EMS	Energy management system
ESR	Early Stage Researcher
ETN	European Training Network
GA	Grant Agreement
HIL	Hardware in the loop
IRP	Individual Research Project
ITN	Innovative Training Network
MSn	Milestone (number)
MSCA	Marie Sklodowska-Curie Actions
OSS	Open-source Software
PC	Project Coordinator
REC	Research Ethics Committee
RSC	Recruitment and Secondment Committee
ToU	Time of Use
TRL	Technology readiness level
WPn	Work Package (number)

1. Executive summary

This chapter deals with WP4 End user of Energy and prosumers and summarizes the core components and findings of the SMARTGYSUM Deliverable 4.4, which outlines business models for transitioning ESR’s (Early Stage Researchers) work and research into commercially viable products.

The primary objective of this report is to present business strategies for three specific Individual Research Projects (IRPs) to ensure their profitability and market readiness. These projects address the broader goals of identifying new ways to manage electric energy, reducing consumption through smart technologies, and engaging customers in energy-related behavior changes. The work is driven by ESRs who have combined technical engineering with entrepreneurial training to bridge the gap between academic research and industry adoption.

The first model focuses on a two-level Energy Management System (EMS) architecture that utilizes an Edge Computing Platform (ECP) and a Cloud Computing Platform (CCP). This system uses a Raspberry Pi running Home Assistant to handle local, real-time decision-making and data acquisition, while a centralized cloud service performs heavy day-ahead optimizations. This "privacy-by-design" approach keeps sensitive household data local while providing users with optimized power references that can extend battery lifetimes beyond 13 years and reduce financial payback periods from 16 years down to approximately 7 years.

The second business model details an EMS designed specifically for DC-based residential microgrids. This software-driven product aims to maximize on-site energy self-consumption, which is a critical strategy in a market where selling surplus electricity back to the grid is becoming less profitable. By coordinating generation, storage, and loads, the system improves overall efficiency and reliability while maintaining a vendor-agnostic design that works with a wide range of standard commercial components.

The third model introduces the Integrated Real-Time Energy Intelligence (IREI) system, which provides diagnostic and optimization tools for smart buildings. It features non-intrusive load monitoring (NILM) to disaggregate energy usage into individual appliance data without requiring expensive per-appliance sensors. This system is designed for easy integration with home automation platforms like Home Assistant and offers a "freemium" revenue model, providing a basic manual tier for free while charging for advanced AI-driven diagnostics and photovoltaic performance analysis.

The objectives of deliverable D4.4 are intrinsically linked to the broader goals of Work Package 4 (WP4), which focuses on "End user of Energy and prosumers". Specifically, this deliverable involves the contributions of researchers ESR9, ESR10, and ESR11, who focus on areas such as fault-tolerant embedded real-time systems, residential energy management systems with online identification of parameters, and the diagnosis and optimization of energy management in smart buildings. The primary objective of Deliverable 4.4 is to present the business model proposals developed by the Early Stage Researchers (ESRs) to ensure the commercial viability and profitability of their research within the framework of WP4. These models leverage the interdisciplinary competencies—ranging from green economy principles to entrepreneurial strategy—

acquired by the ESRs through the specialized doctoral training modules provided by the SMARTGYsum project.

WP4 (End user of Energy and prosumers) objectives are:

1. to identify and demonstrate new ways of using electric energy enabling ESS and consumption strategies using monitoring and exogenous information;
2. to reduce energy consumption by using emergent technology as smart meters
3. to analyse the benefits and possibilities of cooperation between power converters and ICT in Energy Management Systems;
4. to identify the main energy-related behaviour change requirements necessary to engage customers in energy applications.

WP4 (End user of Energy and prosumers) tasks are:

- Task 4.1: Development of embedded real-time system to enhance the tolerance and reliability of power electronics (UNL-USA-BRIG).
- Task 4.2: Design and in-loop Residential Energy Management Systems based on microgrid integrated Energy Storage Systems (UNL-KIT-OPAL).
- Task 4.3: On-line diagnosis and optimization of Energy Management Systems for Smart Buildings (UNL-USA).
- Task 4.4: Elaboration of partial and final scientific reports (UNL)

IRP09 – Edge computing platform (ECP) for Fault Tolerant, High Reliable and Resilient Power Electronic in Prosumers Applications

Residential prosumers with rooftop PV and Battery Energy Storage Systems (BESS) need smart Energy Management Systems (EMS) to reduce electricity bills, increase self-consumption, and monetize flexibility (e.g., export under feed-in / ToU rules). Many existing solutions either ignore battery degradation (causing unrealistic lifetime and cost estimates) or rely on continuous cloud control (raising privacy, latency, and reliability issues).

This deliverable addresses the proposed two-level EMS architecture that splits responsibilities between:

- Edge Computing Platform (ECP): Raspberry Pi running Home Assistant. It provides a user-friendly interface, acquires measurements, predicts household consumption, and executes real-time decision making.
- Cloud Computing Platform (CCP): runs heavy day-ahead optimization and periodic multiparametric optimization that are sent back to the ECP.

The ECP uploads only what is strictly needed for optimization (e.g., aggregated forecasts such as day-ahead load profile), while sensitive/high-frequency information can remain local. The CCP returns a compact policy representation (critical regions) so the ECP can compute optimized real-time power references for the Energy Router (ER) without cloud latency.

Quantified technical economic details (from the degradation-aware PV–BESS optimization case study in Tallinn) conclude that optimized operation can extend battery lifetime beyond 13 years and reduce payback time from about 16 years (self-consumption only) to about 7 years (when export is allowed), while annual capacity fade is typically around 1.3–1.7% depending on season and conditions.

IRP10 – Energy management systems for Residential micro-grids with integrated energy storage

A comprehensive outline of the proposed business model for the Energy management system (EMS) designed for residential microgrids, developed within the framework of the IRP10 of WP4 of the project is presented. It presents the commercial potential, value proposition, and market opportunities of deploying an EMS designed specifically for DC residential microgrids.

The proposed EMS is conceived as a software-based product intended to support next-generation residential energy systems. Its primary function is to enable both local and global optimization of microgrid resources, including distributed energy generation, storage, and controllable loads. By intelligently coordinating these assets, the EMS seeks to enhance overall system efficiency, economic performance, and operational reliability.

Recent technological advances indicate that DC droop-controlled microgrids are transitioning from laboratory experimentation to pilot-scale deployment, demonstrating superior efficiency and lower conversion losses than conventional AC-based residential systems. As these systems mature, the need for advanced and adaptive energy management becomes increasingly critical. Efficient control and optimization of DC microgrids can deliver tangible benefits to homeowners, particularly those seeking to maximize returns on investment from residential renewable energy installations.

Within the European Union, the steady growth in residential renewable energy adoption, driven by decarbonization policies, rising energy costs, and increased consumer awareness, has reshaped traditional energy economics. Under current regulatory and market conditions, achieving financial break-even solely through the sale of surplus electricity to the grid is increasingly challenging. Consequently, maximizing on-site energy self-consumption has emerged as a key strategy for improving the profitability and sustainability of residential renewable systems. A well-designed, intelligently optimized EMS plays a vital role in enabling this transition by aligning energy generation, storage, and consumption in real time.

IRP11 – On-line diagnosis and optimization of Energy Management Systems for Smart Buildings

The business model designed for the Integrated Real-Time Energy Intelligence (IREI) system is presented. The model supports a hybrid edge–cloud architecture that enables privacy-preserving, real-time non-intrusive load monitoring (NILM), appliance modeling, load forecasting, and photovoltaic (PV) diagnostics.

Three journal articles form the core scientific background of the platform. The first, “Online real-time robust framework for non-intrusive load monitoring in constrained edge devices” [6], introduces the real-time NILM architecture that enables disaggregation directly on user-owned hardware. The second, “Self-adaptive single-diode model parameter identification under small mismatching conditions” [7], presents the PV modeling method used in the Pro tier for diagnostics and trend analysis. The third, “Transfer capabilities of Seq2Seq and Seq2Point CNN architectures in Non-intrusive Load Monitoring with unseen appliances” [8], supports the cloud-trained appliance embedding method by analyzing generalization strategies for appliance recognition using deep learning.

In addition to these journal articles, three conference papers contributed directly to the design of IREI's PV diagnostic capabilities. The first, presented at the 2023 IEEE CPE-POWERENG, "Identification of static and dynamic parameters of PV models through multi-objective optimization" [9], helped establish the methodology for parameter identification under real-world conditions. The second, presented at the 2023 ICCEP, "Challenges in photovoltaic parameter identification under mismatching conditions" [10], highlighted the effects of real-time variability and informed the robustness requirements of the system. The third, presented at the 2025 ICCEP, "Detection of Series Resistance Degradation in PV Modules Using Measured Current-Voltage and Frequency-Domain Impedance" [11], provided direct input for implementing degradation detection in residential PV installations.

The IREI business model has been structured to translate these validated scientific methods into a commercial solution that meets market demands. By combining the technical innovations developed through these six publications with real-world constraints and user expectations, the model defines a path from academic research to product adoption. The collaboration between the University of Salerno and CY Cergy Paris Université ensured that the research was supported by interdisciplinary expertise and access to both laboratory and applied testing environments.

2. Business model presentation

2.1. IRP09 – Edge computing platform (ECP) for Fault Tolerant, High Reliable and Resilient Power Electronic in Prosumers Applications)

Introduction

This section presents the business model for the Edge Computing Platform and Cloud Computing Platform, to provide effective consumer supervision to optimize energy production and enhance the physical and data safety, while reducing their cost and energy requirement and reducing consumer vulnerability and dependency on data connections

Value Proposition & Competitive Advantage

Customer value delivered (measurable outcomes):

- Lower electricity bill via optimal day-ahead scheduling under ToU tariffs and export rules (minimize import cost, maximize export revenue).
- Lower replacement cost and higher reliability by explicitly accounting for battery degradation (calendar + cyclic aging) within the optimization.
- Faster investment return: payback improvement demonstrated in the export-enabled scenario (e.g., ~16 → ~7 years).
- Real-time performance on low-cost hardware: critical regions enable fast ECP decisions without solving heavy optimization online.
- Privacy-by-design: critical household signals can remain on the ECP; cloud receives only aggregated forecasts or user-consented data.

Competitive advantages:

- Two-level architecture: CCP does heavy computation; ECP does real-time execution with guaranteed responsiveness.

- Multiparametric optimization deployment: reusable critical regions = real-time optimality without cloud latency.
- Degradation economics coupling: battery lifetime is dynamic and impacts replacement cost through annualized factors (CRF/SFF), avoiding oversizing.

Data Governance, Confidentiality & Security

Confidentiality principle: keep critical information at the edge by default.

- Default data locality: high-frequency measurements (per-5-min time series, appliance-level signals, occupancy cues) stored locally on the ECP.
- Cloud-minimalism: CCP receives only the aggregated day-ahead consumption forecast (as precise as desired by the user) and necessary tariff/forecast inputs.

Market & Customer Segments

Primary customer segments:

- Residential prosumers with PV planning to add storage.
- Residential prosumers with PV + BESS seeking higher savings and export revenue.
- Installers/integrators looking for a software layer to differentiate PV+BESS offerings.

Secondary/adjacent segments (medium-term):

- Energy communities / pilot microgrids requiring scalable coordination across homes.
- Aggregator / flexibility service providers.

Channels & Customer Relationships

Channels:

- Installer channel: package the EMS with PV+BESS installation or upgrade projects.
- OEM partnership: embed as an add-on module for Energy Router / hybrid inverter vendors.
- Direct-to-prosumer: Home Assistant community + online onboarding.

Customer relationships:

- Self-service onboarding via Home Assistant UI + guided setup.
- Subscription support: updates, tariff configuration, integration maintenance.
- Optional premium services: remote diagnostics and optimization tuning.

Revenue Model & Cost Structure

Revenue options:

- Subscription: day-ahead optimization + critical region updates + continuous improvements.
- Hardware bundle: preconfigured Raspberry Pi with EMS stack (ECP) and installer support.
- Tiered services: basic (self-consumption), advanced (export), premium (uncertainty-aware/robust).

Cost structure:

- Cloud compute for optimization and critical region generation.
- Cloud storage and secure delivery.
- Engineering & maintenance (integration, cybersecurity updates, model updates).

- Customer support and installer training.

Key Resources & Activities

Key resources:

- Optimization engine (day-ahead scheduling + multiparametric region generation).
- Battery lifetime/degradation model coupled to economics (CRF/SFF).
- Edge stack (Home Assistant integration, forecasting, real-time policy execution).
- Cloud stack (containerized solver services, authentication, monitoring).

Key activities:

- Operate the CCP optimization service (multi-tenant scheduling, monitoring, scaling).
- Generate and update critical regions (e.g., every 4 hours or event-driven).
- Improve forecasting models and validate across households/climates.
- Maintain integrations with Energy Router, meters, and tariffs.

Key Partnerships

Partnerships enabling delivery:

- ESR03 collaborator: operation of the CCP optimization service and compute infrastructure.
- ESR011 collaborator: for appliances monitoring and improving the consumption prediction based on NILM algorithms.
- Energy Router / inverter manufacturers: stable API for measurements and power references.
- Home Assistant ecosystem and smart-meter vendors.
- PV+BESS installers and maintenance providers.
- Cloud provider (AWS/Azure/GCP or EU-based).

Sustainability & Scalability

Sustainability:

- Higher PV self-consumption and reduced peak imports support renewable integration.
- Battery lifetime extension reduces material footprint and replacement waste.
- Flexible scheduling can reduce stress on distribution networks.

Scalability:

- CCP multi-tenant optimization: modernize processing reduces marginal cost per household.
- ECP real-time execution is lightweight: critical regions enable constant-time decisions.
- Configurable data retention: local-first storage; cloud storage is optional and minimized.

Financial Overview (Optional)
ECP/CCP Split of Responsibilities:

Edge Computing Platform (ECP): Raspberry Pi	Cloud Computing Platform (CCP): Cloud Service
• Data acquisition (smart meter, PV, BESS, Energy Router) • Home Assistant UI (user-friendly) • Local consumption prediction • Real-time decision making (compute power references for ER) • Local storage (default)	• Day-ahead optimization (heavy compute) • Multiparametric optimization to compute critical regions • Tariff/forecast processing • Policy distribution + updates • Optional cloud storage (limited retention)
Uploads: aggregated day-ahead forecast (and optional consented aggregates), not raw sensitive signals by default.	Returns: compact policy packages (critical regions) enabling fast real-time control on the ECP.
Operates in Real-time.	Runs on schedule (daily + every 4 hours).

Local Data Storage Estimate (5-minute sampling, 1 year)
Samples/year at 5-minute resolution: 365 × 24 × 12 = 105,120 samples.
If each sample stores ~13 fields (timestamp + 12 numeric variables):

- Binary (floats): 105,120 × 13 × 8 bytes ≈ 10.9 MB/year.
- CSV/text (typical): ≈ 30–150 MB/year depending on precision and number of columns.

Edge storage requirements are modest. A typical microSD/SSD can store multi-year histories for a single household.

Edge Hardware Cost (indicative)
A realistic planning range for a complete ECP (Raspberry Pi + power supply + storage) is typically in the order of €80–€150, depending on model and retailer availability.

Cloud Compute Cost Estimate (per household, dedicated worst-case)
Measured runtimes on a local laptop (Intel Core i7 12th Gen, 32 GB RAM):

- Day-ahead optimization: 408–1350 s per run
- Critical-region computation: ~2.04 min per run, every 4 hours (≈ 6 runs/day)

Approximate dedicated monthly compute time (worst-case):

- Day-ahead: ~15 min/day × 30 ≈ 7.5 h/month
- Regions: 2.04 min/run × 6/day × 30 ≈ 6.1 h/month

Total ≈ 13.6 h/month.

Reference price for compute (Europe/Paris region): c7i-flex.4xlarge on-demand is reported at 1.283€/hour [5]. Dedicated worst-case compute cost: 13.6 h/month × 1.283€/h ≈ 17.45 €/month per household. With multi-tenant batching, the marginal cost per household is expected to be significantly lower.

Subscription pricing and provider benefits
A simple pricing structure can combine a one-time deployment fee (hardware + installation) and a monthly subscription for cloud optimization, updates, and support.

Tier	What the customer gets	Indicative price	Notes
Basic (Edge-only)	Local monitoring + prediction (no cloud optimization).	0-4 €/month	Suitable when customers want privacy-first.
Premium (Cloud–Edge + Insights)	Standard + longer data retention (opt-in) + advanced reports (payback, degradation, CO_2) + priority support + bill saving cost+ Demand Side Management (DSM).	20–25 €/month	Targets prosumers with PV+BESS and high tariffs/FiT.

The end user bears the one-time installation cost, which is included in the PV+BESS and Energy Router (ER) installation/retrofit package delivered by certified partner installers. Our company supplies the Edge Computing Platform (ECP) and onboarding support, while partners invoice installation as part of their standard project scope.

Remarks

This work positions a cloud/edge EMS architecture as a practical pathway from research-grade optimization to deployable residential energy management. A key outcome is the availability of an open-access, generic residential load-profile predictor, already implemented on a Raspberry Pi 4 and integrated within a user-friendly interface (Home Assistant). This edge-level capability enables continuous data acquisition and short-term consumption prediction while preserving user confidentiality by keeping high-resolution household data locally when required.

Building on this foundation, the ongoing work focuses on completing (i) day-ahead optimization in the cloud, where heavy computation is executed to generate multiparametric solutions (critical regions), and (ii) the real-time decision-making layer on the ECP, which uses the received critical regions to compute optimized power references for the energy router with minimal computational burden. The final objective is a fully operational real-case study combining day-ahead scheduling and real-time control on a residential prosumer setup.

Finally, a preliminary cost estimation is provided as a first step toward industrialization, covering edge hardware requirements (Raspberry Pi 4), local data storage needs, and indicative cloud compute costs for periodic optimization runs. This assessment supports early feasibility analysis before full customization and experimental validation on the prototyped ER.

2.2. IRP10 – Energy management systems for Residential micro-grids with integrated energy storage

Introduction

This section presents a comprehensive outline of the proposed business model for the Energy management system designed for residential microgrids. It presents the commercial potential, value proposition, and market opportunities of deploying an EMS designed specifically for DC residential microgrids.

Value Proposition & Competitive Advantage

Current residential renewable energy installations face several structural and operational limitations, including multiple power-conversion stages, synchronization requirements across converters, increased material use, and limited operational flexibility. These inefficiencies become more pronounced with high renewable penetration, where residential prosumers are often unable to fully capitalize on the economic potential of their systems. As a result, overall system performance is reduced, and the payback period for capital investments gets extended.

The proposed EMS for DC residential microgrids directly addresses these challenges by enabling a more streamlined, efficient, and flexible energy architecture. By leveraging the inherent advantages of DC systems and advanced control strategies, the EMS enhances both technical performance and economic returns for residential users.

The core value propositions of the EMS include:

- Enhanced Energy Efficiency through the reduction of unnecessary power conversion stages, the use of high-efficiency interface converters, and intelligent optimization of residential energy flows across generation, storage, and loads.
- Improved Energy Flexibility enabled by droop control and real-time, online manipulation of droop characteristics. This allows the system to dynamically respond to varying operational scenarios, such as changing weather conditions, energy market signals, or emergency operating modes.
- Scalable and Multi-Level Integration of Renewable Resources, whereby the EMS can be deployed not only at the individual household level, but also extended to community, district, or aggregated microgrid configurations, supporting coordinated energy management across multiple scales.
- Reduced Environmental Impact achieved through the use of higher switching frequencies in interface converters, which lowers material requirements, reduces system bulk, and contributes to more sustainable hardware designs.
- Simplified electrical infrastructure and appliance Integration through the implementation of droop control at the appliance level, enabling smart, plug-and-play connectivity of distributed assets and reducing installation complexity.

A key competitive advantage of the EMS lies in its vendor-agnostic architecture. The system is designed to support the integration of a wide range of commercial off-the-shelf (COTS) interface converters, appliances, and protection devices, minimizing vendor lock-in and lowering adoption barriers. In contrast to most existing EMS solutions, which are primarily tailored to AC-based renewable systems, the proposed solution is specifically designed for DC microgrids. It aligns with the technological trajectory of future residential energy networks.

By entering a largely untapped market segment with an innovative, software-driven EMS tailored to DC residential microgrids, the solution benefits from a first-mover advantage, minimal direct competition, and increasing market relevance driven by the growing adoption of residential renewable energy systems and prosumer-oriented energy models.

Market & Customer Segments

The EMS addresses a diverse and growing market driven by decentralization, sustainability goals, and regulatory pressures. The primary target customer segments include:

- Energy communities and collective self-consumption groups, seeking efficient, scalable, and easily deployable energy management solutions to optimize shared renewable generation, storage, and consumption while minimizing system complexity.
- Owners and operators of eco-conscious apartment buildings and residential complexes, aiming to reduce energy costs, improve sustainability performance, and enhance energy autonomy through advanced, low-loss DC-based energy infrastructures.
- New homeowners and property developers are required to comply with increasingly stringent renewable energy and energy efficiency regulations, who seek future-proof solutions that simplify compliance while maximizing on-site renewable utilization.
- Residents in remote, islanded, or grid-constrained locations where weak or unreliable grid infrastructure necessitates resilient, locally optimized energy systems capable of maintaining stability and continuity of supply.

Channels & Customer Relationships

The proposed EMS will be delivered to customers through a combination of physical and digital distribution channels, ensuring broad accessibility while leveraging existing partner networks.

The solution will be made available through partners' physical retail outlets, enabling direct engagement with customers who prefer in-person consultation, particularly during the planning or installation phase of residential energy systems. In parallel, the EMS will be offered via a dedicated online sales platform, enabling customers to access product information, configuration options, and purchasing services in a streamlined, scalable manner.

Customer relationships will primarily be structured around a self-service model, supported by comprehensive online resources, including documentation, tutorials, and configuration tools, hosted on the project website. This approach minimizes operational overhead while empowering users to manage and optimize their energy systems independently.

To complement the self-service model, technical support and operational assistance will be provided through collaboration with distribution system operators (DSOs) and energy aggregators. These stakeholders will play a key role in system integration, ongoing optimization, and participation in advanced services such as flexibility markets or demand response programs, ensuring reliable long-term customer engagement and system performance.

Revenue Model & Cost Structure

The proposed EMS is supported by a diversified revenue model that combines one-time product sales with recurring service-based income, ensuring both short-term revenue generation and long-term financial sustainability. Revenue Streams include:

- Sales of Hardware Solutions, comprising the EMS platform and its associated ecosystem of compatible components. This includes self-developed interface converters, power nodes, protection devices, and DC-compatible appliances designed to operate seamlessly within the microgrid, creating additional value through system-level integration.

- Subscription-Based Services, offering advanced functionality beyond the core EMS features. These services may include cloud-based monitoring, artificial intelligence-driven optimization, and enhanced analytics, enabling customers to have continuous performance improvements and generate recurring revenue.
- Revenue and profit-sharing mechanisms with DSOs, particularly in cases where the EMS enables grid-support services such as flexibility provision, congestion management, or participation in local energy markets. This model aligns incentives across stakeholders while unlocking additional income streams.

The cost structure reflects the technology-driven and innovation-focused nature of the solution and includes:

- System design and development costs, which are primarily variable and linked to the ongoing development, customization, and scaling of the EMS software and associated hardware components.
- Marketing, publicity, and dissemination costs, covering customer acquisition, partner engagement, demonstration activities, and communication efforts required to support market entry and adoption.
- Continuous research and development costs, ensuring ongoing innovation, system upgrades, cybersecurity enhancements, and compliance with evolving regulatory and technical standards.

Key Resources & Activities

The successful development, deployment, and commercialization of the EMS relies on a set of core activities supported by strategically important technical and organizational resources. Key Activities include:

- Design and development of EMS hardware and software, including control algorithms, optimization logic, communication interfaces, and embedded functionality for reliable operation in DC residential microgrids.
- System integration and validation up to technology readiness level (TRL) 6, including comprehensive testing procedures such as burn-in testing, Hardware-in-the-loop (HIL) validation, and performance verification under realistic operational scenarios to ensure robustness, safety, and scalability.
- Dissemination and outreach activities, aimed at increasing public and stakeholder awareness through seminars, workshops, technical demonstrations, and project showcases. These activities support market uptake, knowledge transfer, and engagement with industry, policymakers, and end users.

Key resources supporting these activities include:

- Novel DC–DC and AC–DC Converter Architectures with Integrated IoT Connectivity, enabling efficient power conversion, real-time monitoring, and seamless communication with the EMS for advanced control and optimization.
- A Dedicated DC test laboratory, consisting of different power electronic equipment that emulates a DC residential household. This infrastructure enables controlled testing, system validation, and demonstration of the EMS under representative operating conditions.

- Third-party system integrations, including access to existing open-source software (OSS) frameworks, as well as application programming interfaces (APIs) provided by DSOs. These integrations support interoperability, grid interaction, and participation in advanced energy services.

Together, these key activities and resources form the technological and operational foundation required to advance the EMS from development to pilot-scale deployment, while ensuring readiness for future commercialization and large-scale adoption.

Key Partnerships

The successful development and deployment of the EMS relies on strategic collaborations with key stakeholders across the energy value chain. DSOs play a central role in enabling grid integration, validating grid-support services, and aligning with regulatory and operational requirements. Component and device manufacturers are essential partners for ensuring compatibility, reliability, and scalability of converters, protection devices, and DC-compatible appliances within the EMS ecosystem. In addition, collaboration with DC grid guideline and standards organizations supports compliance with emerging standards, contributes to interoperability, and helps position the solution in line with future DC grid regulations and best practices.

Sustainability & Scalability

The EMS offers an environmentally sustainable solution for future residential energy systems by significantly improving energy efficiency and maximizing on-site renewable energy self-consumption. By enhancing the economic performance of residential renewable installations and enabling participation in grid-support and flexibility services, the EMS supports long-term financial sustainability for prosumers and system operators alike. Its modular, vendor-agnostic architecture ensures seamless integration with commercially available components while remaining adaptable to evolving technologies and standards. Furthermore, the software-centric design allows the EMS to scale from individual households to community and district-level applications, positioning it as a future-proof enabler of decentralized, low-carbon energy systems.

2.3. IRP11 – On-line diagnosis and optimization of Energy Management Systems for Smart Buildings

Introduction

This section introduces the business model designed for the Integrated Real-Time Energy Intelligence (IREI) system. The model supports a hybrid edge–cloud architecture that enables privacy-preserving, real-time non-intrusive load monitoring (NILM), appliance modelling, load forecasting, and photovoltaic (PV) diagnostics.

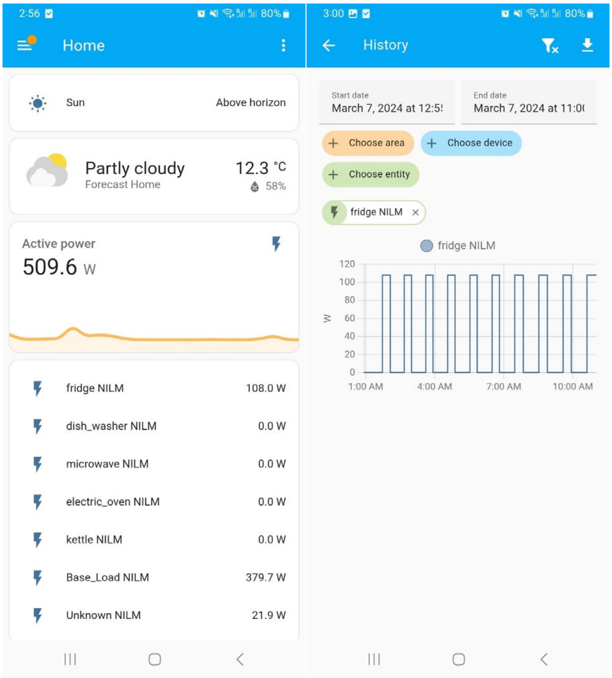
Value Proposition & Competitive Advantage

IREI addresses the problem of inaccessible or costly appliance-level energy monitoring. While many homes are equipped with smart meters, their data remains underutilized due to low temporal resolution, privacy concerns, or lack of compatible solutions. Existing NILM platforms are either cloud-dependent, requiring continuous data upload, or hardware-based, which increases installation complexity and costs.

IREI offers a unique solution by processing energy data locally using user-owned computing platforms such as single-board computers. The free tier enables users to manually define appliance models, while the Pro tier adds AI-trained appliance embeddings, load forecasting, PV diagnostics, and energy efficiency insights. All features operate with compact data models that preserve privacy and minimize bandwidth usage.

Customers will choose IREI because it offers a flexible, low-cost entry point with the ability to scale through modular enhancements. The system's architecture supports both manual and AI-driven modeling, and its integration with home automation platforms ensures seamless operation. Its competitive edge lies in combining accuracy, privacy, and interoperability without the need for costly per-appliance sensors.

As shown in Figure 1, IREI integrates into the Home Assistant interface to provide real-time appliance-level monitoring. This visualization demonstrates the system's ability to disaggregate loads and present individual appliance data such as power use from the fridge, microwave, or dishwasher; all updated in real time.



Sun Above horizon

Partly cloudy 12.3 °C
Forecast Home 58%

Active power
509.6 W

fridge NILM 108.0 W
dish_washer NILM 0.0 W
microwave NILM 0.0 W
electric_oven NILM 0.0 W
kettle NILM 0.0 W
Base_Load NILM 379.7 W
Unknown NILM 21.9 W

Start date
March 7, 2024 at 12:5

End date
March 7, 2024 at 11:0

Figure 1. Real-time appliance-level energy disaggregation in Home Assistant using IREI.

Market & Customer Segments

IREI targets three main customer segments. The first is composed of home automation users who rely on platforms such as Home Assistant to control and monitor their devices. As shown in Figure 2, the number of Home Assistant installations has grown significantly between 2021 and 2025, indicating a rapidly expanding user base interested in energy data and automation. These users often seek deeper energy insight and system automation capabilities. A large portion of this community already employs compatible smart meters such as the Shelly EM. Figure 3 illustrates that Shelly devices account for a notable share of the energy metering hardware in Home Assistant environments. This reinforces that a significant number of users are already monitoring their consumption and are likely to be receptive to paying for advanced analytics, including load disaggregation, forecasting, and diagnostics. The second customer segment includes PV system owners who need diagnostic tools to monitor panel performance and ensure long-term reliability. The third group consists of energy service providers, including installers and consultants, who seek scalable and cost-effective solutions for residential energy monitoring.

Customer needs include accurate real-time monitoring, data privacy, ease of integration with existing systems, and actionable energy insights. Pain points addressed by IREI include the high cost of smart plugs or hardware sensors, privacy risks associated with cloud-based NILM, and the lack of real-time capabilities in existing solutions. The residential energy market is evolving toward digitalization, decentralization, and user empowerment. The rise of smart homes and self-generation systems has created demand for solutions like IREI that maximize existing infrastructure. IREI is positioned to compete with both traditional monitoring hardware and cloud-based energy analytics platforms by offering a leaner, privacy-focused alternative.

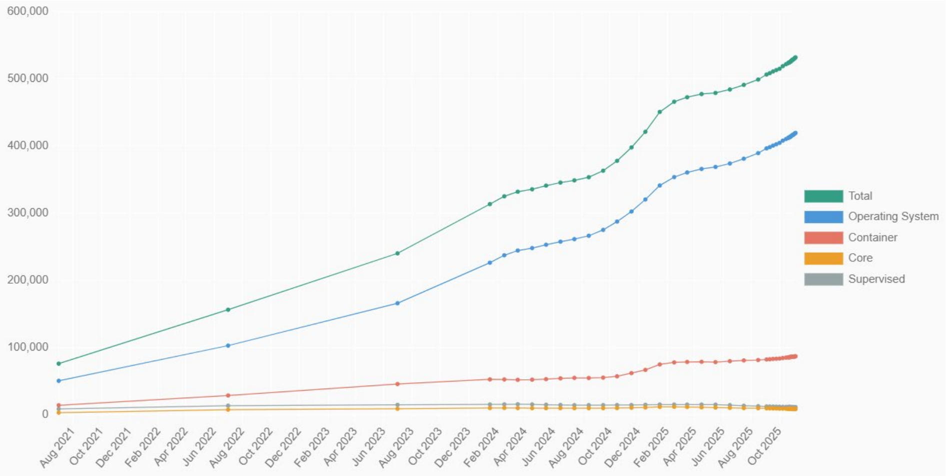


Figure 2. Growth of Home Assistant installations from 2021 to 2025.

20	Internet Printing Protocol (IPP)	124,873 (28.4%)
21	DLNA Digital Media Renderer	124,214 (28.2%)
22	Zigbee Home Automation	113,171 (25.7%)
23	ESPHome	111,899 (25.4%)
24	Shelly	100,122 (22.8%)
25	DLNA Digital Media Server	93,470 (21.3%)
26	Input number	90,330 (20.5%)

Figure 3. Adoption rate of Shelly devices in Home Assistant installations.

Channels & Customer Relationships

IREI is distributed through digital channels including GitHub, the Home Assistant addon ecosystem, and energy-focused online communities. Marketing and outreach efforts target forums, conferences, and open-source platforms that cater to home automation and energy efficiency users. Strategic partnerships with hardware vendors and PV installers help reach non-technical audiences through bundled solutions.

Customer relationships vary depending on the product tier. The free tier operates on a self-service basis with community-driven support, while the Pro tier includes access to structured documentation, updates, and optional technical assistance. Communication is primarily digital, ensuring scalability while keeping support costs manageable.

Retention strategies focus on demonstrating the value of appliance-level data through virtual sensors and automation. By offering visible performance improvements and convenience in the free tier, the system naturally encourages users to upgrade to paid features. The modular structure allows incremental investment, reducing barriers to long-term engagement.

Revenue Model & Cost Structure

The IREI business model includes multiple revenue streams. The free tier serves as a user acquisition tool, offering appliance modeling through finite state machines at no cost. Revenue is generated from the Pro features via two models: a one-time fee per appliance embedding (3–5 euros) and a monthly subscription (5–7 euros) that includes up to ten embeddings per year along with forecasting, diagnostics, and AI-based insights. Pricing is designed to be accessible while delivering high perceived value. The per-appliance model allows for gradual user engagement, while the subscription model offers bundled services with ongoing updates.

Major cost drivers include R&D for algorithm development, cloud infrastructure to support Pro features, software maintenance, and user support. Cost optimization is achieved through reliance on user-owned hardware, lightweight data processing, and open-source distribution channels that reduce overhead and marketing expenses.

Key Resources & Activities

Core resources include the local NILM engine, cloud-based analytical services, appliance modeling infrastructure, and integration interfaces for home automation systems. Intellectual assets consist of the algorithms, training pipelines, and software components that enable local processing and secure cloud interaction.

As shown in Figure 4, installation of IREI relies on integrating devices such as the Shelly EM, which requires minimal hardware effort while delivering full compatibility with the IREI platform. This supports rapid deployment in both self-install and professional scenarios.

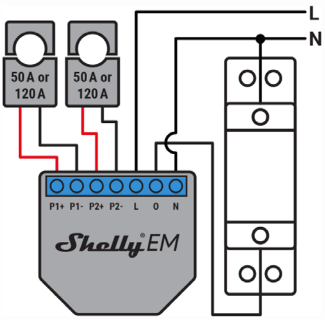


Figure 4. Installation diagram of the Shelly EM meter for IREI deployment.

A large share of Home Assistant users rely on low-cost, single-board computers and embedded platforms that are compatible with local energy analytics, such as the IREI model. These include Raspberry Pi variants, ODROID boards, and pre-configured appliances like Home Assistant Yellow. Figure 5 illustrates the distribution of hardware platforms among Home Assistant users. The prevalence of Raspberry Pi 4 and 5, together with other embedded systems, confirms the feasibility of deploying the local NILM engine without the need for high-end devices.

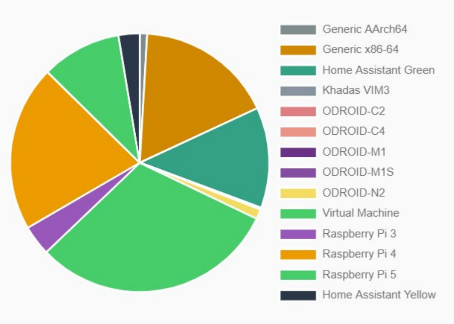


Figure 4. Distribution of Home Assistant hardware platforms among users.

The main business activities are research and development of NILM and PV diagnostics, appliance modelling, software updates, user support, and strategic partnership management. Continuous improvement of model accuracy and compatibility is central to maintaining a competitive edge. Community engagement and documentation are also vital for user onboarding and retention.

Key Partnerships

IREI benefits from partnerships with smart home communities, hardware manufacturers, and energy service providers. Collaborations with inverter manufacturers ensure compatibility with PV diagnostics features. Partnerships with Home Assistant developers and GitHub contributors help maintain platform integration and visibility.

Alliances with PV installers and smart energy consultants enable field testing, direct deployment, and expansion into service-based markets. These relationships reduce market entry barriers and accelerate adoption, especially among users who prefer plug-and-play solutions over manual configuration.

Sustainability & Scalability

IREI is designed to scale horizontally through software distribution and vertically through Pro feature adoption. Its modular structure allows the addition of new cloud-based services without altering the core local engine. The system's reliance on user-owned hardware ensures that scaling does not require significant capital investment in infrastructure.

From a sustainability perspective, IREI contributes by reducing the need for dedicated sensors and hardware, which lowers material waste. Its ability to optimize household energy use and detect PV performance issues supports long-term environmental benefits. The business model is inherently adaptable. As the number of supported appliances and analytical modules grows, the system can address new market segments, including small commercial buildings and community energy monitoring setups.

Financial Overview

Initial revenue projections are based on conservative conversion rates within the Home Assistant user base. With over one million active users, a 5 percent conversion to paid appliance embeddings could generate significant one-time income. A smaller percentage subscribing to the Pro tier could establish a stable monthly revenue stream. Key expenses include R&D, cloud services, and community management. The open-source model reduces support costs and allows the project to grow with minimal financial overhead. Future funding could support service expansion, including AI model refinement, broader appliance coverage, and partnerships with energy providers.

3. General Conclusions

The three Individual Research Projects within Work Package 4 showcase an interesting suite of end use of energy and prosumers solutions covering the entire value chain from hardware to software, aligned with Work Package 4 objectives.

IRP09 – Edge computing platform (ECP) for Fault Tolerant, High Reliable and Resilient Power Electronic in Prosumers Applications

This work positions a cloud/edge EMS architecture as a practical pathway from research-grade optimization to deployable residential energy management. A key outcome is the availability of an open-access, generic residential load-profile predictor, already implemented on a Raspberry Pi 4 and integrated within a user-friendly interface (Home Assistant). This edge-level capability enables continuous data acquisition and short-term consumption prediction while preserving user confidentiality by keeping high-resolution household data locally when required.

Building on this foundation, the ongoing work focuses on completing (i) day-ahead optimization in the cloud, where heavy computation is executed to generate multiparametric solutions (critical regions), and (ii) the real-time decision-making layer on the ECP, which uses the received critical regions to compute optimized power references for the energy router with minimal computational burden. The final objective is a fully operational real-case study combining day-ahead scheduling and real-time control on a residential prosumer setup.

Finally, a preliminary cost estimation is provided as a first step toward industrialization, covering edge hardware requirements (Raspberry Pi 4), local data storage needs, and indicative cloud compute costs for periodic optimization runs. This assessment supports early feasibility analysis before full customization and experimental validation on the prototype of ER.

IRP10 – Energy management systems for Residential micro-grids with integrated energy storage

This deliverable presents a comprehensive business and technical perspective on an energy management system (EMS) for DC residential microgrids, highlighting its value proposition, market relevance, and competitive advantages. The proposed solution addresses key inefficiencies of conventional residential energy systems by enabling higher efficiency, flexibility, and renewable self-consumption through advanced DC-based architectures. A diversified revenue model, a lean operational structure, and a strong partner ecosystem strengthen the EMS's commercial viability and long-term sustainability. Its modular, vendor-agnostic, and standards-aligned design ensures scalability across households, energy communities, and district-level applications. Overall, the EMS represents a future-proof, impactful solution that supports the transition toward decentralized, efficient, and low-carbon residential energy systems.

IRP11 – On-line diagnosis and optimization of Energy Management Systems for Smart Buildings

The Integrated Real-Time Energy Intelligence (IREI) system is a hybrid edge–cloud platform designed to deliver real-time, privacy-respecting, appliance-level energy disaggregation and analytics. It leverages existing user-owned smart meters and local computing infrastructure to provide accurate monitoring without requiring additional hardware. The business idea focuses on enabling homeowners, solar system users, and energy service providers to access advanced energy intelligence at a fraction of the cost of conventional systems.

The mission of IREI is to democratize access to smart energy monitoring by making it affordable, accurate, and respectful of user privacy. Its vision is to become a reference solution in residential energy intelligence by transforming underused smart meter data into actionable insights. Key goals include widespread adoption among home automation users, strategic integration with solar energy ecosystems, and continued development of modular analytical services.

Success will be measured through free-to-paid conversion rates, Pro subscription retention, disaggregation accuracy benchmarks, and the volume of cloud-trained appliance embeddings delivered. Strategic priorities include strengthening platform integration,

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Chapter 4

Market solutions and business models to enable the growth and sustainability of distributed EES

Coordinator: Bocconi University (UB)

List of abbreviations used in this chapter

BEN	Beneficiary
BESS	Battery Energy Storage System
BMC	Business Model Canvas
BMs	Business Models
CAPEX	Capital Expenditure
CES	Community Energy Storage
CNR	Consiglio Nazionale delle Ricerche
COE	Cost of Energy
DERs	Distributed Energy Resources
D5.3	Deliverable 5.3
DoA	Description of Action
DRL	Deep Reinforcement Learning
DS	Doctoral School
ECs	Energy Communities
ECPE	European Center for Power Electronics
EES	Electrical Energy Systems
EMS	Energy Management System
ESR	Early-Stage Researcher
ESS	Energy Storage Systems
ETN	European Training Network
EU	European Union
EVCS	Electric Vehicle Charging Stations
FIFO	First in First Out
FLC	Fuzzy Logic Control
FS	First Scenario
GA	Genetic Algorithm
GAMS	General Algebraic Modelling System
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas Emissions
ICE	Internal Combustion Engine
IEMD	Internal Energy Market Directive
IRP	Individual Research Project
ITN	Innovative Training Network
LCF	Lean Canvas Framework
LSTM	Long Short-Term Memory
MILP	Mixed Integer Linear Program
MLP	Multilevel Perspective
MSCA	Marie Sklodowska-Curie Actions
NPC	Net Present Cost
OPEX	Operational Expenditure
P2P	Peer-to-Peer
PC	Project Coordinator
PV	Photovoltaic
REC	Research Ethics Committee
RED	Renewable Energy Directive
RES	Renewable Energy Source
RNN	Recurrent Neural Network

List of abbreviations used in this chapter

RSC	Recruitment and Secondment Committee
SIEM	Siemens
SMEs	Small and Medium Enterprises
SNM	Strategic Niche Management
SOC	State of Charge
SS	Second Scenario
TOA	Time of Arrival
TOD	Time of Departure
TS	Third Scenario
UB	Università Bocconi
UNL	Universidade Nova de Lisboa
V2G	Vehicle to the Grid
V2H	Vehicle to Home
VPP	Virtual Power Plants
WP5.3	Work Package 5.3
WT	Wind Turbines
ZCMES	Zero-Carbon Multi-Energy System

1. Executive summary

Work Package 5 (WP5) focuses on coordinating research and supporting the development and application of business models for collaborative renewable energy systems, microgrids, and energy management. This deliverable builds on the research conducted by ESR14 and ESR15, which enhances the understanding of market solutions and business models that can enable the growth and long-term sustainability of distributed electrical energy systems (EES). The outcomes are also relevant to the technological advancements achieved under WP2, WP3, and WP4.

Within this context, both ESR14 and ESR15 concentrated their work on the concept of Energy Communities (ECs). The European Union recognizes ECs as legal entities designed to facilitate the energy transition toward a more sustainable system, as defined in two legislative frameworks: the Renewable Energy Directive (RED II – EU 2018/2001), which establishes Renewable Energy Communities, and the Internal Energy Market Directive (IEMD – EU 2019/944), which establishes Citizen Energy Communities. Despite their differences, both directives share the objective of empowering local actors—such as citizens, small and medium enterprises, and municipalities—to actively participate in the production, consumption, and management of energy. In this way, ECs contribute to democratizing energy management and can engage across the energy value chain, providing a wide range of services including self-consumption, flexibility to the grid, and the operation of electric vehicle charging infrastructure.

In order to advance the objectives of WP5, ESR15 carried out a bibliometric literature review on Energy Communities. This review provided a comprehensive mapping of the academic research in the field, identified the progress achieved to date, and revealed existing gaps that are relevant for further inquiry. One of the main gaps concerns the understanding and categorization of business models (BMs) for ECs. To address this, ESR15, in collaboration with ESR14 and the Bocconi research team, developed a conceptual framework for the analysis of EC BMs and identified four archetypes that represent the different ways in which ECs can organize their activities. These archetypes clarify the services and benefits that ECs can deliver both to their members and to society at large, thereby informing the design of market solutions, such as flexibility services to the electricity grid.

In parallel, ESR14 worked on the integration of electric vehicle charging stations (EVCS) into ECs, in collaboration with ESR15 and the Bocconi research team. The work consisted of developing a techno-economic-environmental optimization methodology, which was first applied to a university as a test case. The objective was to reduce both the cost of energy and greenhouse gas emissions (GHG), thereby addressing energy demand from buildings and transport in a holistic way. This research represents an initial step toward the comprehensive assessment of community-level energy consumption.

Overall, the joint efforts of ESR14 and ESR15 contribute to the goals of WP5 by providing a systematic framework for the analysis of ECs BMs, by clarifying their role within energy markets through the definition of archetypes, and by proposing innovative methods to integrate EV charging infrastructure into local energy systems. These results strengthen the knowledge base required to develop market solutions and BMs that support the feasibility and sustainability of distributed EES.

1.1. Objectives and structure of the deliverable

The purpose of this deliverable is to present the progress of WP5 activities, and the research outcomes achieved by the ESRs in the context of Deliverable D5.3, titled "Report including market solutions and business models to enable the growth and sustainability of distributed EES." This report focuses on two Individual Research Projects (IRPs), namely IRP14 and IRP15. IRP14 is related to energy value chains and markets development with the new paradigm of distributed EES, while IRP15 focuses on identifying enablers and barriers to foster the replicability and transfer of BMs for green energy systems. The results reflect the research achievements reached within the first 45 months of the project.

Specifically, the deliverable mainly focuses on market solutions and BMs that enable the growth and sustainability of distributed EES. The ESRs research is related to the topic of ECs, aiming to analyse the various BMs that exist and suggest solutions for the development of green energy systems. Initially, bibliometric analysis of ECs was performed, later BMs archetypes were analysed which found in the literature. After that, one BM archetype was taken into account and validated by performing feasibility studies. Finally, the deliverable presents the link between the research outcomes achieved and the overarching goals of WP5, contributing to the broader understanding of how innovative BMs can be adopted and replicated across different contexts within the green energy landscape.

1.2. WP5 Objectives and tasks

The deliverable is part of WP5, “Green Economy Models and Management Systems,” which addresses innovative energy management tools and BMs to meet the new challenges posed by the electric energy system. WP5 involves four IRPs, each focusing on distinct topics related to innovative management solutions and BMs. Specifically, IRP12 concentrates on developing sustainable strategies for Net Zero Energy buildings and user energy awareness using smart appliances; IRP13 explores digital twins of prosumers using socioeconomical factors and big data for optimization of customer's bill savings and the adoption of concepts of self-consumption and presumption; IRP14 focuses on energy value chains and markets developed with the new paradigm of distributed EES; and IRP15 is dedicated on identifying enablers and barriers to foster the replicability and transfer of BMs for Green Energy Systems. The research outputs aim to enhance understanding and promote the adoption of technological and business solutions that support the sustainable energy transition. WP5 included 5 Tasks:

- Task 5.1: Development of sustainable strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances (UB, UNL).
- Task 5.2: Generation of digital twins of prosumers using socioeconomical factors and big data for Optimization of Customer's bill savings, (UB-SIEM-UNL).
- Task 5.3: Energy value chains and markets developed with the new paradigm of distributed EES (UB-UNL-CNR).
- Task 5.4: Identifying enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems (UB, UNL, ECPE).
- Task 5.5: Elaboration of partial and final scientific reports (UB).

Tasks 5.1 and 5.2 have been completed and the corresponding deliverables submitted. Tasks 5.3 and 5.4 are ongoing and are scheduled to be finalized by September 2025, remaining on track with the project timeline. This deliverable specifically presents the final insights from Task 5.3, while the main results from Task 5.4 are addressed separately in Deliverable 5.4. Both ESR14 and ESR15 have successfully completed their research activities, fully meeting the objectives outlined in their respective IRPs (see section 2.2).

The work carried out in Task 5.3 provides a structured and validated analysis of the energy value chain and market developed with the new paradigm of distributed EES, focusing on EC initiatives. Through mixed-method approaches, including bibliometric literature review, semi-structured literature review, and techno-economic feasibility studies, this research has contributed significant new evidence to inform the design of scalable and context-sensitive BMs. These results directly support WP5's ambitions to inform business strategies, enable effective policy design, and promote sustainable energy innovation across diverse socio-technical contexts.

1.3. WP5 – IRPs and ESRs progress

The research activities carried out within IRP14 and IRP15 directly contribute to the objectives of WP5 and to the preparation of this deliverable.

ESR14 (within IRP14) focused on the techno-economic-environmental analysis of EVCS. The first stage of this research was conducted during the initial secondment at Nova University Lisbon (June–July 2023), under the supervision of Professor João F. Martin. In this phase, a methodology was developed to reduce both the Cost of Energy (COE) and greenhouse gas emissions for end-users. The analysis relied on optimization techniques applied to a university campus as a test case. The research was further expanded during the second secondment at the University of Extremadura (November 2024–February 2025), under the supervision of Professor Enrique Romero-Cadaval. In this phase, ESR14 applied advanced mathematical optimization methods, including genetic algorithms implemented in HOMER software, to assess EVCS integration at both university and community (building-scale) levels. The approach also considered the role of Virtual Power Plants (VPPs) in optimizing energy use[1]. During this secondment, ESR14 collaborated with ESR03, developing an integrated feasibility study for EVs and community buildings, with a particular focus on services for EC users.

ESR15 (within IPR15) carried out a bibliometric literature review aimed at mapping the academic landscape on ECs and identifying research gaps relevant to WP5 objectives. This work was conducted during the first secondment at the University of Extremadura (October–December 2023), under the supervision of Professor Patricia Milanes Montero[2]. During this period, ESR15 received training in bibliometric methods, particularly the use of VOSviewer software, and performed direct citation and keyword co-occurrence analyses. The results provided an overview of existing research, highlighted gaps, and informed the subsequent development of a targeted analytical framework to assess EC BMs. The research related to EC BMs have been carried out at Bocconi University in collaboration with the university's research team and under the supervision of Professor Edoardo Croci. The current research spans eight months, beginning in September 2024. The resulting paper was presented at a conference on May 22, 2025, and subsequently published [1] in IEEE Xplore in June 2025[3]. Specifically, ESR15 conducted a literature review and content analysis on the topics of EC BMs and developed an analytical framework consisting of five dimensions. This framework was then applied to define four distinct ECBM archetypes: the self-consumption model, the third-party model, the aggregator model, and the integrated services and e-mobility model. A detailed analysis of the methodology and scientific outcomes will be presented in the following section.

2. Energy Community concept and Business Model analysis

2.1. A bibliometric literature review on energy communities

The new wave of 5D, decarbonization, decentralization, democratization, distribution, and digitalization mark a significant shift in the energy market [2]. This transition from a centralised monopoly to a decentralised model where different participants, including citizens, local authorities and private companies, can participate in the energy market [3]. Within this context, ECs have attracted a lot of attention, both in academia and in policy. Recognized as legal entities through two EU directives, the Renewable Energy Directive (RED) and the Internal Electricity Market Directive (IEMD), ECs aim to empower citizens, small and medium enterprises (SMEs), and local authorities to produce, consume, and manage their own energy [3].

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[1] This work published as conference paper can be referred as “Ahmed, SM Masum, et al. "Techno-Economic Optimization of Electric Vehicle Charging Station with Virtual Power Plant–a University Campus Use Case." IEEE EUROCON 2025-21st International Conference on Smart Technologies. IEEE, 2025.” DOI: https://doi.org/10.1109/EUROCON64445.2025.11073409.

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Although citizen participation in the energy systems has a long history that goes back to the late 19th and early 20th centuries [4], ECs start to get recognition and develop in numbers, especially after the abovementioned directives were published that define the two types of ECs, namely RED and CEC. Currently, there are over 10,000 ECs that have initiated around 22,000 projects, and this number is expected to rise in the coming years [5].

However, the topic of ECs remains complex due to the various terms and definitions found in academic literature [6], [7]. Apart from the term "energy community," several similar terms exist in the literature, such as "community energy," "citizen energy community," "local energy community," and "energy cooperative" [7]. Furthermore, research from different disciplinary backgrounds has sought to analyse the composition of ECs, the benefits they offer to society, and the barriers they encounter in further development [8]. Some scholars aim to clarify the fluid meaning of "community" and propose definitions [9], [10], while others develop typologies of ECs based on energy citizenship [11]. Furthermore, other studies have examined the potential of ECs to democratize the energy system and promote justice [12], [13], [14].

The information presented indicates a notable increase in the number of studies focused on ECs in recent years. As a result, many scholars have undertaken literature reviews to map the existing body of knowledge related to the topic of ECs. For instance, Gruber et al. [7] conducted a literature review that highlights the current state of EC development. They specifically examined the various terminologies associated with ECs and identified the renewable energy technologies most frequently analysed in literature, such as wind and solar power, along with the main characteristics and structures of ECs. Similarly, Koltunov et al. [15] performed a comprehensive literature review and desk research to provide a detailed overview of the academic literature regarding the study and classification of ECs.

The studies mentioned above have enhanced understanding of how the topic of EC has been addressed in academic literature. However, most of them either focus on a specific country or analyse the literature from a particular disciplinary perspective. For example, Koltunov & de Vidovich [16] conducted a literature review on ECs, concentrating solely on the social sciences. Thus, there is a noticeable gap in academic studies that encompasses the full range of current epistemic data related to the topic of ECs and that offers a comprehensive overview of the academic landscape. Hence, ESR15 conducted a bibliometric literature review regarding ECs, aiming to map all academic literature and identify the various research areas that have addressed this topic. The findings from this research represent an initial step that supports the subsequent phase of ESR15 research by helping to identify research gaps and develop research questions.

ESR15 conducted a bibliometric analysis by extracting papers from the Web of Science database and analysing them using the VOSviewer program. ESR15 utilized various keywords related to the topic of ECs, such as “renewable community of citizens,” “energy community,” “renewable energy community,” “local energy community,” “smart energy community,” and “zero energy community”. Only research papers that underwent a double or peer-review process were considered, resulting in the extraction of 1,445 research papers. Bibliometric analysis primarily serves two purposes: (i) performance analysis, which is descriptive and provides insights into the publication performance of authors' institutions or countries, and (ii) science mapping, which examines the relationships between research elements to reveal the dynamics and structures of a scientific field [17].

ESR15 engages in both descriptive analysis and science mapping analysis by employing various research methodologies. Specifically,

- Descriptive analysis: ESR15 performed a descriptive analysis to explore the evolution of research in EC. This segment of the study emphasizes the annual publication count and identifies the most influential authors, countries, and journals related to the topic.
- Science Mapping: Additionally, ESR15 conducted a keyword co-occurrence analysis to investigate the conceptual structure and highlight the main scientific themes associated with ECs.

2.2. Descriptive analysis

The research outcomes from this study indicate an increase in publications related to the topic of EC after 2017. Specifically, until 2012, the number of publications on ECs was limited to around six papers per year. However, from 2012 onward, a steady increase in publications was noted, with only 43 publications on the topic in 2017. Since then, there has been exponential growth in academic papers, reaching over 300 publications on the topic by 2022.

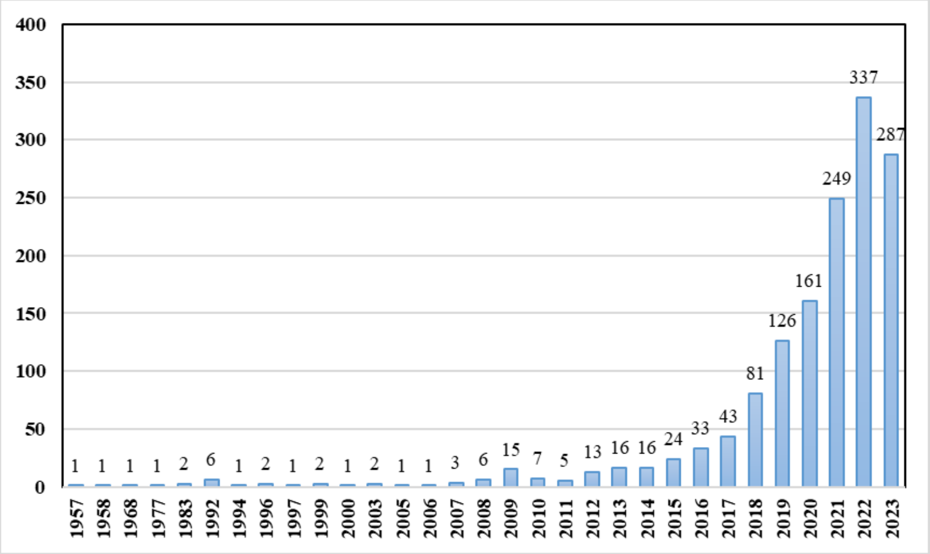

Figure 5: Annual publication related to the topic of Energy Communities.

The analysis reveals an uneven spatial distribution in publications on the topic, indicating that European countries are more productive in both the quantity of documents published and the citations received. Specifically, five out of the six most productive countries for publications are European: Italy, Germany, the Netherlands, Portugal, and Spain. In contrast, only one non-European country, the USA, appears in this group. When considering the number of citations, the results show a similar trend, with European countries still leading. The USA ranks first with 3,004 citations, followed by Italy and Germany, each receiving over 2,000 citations. The Netherlands and England are close behind, each with fewer than 2,000 citations. China rounds out the top six, having garnered approximately 1,300 citations.

Table 2
Most productive countries, in terms of number of papers published and citations

Country	Documents	Country	Citations
Italy	319	USA	3004
Germany	144	Italy	2887
USA	129	Germany	2562
Netherlands	115	Netherlands	1957
Portugal	111	England	1763
Spain	107	China	1306

Table 3
List of authors with more than 200 citations.

Authors	Citations
Bauwens, Thomas	516
Auer, Hans	330
Vale, Zita	264
Guo, Jiacheng	237
Wu, Di	237
Liu, Zhijian	229
Yang, Xinyan	229
Zhang, Shicong	229
Soares, Joao	212

The most influential journals in terms of the number of publications include *Energies*, which has 178 papers, followed by *Applied Energy* with 68 papers and *Sustainability* with 58 papers published on the topic of EC. However, when considering total citations, *Energy Policy* leads with 1,561 citations, followed by *Applied Energy* with 1,276 citations, and *Sustainability* Journal with 567 citations (see fig. 2). The most influential authors, each with over 200 citations, are listed in Table 2.

2.3. Science Mapping: Keyword co-occurrence analysis.

The second part of the analysis conducted by ESR15, namely the keyword co-occurrence analysis, revealed the composition of current literature and the research areas that have been developed in relation to the topic of ECs. Specifically, three main research areas have emerged and are depicted in different colours in the following picture (see Fig. 2).

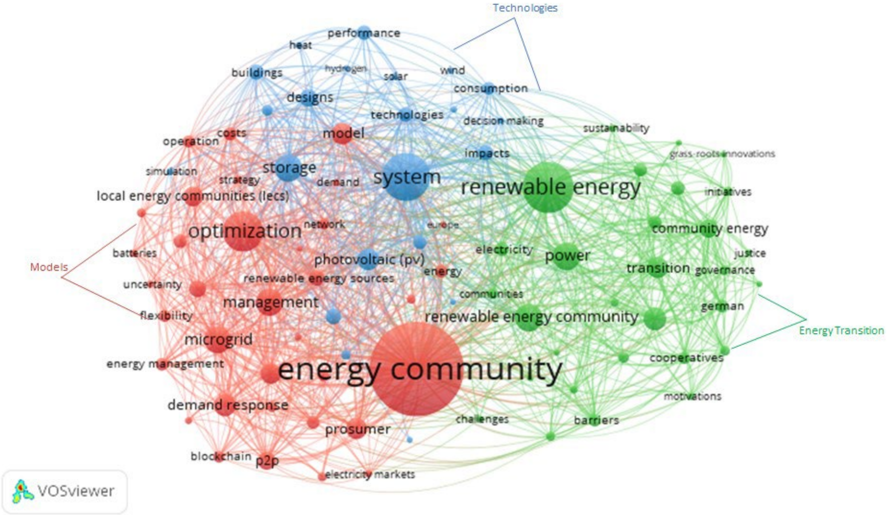

Figure 6: Keyword Co-occurrence analysis related to the topic of ECs.

The first cluster, represented in green, includes studies that analyze the topic of ECs by offering definitions and terminologies. The interpretation of the current research area is based on the types of keywords that appear most frequently within this specific cluster. Notably, the keywords that appear with high frequency include "renewable energy," "power," "renewable energy community," "energy transition," "transition," "community energy," "energy cooperative," "participation," "barriers," "grassroots innovations," etc. (see Fig. 2).

Based on the information provided, ESR15 designates the current research area as "energy transition." This designation stems from the focus of studies within this cluster on analyzing the role of ECs in the energy transition, alongside exploring relevant definitions, terminologies, barriers, and opportunities. For example, Walker and Devine-Wright [10] aim to clarify the fluid meaning of “community” by considering two crucial dimensions essential for understanding the full spectrum of “communities’ social arrangements”: the outcome dimension (i.e., “who the project is for” and “who benefits socially and economically”) and the process dimension (i.e., who “participates,” “manages,” and has “influence” on communities). Moreover, Brummer [18] emphasizes that despite the various definitions of ECs in the literature, there is a general consensus among scholars that the concept includes two key elements: (i) the democratization of the energy system and (ii) the transition to more sustainable energy technologies. Additionally, some studies within this research area aim to investigate the role and potential of ECs in the energy transition by utilizing socio-technical transition theory frameworks such as the Multilevel Perspective (MLP) or strategic niche management (SNM) [19], [20].

The second research area highlighted in red examines various configurations related to ECs and their potential to transform the energy market by providing new services. Some of the most frequently occurring keywords in these research areas include "optimization," "microgrid," "management," "demand-response," "model," "prosumer," "peer-to-peer," and "smart grid." Consequently, ESR15 designates these research areas under the title "models," indicating that studies in this domain explore the different ways ECs operate within the energy market and their transformative potential.

For example, research by Koskela et al. [21] suggests that integrating electricity storage with photovoltaic (PV) power generation can improve economic efficiency compared to relying solely on PV power generation, thereby increasing residential energy production from PV systems. Additionally, electrical energy storage offers benefits such as enhanced self-consumption capacity, demand response capabilities, and the mitigation of high load peaks. Olivella-Rosell et al. [22] proposes a market-oriented framework for managing various flexibility services within the local energy market. This framework enables multiple stakeholders to buy and sell flexibility services. Specifically, an aggregator acts as the operator of the local market, facilitating transactions within the local EC. This approach could yield numerous advantages, including reduced energy costs and an increased distribution hosting capacity for the grids. In contrast, Sousa et al. [23] concentrate on peer-to-peer (P2P) markets, providing an overview that analyzes motivations, challenges, and various market designs.

Finally, the third research area depicted with the blue color focuses on the various technologies that EC has or can utilize. The most frequently appearing keywords in this research area are "system," "storage," "photovoltaic," "design," "self-consumption," etc. Therefore, ESR15 designates this research area with the title "technologies." The studies in this area focus on evaluating various technologies and services, including, among others, energy storage, electric vehicles, demand response, etc., from a techno-economic perspective. Additionally, optimization techniques and methods are proposed to enhance the performance of these technologies. For example, Terlouw et al. [24] developed an optimization model aimed at reducing the environmental and economic costs of ECs utilizing different battery technologies within a community energy storage (CES) system. They proposed two scenarios for CES: an energy arbitrage scenario and an energy arbitrage peak shaving scenario. Likewise, Liu et al. [25] developed a P2P energy optimization, management, and trading approach for hybrid renewable energy systems that include vehicle storage, batteries, and hydrogen vehicles. In their study, the authors compared different ECs featuring various types of vehicle storage, specifically hydrogen and batteries. Furthermore, they assessed different commercial applications and evaluated their performance from both techno-economic and environmental perspectives.

The importance of the current work goes beyond the identification of the research areas that have examined the topic of ECs. As previously mentioned, the size of the nodes in the figure (see Fig. 2) represents the number of occurrences of specific keywords in literature. Consequently, smaller nodes indicate that the associated topics have received less attention in academic literature, indicating potential research gaps. The first research area, "transition," reveals that the keywords "barriers" and "challenges" are significantly less prominent, as indicated by the smaller nodes representing these keywords compared to others that dominate this field of study concerning ECs. In the second research area, "models," there is a noticeable lack of keywords related to the ownership or BMs of ECs. Lastly, in the third research area, which focuses on the technologies associated with ECs, the absence of keywords such as "e-vehicle" and "charging stations" suggests that research on the relationship between ECs and e-vehicle charging stations has been relatively underexplored in academic literature.

The results of the current study highlight research areas that remain relatively unexplored and provide support for the subsequent research phases of ESR15 and

ESR14. Specifically, ESR15 focuses on analyzing BMs and ECs, while ESR14 examines ECs that have implemented projects related to EVCS. The analysis and findings from this research are presented in the following sections of the current deliverable. Finally, the research gap concerning the barriers faced by ECs is addressed in the deliverable, "D.5.4, identifies enablers and barriers to promote the replicability and transfer of business models for Green Energy Systems."

2.4. Energy community business models

As already mentioned, ECs can engage in different activities and involve different types of actors, such as citizens, local authorities, or private actors, with various motivations and different goals [3]. Consequently, ECs can adopt different BMs depending, among other things, on their goals and technological choices. The BM describes the fundamental logic of a firm and how it operates to achieve its objectives. According to Ostervalder et al. [26], a BM outlines how an organization creates, delivers, and captures value. Nonetheless, as sustainability issues gain increasing attention, new definitions and perspectives have emerged in BM research, notably the concept of "shared value." According to Porter et al. [27] shared value can be defined as a way that a business “creates economic value in a way that also creates value for society by addressing its needs and challenges” [27]. This concept is particularly relevant to ECs, which prioritize sustainability objectives such as alleviating energy poverty, raising awareness of environmental concerns, and promoting clean energy solutions.

Based on the various interpretations of BMs and the complexity of EC configurations, many scholars have employed different methodological frameworks to study the topic of ECs [28], [29], [30]. ESR15, by conducting a literature review on ECs and BMs, identified that various frameworks have been utilized to analyze and categorize EC BMs, such as the business model canvas (BMC) [29], [31] and lean canvas framework (LCF) [32]. Additionally, some studies have sought to analyze and categorize EC BMs based on unique characteristics of ECs, such as membership and governance [33].

Currently, there is no widely accepted analytical framework in academic literature for analyzing and categorizing various EC BMs. To address this gap, ESR15 aims to identify and categorize all key dimensions present in the literature and highlight the most recurrent ones. Through this study, ESR15 aims to develop a customized analytical framework for EC BM analysis. This framework has been implemented, resulting in the definition of four distinct EC BM archetypes. These archetypes function as general theoretical models that illustrate mechanisms for describing the differences among EC initiatives in their processes of generating, delivering, and capturing value.

2.5. A tailor-made analytical framework

ESR15 conducted a semi-structured literature review to analyze the current literature on EC and BMs. To achieve this, papers were extracted from the Web of Science and Scopus databases. Various keywords were utilized based on the most frequent and relevant terms related to the topic of ECs [7], including "energy community," "community energy," and "renewable energy community." Additionally, to examine the unique characteristics of ECs, keywords such as "business models," "archetypes," "model," "cluster," "taxonomies," and "categories" were also incorporated. As a result of this search, 30 relevant papers were selected, comprising 25 journal articles, 4 reports, and 1 book chapter.

All papers identified through the literature review were analyzed to determine the most essential dimensions used for EC BM analysis. A content analysis was conducted for this purpose. Initially, 30 dimensions were identified; however, due to the thematic relationships among them, terms with similar meanings were consolidated, leading to the identification of 13 unique dimensions.

Table 4. The five dimensions of the tailored BM framework for ECs.

Dimensions	**Description**	**Occurrences in the literature**
Value proposition	Refers to EC's main objective and the benefits provided to its members and society.	21
Value capture	Refers to revenue stream and cost structure of the EC.	9
Main functions	Refers to the main activities, technologies and services of the EC.	12
Governance	Refers to the management, decision-making and control of the EC.	9
Membership	Refers to the different types and roles of actors participating in the EC as members.	16

From those 13 dimensions, however, only 5 were kept because of the high occurrence in the literature and the relevance to the topic under investigation. ESR15 excluded dimensions that appear only sporadically or do not align with the primary objectives of BM analysis. Specifically, the dimensions that consist of the analytical framework found by ESR15 are “value proposition,” “value capture,” “main functions,” “governance,” and “membership.” (see Tab. 1).

The dimension that appears more in the literature is the “value proposition,” which is the cornerstone for BM analysis. It appears 21 times, albeit in various terms, in the literature review, such as organizational purpose [3], goals [34], or benefits [35], and it describes the EC’s main objective. Based on Osterwalder et al. [26], ESR15 defined the value proposition as the advantages members gain from EC services. “Value capture” is the second dimension of the analytical framework, noted 9 times in the literature review. It pertains to cost structures and revenue streams, although various terms are utilized in the literature, such as financial models [30], value-sharing mechanisms [36], and energy value capture [33]. These terms illustrate how ECs allocate profits among their members [37]. Therefore, all these terms were categorized by the ESR15 dimension, as they all relate to the methods by which the EC can secure value for its members or clients.

The dimension "main function" pertains to the key activities, technologies, and services employed by ECs, appearing 12 times in the review, albeit under varying terminology. Regardless of the specific terms used, they all highlight the crucial role of ECs in participating in diverse energy services and activities [37], which include, among others, energy self-production and consumption, energy sharing, energy supply, and retail. Furthermore, ESR15 incorporates terminology from studies that examine the technologies used by ECs [15], [38], [39], as these technologies are vital for achieving the objectives of ECs [33]. It is also important to note that the main function dimension includes both value creation and value delivery, outlining the functions that ECs must fulfil to generate and provide value to their members or the local community.

The last two dimensions that complete the BM analytical framework are "governance" and "membership." Governance refers to the management and control of an organization, as well as the interactions among its participants [40], and appears 9 times in our literature review. However, not all studies use the same terminology. For instance, Caramizaru & Uihlein [3] categorize ECs based on the extent of their "autonomy" and "effective control" of strategic assets, such as energy generation assets. "Autonomy" refers to the ability of ECs to remain independent from individual members or market actors participating in the community. "Effective control" implies that community members have the capacity to exert decisive influence over the EC's decision-making and operations [3]. Moreover, ESR15 includes in the governance dimension reports and papers that consider the legal forms of ECs, as these are closely linked to the governance structure. Cooperatives that operate as ECs typically follow the principle of "one member, one vote," while partnerships and other legal forms adhere to different principles, such as quotas or shares, utilizing various governance types.

The "membership" dimension is mentioned 16 times and pertains to the various types of actors involved in the EC, including citizens, SMEs, and local authorities, as well as their respective roles within the community. Scholars employ different terms, such as participants [3], members of the EC [33], or actors [39]. Reference [11] distinguishes between the types of actors engaged in ECs and examines their functions across different EC BMs. Some studies concentrate on the diverse types of actors who can join and collaborate with an EC [41], while others highlight their positions in the energy market, differentiating between categories like "prosumers," "pure consumers," and "storage operators" [2]. Consequently, the "membership" dimension in our analysis encompasses not only the types of actors but also their roles within the EC.

The five dimensions mentioned above form the analytical framework intended to serve as a conceptual tool for academics, policymakers, or even ECs to analyse and categorize various EC BMs. ESR15 utilizes this framework to define EC BM archetypes, which are detailed in the following section.

2.6. Energy Community Business Model Archetypes

As mentioned earlier in this report, an archetype is an abstract theoretical model that represents a set of mechanisms distinguishing EC initiatives based on how they generate, deliver, and capture value. Utilizing the 5-dimension framework, ESR15 identifies four distinct EC business model archetypes: the self-consumption model, the third-party model, the aggregator model, and the e-service and e-mobility model. These four archetypes are differentiated across all five dimensions of the analytical framework. A detailed representation of the archetypes is provided below.

2.7. Self-consumption model

The self-consumption model seeks to lower energy bills by establishing collective power plants that generate and utilize energy for members of the EC. In this way, it functions as a collective prosumer, opting to self-consume energy rather than selling it to the grid. This model protects EC members from price fluctuations and can benefit vulnerable households by combating energy poverty.

The value capture mechanisms of this EC BM archetype rely on various strategies. Initially, opt-in or opt-out fees are implemented for members so the community can cover the costs, like power plant installation and maintenance. In addition, members buy shares in the EC, increasing the community's share capital. Finally, annual fees can cover labour and other expenses. Nevertheless, ECs under this archetype typically rely on voluntary work and do not incur high maintenance costs. The largest cost is power plant installation, which can be raised through public funding or crowdfunding campaigns.

The main function of this model is to create and supply energy through a PV energy production system owned by the community, which supplies energy to the grid. However, different types of technologies, such as wind, can be applied. A licensed supplier assesses the community's energy output and deducts it from the total energy consumed by the community. This process of offsetting the energy produced against the energy consumed ensures that community members either pay nothing for electricity or only incur charges if their consumption exceeds their production.

Regarding the membership and governance, it should be noted that this EC BM archetype is citizen-driven, with different types of members, such as SMEs or local authorities, participating. All members can be considered collective prosumers, with no distinct roles within the community. To enhance community performance, the EC operation may assign specific responsibilities to certain members. The governance structure is typically based on the cooperative model, applying the one-member-one-vote principle.

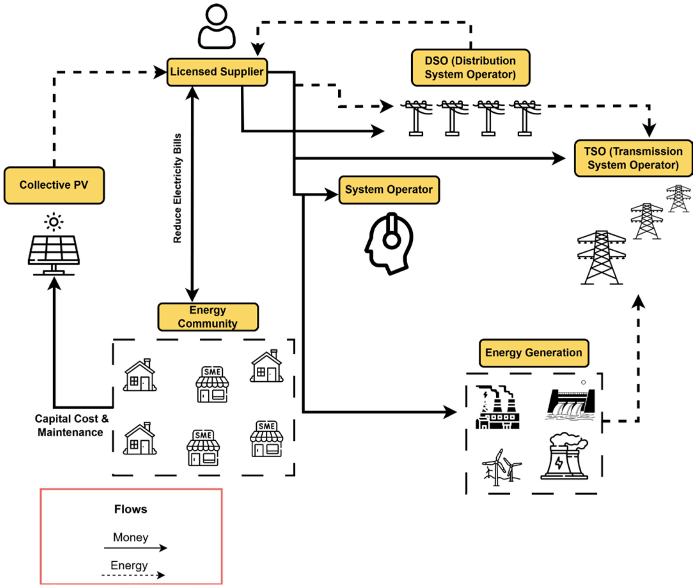

Figure 3: Self-consumption business model archetype.

2.8. Third-party model

The value proposition of third-party modes centers on lowering energy costs for EC members by enabling collective purchases of renewable energy at reduced prices or by facilitating the rental of energy production assets provided by third parties. In this EC business model archetype, the third party plays a vital role as an external stakeholder, assisting in the establishment and operation of the EC by offering energy services, providing technical and management support, or potentially financing the entire project. There are two distinct mechanisms for value capture, one for the third party and another for the EC members. The value capture mechanism for the third party relies on a long-term revenue stream from the EC members, which can occur through the sale of energy or services at predetermined prices via long-term agreements or through the lending of energy production assets to the ECs. For the members of the ECs, the value capture is derived from reduced electricity bills and the fact that the third party assumes responsibility for the project. As a result, there is no financial risk or maintenance cost burden for the members of the EC.

The main function of this model is to facilitate energy purchases by establishing an EC that serves as an energy buyer. In this arrangement, a third party is responsible for the installation and maintenance of the energy production project. Consequently, this third party oversees and manages the project. Because EC members rely on the third party to deliver specialized services tailored to the community's needs, they are excluded from decision-making and control regarding energy production assets. Typically, this EC model encompasses residents or small and SMEs in proximity, such as those in large building complexes, social housing, or small towns. All EC members are consumers who own the properties where the power plants are located.

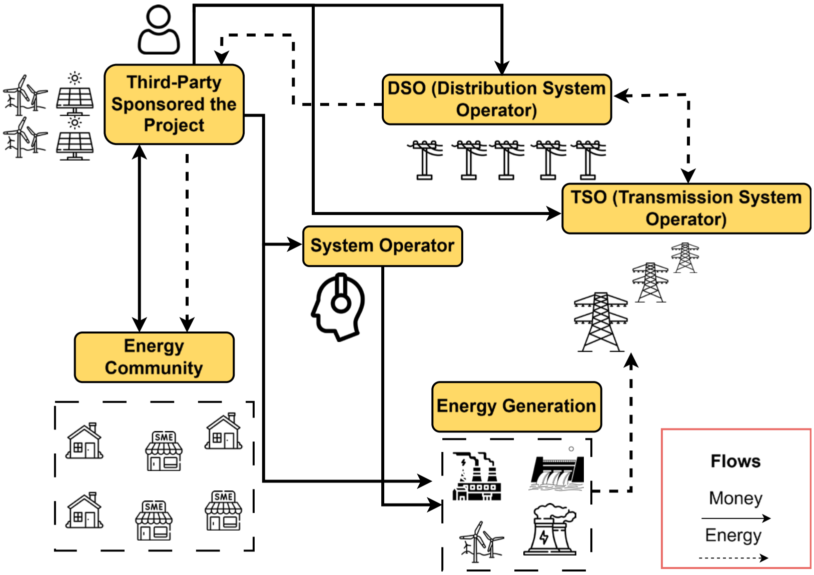

Figure 4: Third-party business model archetype.

2.9. Aggregator model

The value proposition of the EC aggregator archetype lies in the benefits that economies of scale provide for managing energy production and demand. An aggregator can dispatch energy more efficiently than a single agent or an EC with few members that act individually, optimizing the energy it produces and consumes while also offering flexibility and balancing services to the grid.

The value capture mechanism of this archetype varies by member, with some acting as prosumers, some as producers, and others as consumers. It is important to note that all EC members are responsible for owning, financing, and installing the storage systems and technologies necessary to monitor and optimize services. This arrangement allows the aggregator to save energy, while prosumers can earn revenue from the energy they supply to consumers or the grid. Additionally, revenue for the aggregator can be generated through opt-in and opt-out mechanisms, as well as through fees for services provided to external entities. However, the distribution of revenues depends on the roles of the members and the services they provide.

The main function of this archetype centres on the concentration of total supply and demand within a community. In this context, producers, or prosumers, members of the community, supply energy to other members of the community or to external stakeholders, such as grid operators. The aggregator plays a crucial role by providing energy, flexibility, and ancillary services on both the supply and demand sides. It can store excess energy from the system or transfer surplus energy generated by the community back to it. Additionally, the aggregator utilizes a platform for daily operations to coordinate the various members of the EC. While the implementation of this model may vary, its fundamental function involves using the platform to manage energy sharing and optimize demand management within the community, as well as to facilitate interactions among members and external entities.

The membership of this archetype may vary; however, it is evident that it can involve a range of actors, including citizens, local authorities, and private entities. It is important to note that EC members may assume different roles, as previously mentioned; some may act as prosumers, while others may be simple consumers. Despite these varying roles, all members share a common interest in energy sharing, participating in the energy market, and being managed by an aggregator. Regarding governance, all members take part in decision-making processes, and energy assets can be owned and controlled either individually or collectively. However, the aggregator oversees, manages, and facilitates interactions with suppliers and network operators.

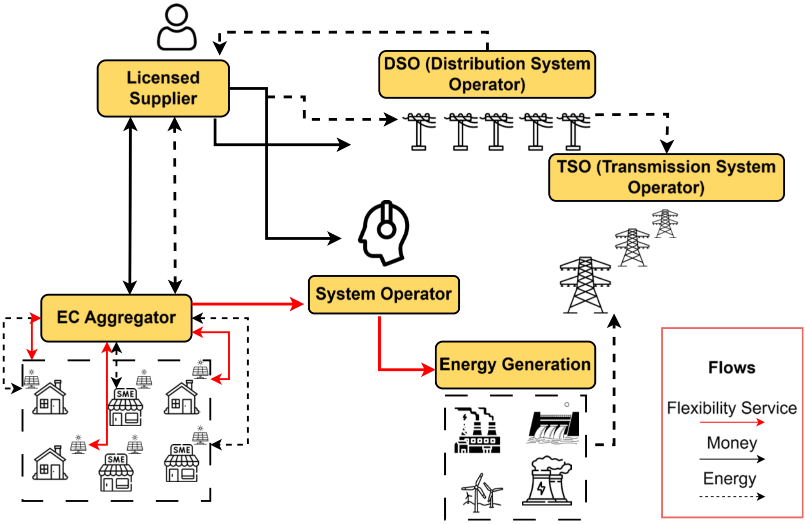

Figure 5: Aggregator business model archetype.

2.10. Integrated energy services and E-mobility model

The value proposition of this archetype lies in offering integrated, low-carbon services that can support various actors. Consequently, BMs that fall under this EC archetype are characterized by the diverse range of services they provide to both their members and external stakeholders. The value capture mechanisms differ among the participating actors, the services utilized, and their respective roles. Consequently, e-vehicle services, energy savings, and opt-in and opt-out membership fees can function as revenue streams.

The main function of this EC shares characteristics similar to that of the previously mentioned aggregator archetype, as the members of the EC have specific roles and provide services both within the community and externally. However, this model also encompasses activities that extend beyond energy generation and flexibility provision, offering additional services such as EVCS and car sharing.

The membership structure includes various types of participants, such as citizens, local authorities, and SMEs. Members of this EC business model archetype can hold the EC's assets collectively or individually and engage in decision-making based on their respective quotas. The EC in this model provides management services and collaborates with suppliers and network operators, offering tailored solutions to secure long-term contracts. Moreover, this model is designed to adapt its services to meet the specific needs of its members.

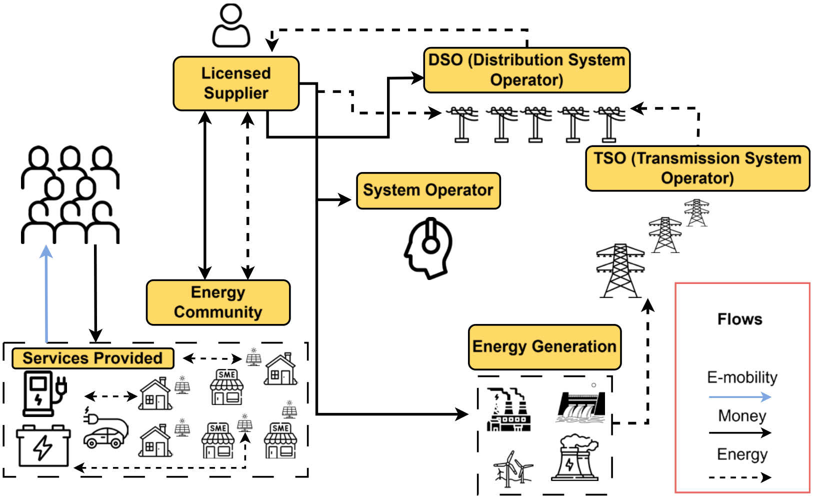

Figure 6: Integrated energy services and e-mobility business model archetype.

3. Electric Vehicle Charging Station for university (Case Study I: RES-powered EVCS for a university)

After analysing four BM archetypes, attention turned to assessing the viability and opportunities of introducing electric vehicle services, such as EVCS offered as a service for ECs members and other end-users. The purpose of this subsection is to evaluate how renewable energy source (RES)-powered EVCS can support both university authorities and energy users from a technical and economic perspective, positioning them as innovative energy services within ECs. The subsection presents the results of a techno-economic assessment of RES-powered EVCS, highlighting their potential to enhance the sustainability and economic viability of ECs. Demonstrating the integration of EVCS into ECs is crucial, as it shows how such solutions can enable local citizens to achieve greater energy independence while advancing the transition toward sustainable and decentralized energy systems.

3.1. Background and Literature Review for Case Study I

More than 25% of the EU's total CO_2 emissions were produced from the transportation sector in 2022, where road transport (cars and heavy-duty trucks) is responsible for 71.7% of total emissions produced by the transportation sector. 92% of cars in the European Union (EU) are Internal Combustion Engine (ICE) vehicles powered by fossil-fuels (petrol and diesel) according to the European Automobile Manufacturers' Association, or ACEA. To reduce emissions, the EU fleet-wide CO2 emission target set for both cars and vans is 0 g CO2/km from 2035 onwards, subsequent to achieving a 100% emission reduction [42]. The market must be able to accept new EV customers, since EVs are essential in mitigating GHG emissions. Furthermore, EV consumers are facing several barriers to buying EVs, including a lack of knowledge [43], high purchase cost [44], and limited autonomy, but mostly about the lack of EVCS availability [45]. The lack of availability of EV charging infrastructure slows down interest in buying EVs in many countries [46], [47]. Therefore, to increase EV adoption and fulfil the demand of EV users, adequate EVCS's are required to charge their EVs. Nevertheless, the majority of EVCS's rely on fossil fuels (as 60.65% of total energy generation of the world is from fossil fuels), resulting in higher grid emissions as most of the EVCS powered by energy grid.

EVCS can be integrated from the local level, including ECs, to enhance the integration and solve some technical and infrastructural barriers. ECs are primarily responsible for producing RES for self-consumption and energy sharing among EC members. However, one of the primary challenges faced by ECs is the intermittent nature of RES, such as solar and wind, which can lead to imbalances between energy production and consumption, and solar energy is not available during nighttime. The intermittent nature of renewable energy sources and the lack of energy availability during nighttime can significantly hinder the operation of ECs, where EVs can be utilized as a key storage solution. EVs function as decentralized storage units with batteries that store excess energy during peak production and release it during periods of increased demand. In addition to storage, EVs can provide vehicle-to-grid (V2G) and vehicle-to-home (V2H) services, enabling bidirectional energy flows that support both the grid and individual households. But adapting EVs and charging them with renewable EVCS is a key option, and it can be worked as a service for ECs to generate benefits for their members. These services support the grid and provide flexibility to EC members. In the next part a literature analysis was done to see what the progress in current research field regarding the EVCS are. A summarized literature matrix of the selected papers is presented in Table 5.

Table 5. Summarized literature matrix of the selected paper.

Ref	Location	Year	Simulation tool/Method	Application	Charger Method	MG configuration	Charger number	Economic Parameters
[48]	Portugal	2022	HOMER Grid	Not Found (NF)	Leverl-2 (L-2), Leverl-3 (L-3)	PV-ESS-Grid	2	COE, NPC, CAPEX, OPEX
[49]	Romania	2019	HOMER Pro	Residential	L-2	PV-Grid-WT-BESS	2	COE
[50]	Portugal	2021	GAMS, MILP	University	L-2	PV-Grid	110	COE
[51]	Bangladesh	2023	FLC, RNN, LSTM, HOMER Pro	Airport	L-3	PV-WT-Grid	25	COE, NPC, CAPEX, OPEX
[52]	Qatar	2022	HOMER Pro	NF	L-3	PV-WT-Biomass-ESS	50	COE, NPC
[53]	Turkey	2019	ETAP	NF	L-2	PV-Grid	100	Not Found (NF)
[54]	NF	2020	MILP, GAMS	NF	Leverl-1 (L-1), L-2, L-3	BESS-WT-Grid	14	CAPEX
[55]	Australia	2020	MATLAB 2018b	NF	NF	WT-PV-CSP-Grid	NF	COE, CAPEX
This work	Portugal	-	Python, HOMER [4]	University	L-3	PV-WT-Grid	25	COE, CAPEX, OPEX, NPC

Costa et al. were working on an energy system for EVCS by proposing an energy system considering PV-Energy Storage System (ESS)-Grid by utilizing HOMER Grid software in Portugal [48]. The energy system was designed for two levels of EV chargers (L-2 is semi-fast charging, and L-3 is fast charging) [48]. To develop the energy system, 30,324 euros were required as Capital Expenditure (CAPEX) and achieved a COE of 0.156 euro/kWh.

Osorio et al. proposed a model for EVCS with solar rooftop in Portugal [50]. The model was developed in the General Algebraic Modeling System (GAMS) using the Mixed Integer Linear Program (MILP) solver. PV-Grid was considered an energy system for the EVCS, where 110 EVs were recharged from EVCS, whereas only an L-2 charger was taken into consideration. To conduct the analysis different energy prices were considered and profitability was achieved by proposing the EVCS. Hence, State of Charge (SOC) [5] and load profile estimation are not clearly mentioned in the research. Turan et al. investigated the effect of EVCS equipped with roof-mounted PV panels in Turkey [53].

Furthermore, Hasan et al. proposed an EVCS for an International airport in Bangladesh [51]. They utilized Fuzzy Logic Control (FLC), Recurrent Neural Network (RNN), and Long Short-Term Memory (LSTM) to develop the load profile, and they conducted an energy-economic assessment using HOMER Pro software. Also, the most optimal energy system was the PV-WT-Grid for 25 EVs. Also, to achieve the best results, 3.6 million $ was required as CAPEX for setting up the charging station, which had 84.3% of renewable energy fraction with a payback period of 6.30 years [51]. Although SOC estimations or assumptions are not clarified in the research. In addition, Wahedi et al. proposed a stand-alone RES-based EVCS for four cities in Qatar [52]. In this research work, the combination of the best configurations was Photovoltaic, Wind Turbin, Biomass and Energy Storage Systems (PV-WT-Biomass-ESS). They used HOMER Pro software to optimize the COE, and their proposed design could charge 50 EVs

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[4] HOMER is a simulation software that assists users to perform energy-economic optimization with RES's [63].

[5] The term "SoC" refers to the ratio of a cell's operational capacity to its maximum achievable capacity [64].

simultaneously. Moreover, the COE of their proposed system was between 0.285 to 0.329 $/kWh. Since this was a proposed EVCS, load profile design assumptions could be justified in the study, because without proper assumptions, the feasibility study will not be reliable.

After analysing current literature [48], [49], [50], [51], [52], [53], [54], [55], only some of these studies mentioned how they collected data or prepared the load profile with collected data or estimation. It is crucial to consider predicting or estimating load profiles to understand the electricity demand of EVCS. Therefore, it is crucial to estimate the load profile with better estimations.

Moreover, the majority of EVCS's are directly linked to the traditional electrical grid, which in several areas continues to depend significantly on fossil fuels like coal and natural gas. Consequently, charging EV's with grid energy still generates considerable GHG emissions, particularly if the electricity is not derived from RES's. This constrains the environmental advantage of EV adoption. Consequently, to efficiently reduce fossil fuel energy usage and enhance sustainability, it is essential to establish and deploy EVCS's powered by RES's, such as solar or wind energy. Therefore, the main goal of our study is to perform an energy-economic[6]-environmental optimization by conducting the feasibility of RES-powered EVCS at the NOVA University Lisbon, Caparica, Portugal (this location is considered as a pilot case[7]).

3.2. Methodology of the Case Study I

An energy resource assessment was conducted to determine the suitability of the EVCS site, considering solar radiation, wind speed, and grid connectivity options. Following this investigation, solar and wind energy were identified as the primary renewable energy sources. PV panels were selected based on favourable solar conditions, with an average daily radiation of 4.86 kWh/m^2/day. Additionally, wind turbines (WT) were chosen due to the site's proximity to the sea, which offers favourable wind conditions, averaging 6.68 m/s [56]. A grid-connected architecture was selected, allowing for the import of energy during periods of insufficient renewable production and the export of excess electricity to the grid, thus generating potential revenue streams. Figures 7 and 8 show the monthly profiles of solar radiation (including clearness index) and wind speed, highlighting the renewable energy potential of the chosen area.

At first, data (TOA and TOD of parked cars in the university) is collected from the FCT NOVA parking lot, to understand the occupancy of the vehicles and their average staying time in the parking lot. When the dataset was analysed, certain challenges were identified: due to the General Data Protection Regulation (GDPR) law, it was not possible to accurately identify when a vehicle arrived or left the university. Therefore, specific information could not be found about which car would arrive at or leave the university. However, the data on the TOD and TOA of the cars are available. A Python

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[6] Techno-economic analysis (TEA) is a technique for assessing a technology's financial performance, according to the US Department of Energy (DOE). A TEA evaluates a technology's total worth, enabling analysts to appropriately balance costs and advantages [65].

[7] Many people arrive every week at the university, including teachers, researchers, staff, students, and visitors. As a lot of people came to the university by utilizing different transportation systems (including cars) we considered this location as a living lab for our analysis.

script was written with a developed algorithm by utilizing the first in first out (FIFO [8]) method [57]. As we found in the literature, many researchers employed the FIFO method for EVCS parking lot scheduling [58], [59], [60], [61].

To calculate the load of EVCS, equations are required; therefore, in this subsection, two equations are developed to estimate the load profile. With the first equation, the number of EVs are calculated that arrive every day in the parking lot by employing equation (1).

$$N_{T\_EV} = N_{T\_C\_E} * A_{P\_EV} \tag{1}$$

N_{T_EV} is the Number of EVs, $N_{T\_C\_E}$ is the number of cars arriving every day, A_{P_EV} is the assumed percentage of EVs. Also, the load estimation will be done by utilizing the data curation output precisely the output of the cars arriving in one day and multiplying with pattern percentage, the dedication hour to charge EVs and the SOC power level by utilizing equation (2).

$$L_{Est} = N_{T\_EV} * A_{PP} * t * P_{SOC} \tag{2}$$

Where Load Estimation denotes as L_{Est} , Total EV number is N_{T_EV} , Assumed Pattern Percentage indicates as A_{PP}, Hour is t, and Starting Power of Charger at different SOC levels denotes as P_{SOC}. After designing the load profile from equation (2), this load profile will be fed with collected energy-economic-environmental parameters into the HOMER optimization tool for the EVCS integrating a decentralized microgrid.

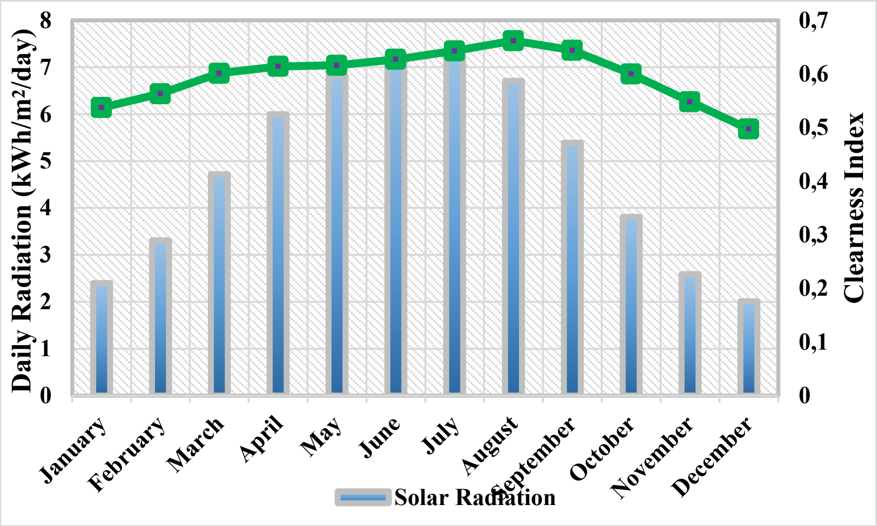

Figure 7: Monthly solar radiation to understand the potential of the selected location with clearness index.

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[8] FIFO means "First In, First Out" and is an asset-management and valuation method in which assets produced or acquired first are sold, used, or disposed first [66].

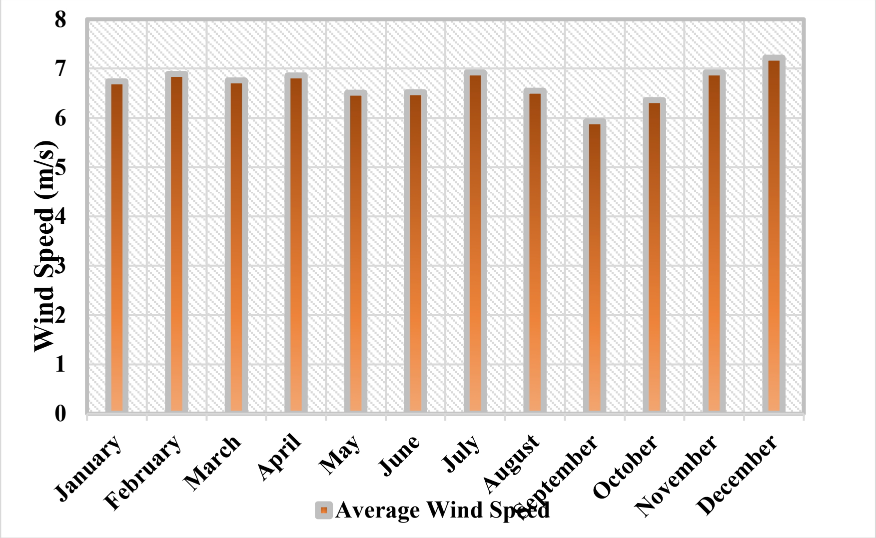

Figure 8: Wind speed to understand the potential of the selected location.

After developing the equation, the scenario development has been done. In energy-economic-environment feasibility studies, a few scenarios are considered when analysing the developed energy system. Overall, four scenarios were considered to conduct our analysis: (i) Scenario-1 (S1) is PV, WT and Grid, (ii) Scenario-2 (S2) is PV and Grid, (iii) Scenario-3 (S3) is WT and Grid, and (iv) Scenario-4 (S4) is only Grid (Base Scenario). In the S1, energy is supplied through the grid and on-site RES combined with PV, WT, reducing reliance on the conventional grid. S2 incorporates a PV and grid facility as backup energy. On the other hand, the main source of energy is WT and utilizes the grid as a backup system for buying energy from the grid. S3 is dedicated to WT instead of PV but similarly grid connections are available like S1 and S2. Furthermore, the S4 serves as the baseline, where EV's are charged solely from the grid without any direct integration of RES. This scenario provides a reference point for evaluating the performance of the other three scenarios.

The system sizing was done with the assistance of HOMER, a built-in optimizer. First, the auto optimizer option was utilized, and, later, the different component capacities were calibrated manually by setting the upper and lower limits of the system as constraints. Afterward, the software iterates several times to obtain the best possible solution for various configured systems. Techno-economic analysis was conducted through the input of estimated load, technical, economic, and environmental data from research papers and reports into HOMER software. Energy-economic optimization uses HOMER to compute Net Present Cost (NPC[9]), CAPEX[10], Operational Expenditure

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[9] The NPC is the difference between the total cost of the project and the revenue generated by the system during the project period [67].

[10] CAPEX refers to an organization's funds to acquire, upgrade, or maintain physical assets such as property, buildings, technology, or equipment [68].

(OPEX[11]), COE[12], and CO2 reduction. Table 6 displays the summarized economic analysis of Case Study I.

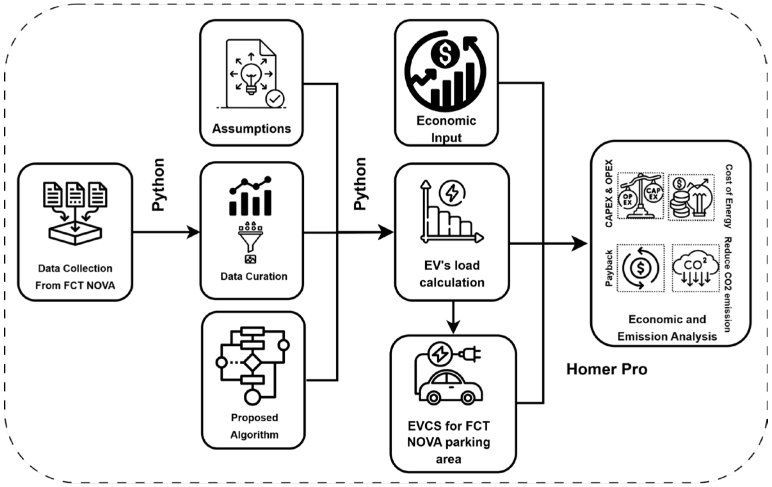

Figure 9: Methodology of the work.

3.3. Results of the Case Study I

Table 6

Summarized Economic Analysis results of Case Study I

Scenario	NPC (million $)	CAPEX (million $)	OPEX (million $/year)	COE ($/kWh)
S1	13.62	0.74	0.35	0.23
S2	5.66	3.67	0.023	0.027
S3	11.16	3.34	0.21	0.11
S4	5.89	5.89	-0.045	0.019

Among the four cases, S1 has the highest NPC of 13.62 million $. With a COE of 0.23 $/kWh, S1 leads in terms of achieving lowest COE among four scenarios. Additionally, S1 has the lowest CAPEX at 0.74 million $, primarily due to its allocation to network-related expenses. Among the four cases, S1 has the maximum OPEX. Moreover, S2's NPC is 5.66 million $, higher than S1's NPC. Hence C2's OPEX is 0.023 million $/year. Furthermore, S2 has a CAPEX of 3.67 million $. Besides, S3 has an NPC of 11.16 million $. The OPEX of S3 is 0.21 million $/year. S3's CAPEX also comes at 3.34 million $.

Among the four cases, S4 has the least NPC of 5.67 million $. On the other hand, S4 had the best CAPEX at 5.89 million $. Nevertheless, with the highest CAPEX, S4 is

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[11] OPEX or Lease Operating Expenses (LOE), lifting, or production costs, refer to items with a useful life of one year or less. Their costs are recorded as expenses in the accounts [69].

[12] The COE is defined as the annual cost ratio to the supplied electrical load [67].

regarded as the best scenario among the four cases. Furthermore, S4 has the lowest -0.045 $/year OPEX. Conversely, S4 has the lowest energy purchase and the largest energy sales from the grid. Therefore, in the most ideal case, economic parameters were calculated in the best-case comparison to the grid scenario; so, NPC and COE in the best cases are lower than in the grid cases as base.

This study's results demonstrate that the implementation of EVCS is both technically and economically viable within the analysed scenario. This substantiates the feasibility of extensive infrastructure development as an essential facilitator of the EU's shift to electric transportation. However, there are several limitations to this study. First, the percentage of EVs among cars arriving in the parking lot was estimated. This is an assumption made to estimate the load profile as are proposing this EVCS for the next 25 years. The second constraint of our work is that only considered the most sold EV car brand in Portugal. In our future work, different EV models and hybrid EVs will be considered to determine their feasibility with EVCS. Also, machine learning techniques will be integrated to predict load profiles for the EVCS. Furthermore, a sustainable service for the university's people will be planned. Categories of actors will be examined who can cooperate with for investments and offer a sustainable service. Furthermore, further studies must be performed globally to check their feasibility among various parts of different countries.

As observed, this case study is quite helpful for universities planning to build an EVCS and can be replicated to develop EC projects in the following case study combining university and community settings.

3.4. EVCS for EC (Case Study II: RES-powered EVCSs for a Building Community and a university)

In Case Study I, a university campus is considered to evaluate the technical and economic feasibility of a RES-powered EVCS. While this case study does not focus on an existing EC, a university campus is chosen because of its high energy consumption by many users and its local generation potential, which is similar to that of an EC. These similarities make university campuses ideal for testing EVCS. Furthermore, the optimisation analysis conducted for this Case Study I was conducted in a single step. In contrast, Case Study II involves integrating a building community with the university campus. The main difference lies in the optimization analysis methodology and comparison with and without VPP, which now employs a two-step optimization process and incorporates VPPs to improve the technological advancement of energy integration. VPP is considered for integrating new solutions into the energy grid. VPPs coordinate distributed resources (PV, energy storage, and EVs) to optimize energy flows, offer flexibility services, and increase economic and technical feasibility, unlike Case Study I, but it can operate remotely as well. VPPs enable decentralized RES production and EV within VPP frameworks.

Techno-economic analysis of RES-powered EVCS can deliver useful results such as (a) assist ECs' managers to understand the initial investment and possible profitability, (b) optimize energy-economic parameters and see their variances before even the project is built, and (c) convince investors to invest in sustainable projects with validation of the payback period.

3.5. Background and Literature Review for Case Study II

Many EVCS operate on carbon-intensive energy sources, limiting potential emissions reductions. To mitigate this issue, integrating RES with EVCS, either on-site or through VPP [13], is a promising approach to reducing GHG emissions and improving overall energy sustainability in the transport sector. However, the intermittent nature of RES, along with challenges related to energy storage and the spatial requirements for RES installations, complicates the implementation of EVCS powered by RES [4]. Therefore, the techno-economic feasibility of such solutions remains an area that needs to be examined.

Some studies attempted to analyse EVCSs from a techno-economic point of view, considering different techno-economic parameters. Arslan and Karasan examined the economic and emission impacts of VPP development in networks with plug-in hybrid EVs [5]. Moreover, Alabi et al. suggested a unique hybrid robust-stochastic approach to facilitate the optimum scheduling of a Zero-Carbon Multi-Energy System (ZCMES) using a VPP, taking into account EV adaptability while calculating OPEX and revenue [6]. Furthermore, Wang et al. developed a Deep Reinforcement Learning (DRL) approach for a VPP including EVCSs. The findings indicate that the VPP agent is capable of acquiring the strategy for selling energy to EVs, optimizing the scheduling of Distributed Energy Resources (DERs), and formulating a bidding strategy for engagement in the electricity market [7]. Besides, González-Romera et al. proposed an Energy Management System (EMS) for a residential VPP by incorporating PVs, Battery Energy Storage System (BESS), and EVs. They employed a Genetic Algorithm (GA)[2] to optimize energy costs and improve technical aspects by changing their scheduling [8]. Moreover, Alabi et al. proposed a deep learning approach (GRU-BiLSTM) and optimization model for multi-energy systems by the inclusion of EV's and carbon capture systems [9].

Although the above-mentioned studies have boosted research in this area, they still present some limitations, as a comprehensive assessment of economic viability has not yet been fully addressed. For example, Wang et al. considered profit, EVCS cost, and penalty cost. However, they did not calculate the overall economic feasibility [7]. Similarly, Alabi et al. did not consider key economic aspects such as COE and CAPEX [9], while González-Romera et al. did not perform a detailed economic analysis [8]. Therefore, a gap exists in academic literature due to the lack of robust techno-economic analysis that encompass both key economic parameters and technical comparisons between on-site RES production and storage and VPP. Hence, to address this gap, the goal of this work is to perform a techno-economic feasibility analysis of combining an EVCS with a VPP or on-site RES at the NOVA University Lisbon and considered residential-load3. This study seeks to provide insight into both the economic and environmental benefits of using RES or VPP-supported EVCS infrastructure. H. The

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[13] A Virtual Power Plant (VPP) is described identically to an autonomous microgrid [25]. VPP can work as a distant energy storage and energy generation plant. Also, VPP is an aggregation of decentralized units whose operations for the power grid are managed by a unified control system [26]. These units could encompass electricity producing systems such as biogas, wind, and photovoltaic energy conversion systems, cogeneration hydroelectric power plants, electricity consumers, and electricity storage facilities [26]. A VPP can play a vital role in energy export and import to the grid [27]. Also, it can work as an aggregator [28]. The energy generator and grid operator formalize an agreement that may include net metering or virtual accounting, ensuring hourly alignment between energy supplied to the grid and withdrawn by the EVCS. These agreements may also consider EVs as storage or assume full generation capacity of the RES facility.

main contribution of this study is performed one-layer technical optimization and two-layer economic optimization for energy systems serving an EVCS and residential load.

3.6. Schematic diagram of the prototype

To conduct this work, first, data were collected from a specific location to perform the analysis, which is NOVA University Lisbon. Later, for the residential load, a building dataset was utilized [13]. By combining these two datasets a load profile [14] was developed. This load profile, technical and economic data was entered into the HOMER [14]) software to perform a first layer technical and economic optimization. After performing the first layer optimization, the CAPEX, OPEX, COE, NPC, and CO_2 emissions rate were obtained. Then, the techno-economic output of HOMER was given as input to MATLAB. In MATLAB, GA was used to perform the second layer of economic optimization. In Fig. 10, displays the two-layer optimization methodology for EVCS.

In techno-economic feasibility studies, a few scenarios are considered to analyse and check which one is better for the developed energy system. Overall, three scenarios were considered to conduct our analysis: (1) First Scenario-FS (Base scenario-BS) is a G2V infrastructure, (2) Second Scenario-SS is EVCS with RES on-site including BESS technologies, and (3) Third Scenario-TS is EVCS powered by VPP. Fig. 2 displays three considered cases in this work.

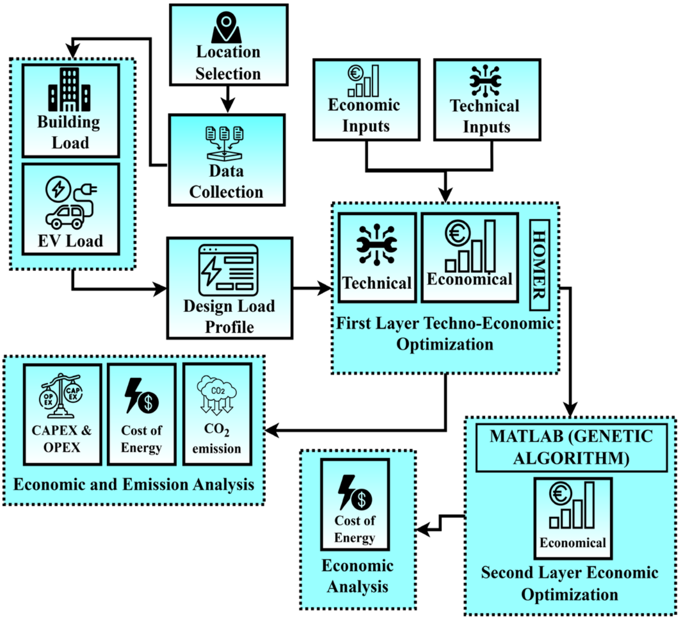

Figure 10: Methodology of two-layer optimizations for EVCS [62].

The FS serves as the baseline, where EV's are charged solely from the grid without any direct integration of on-site RES generation. This scenario provides a reference point

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[14] A load profile is a graph depicting power consumption over time, whereas load profile diagram illustrates accumulated power consumption in relation to operating period [30].

for evaluating the performance of the other two scenarios. In the SS, energy is supplied through on-site RES generation combined with a BESS, reducing reliance on the conventional grid. TS incorporates a VPP for remote energy storage and a DER-based PV generation facility. Both are located at the same site, which is physically separated from the university and residential loads. While the first two scenarios are primarily simulated using the HOMER tool. Afterward, the output of HOMER was extracted and manually gave technoeconomic input (technical: PV generation, battery capacity, energy loads, amount of energy sold, and amount of energy bought at different hours; economic: cost of energy in different hours) in the MATLAB which is the TS for 2nd stage economic optimization. The TS is analysed using GA in MATLAB (GA has been utilized in this work to compare algorithm-based optimization with HOMER software-based optimization). This study integrates GA to automate load scheduling through an optimization approach. Conversely, HOMER necessitates manual hourly scheduling, which requires additional effort. GA simplifies the scheduling process by increasing efficiency, flexibility, and the ability to manage complex optimization scenarios without direct user involvement [62].

3.7. Results of the Case Study II

In this subsection economic analysis results of case study II are summarized.

The FS has the highest COE at 0.19 $/kWh among the three scenarios. Also, it has the lowest CAPEX at 0.22 million $, as no on-site RES generation is integrated for the developed system. However, it has the highest OPEX of 0.15 million $/year and produces the highest emissions, amounting to 565.294 tons/yr. Furthermore, energy sales to the grid are absent, since the system does not produce any RES, so energy flows directly to the EV from the grid. Indeed, 894.453 MWh of energy is bought from the grid. However, this scenario has the highest NPC 6.52 million $, among the 3 scenarios [62].

Table 7 Summarized Economic Analysis results of Case Study II

Scenario	**NPC (million $)**	**CAPEX (million $)**	**OPEX (million $/year)**	**COE ($/kWh)**
FS	6.52	0.22	0.15	0.19
SS	5.38	0.51	0.112	0.13
TS	5.38	0.51	0.112	0.12

The SS has the lowest NPC, 5.38 million $, among the 3 scenarios. Also, it has a COE of 0.113 $/kWh and CAPEX of 0.51 million $. However, this SS's OPEX is 0.112 million $/year, which is comparatively lower than the FS. SS presents a strategic advantage as it integrates RES, enhancing the profitability and sustainability of the EVCS. A total of 231.645 MWh of energy is sold to the grid with a RESFr of 34.6%. Consequently, energy purchases are reduced to 726.024 MWh. Moreover, CO_2 emissions are lower than in the FS, amounting to 458.847tons/yr [62].

Using the SS output from HOMER, we provided inputs to TS for cost optimization. In TS, our focus was on reducing COE and overall energy bills through GA within a VPP framework. In the initial EV charging configuration, EVs were assumed to charge at maximum power starting at 09:00 until fully charged. Under FS, the daily energy bill is 49.02 $/day. GA then rescheduled the EV load across various hours to reduce energy bill and COE [62].

An analysis of the two case studies reveals significant differences. In Case Study I, the use of renewable-powered EVCSs was effective in reducing energy costs and emissions. However, the first case only utilized one-step optimization, whereas Case Study II employed two-step optimization, which resulted in a lower energy bill compared to Case Study I. Additionally, Case Study II incorporates a VPP with the building community, which provides extra flexibility to ECs. The primary conclusion is that both of these case studies assist in reducing COE and energy bills, which can be replicated in ECs, particularly when combined with advanced management strategies, such as VPP, with the methodology developed during our analysis.

In the future, other mathematical based optimizations, such as ant colony optimization, can be utilized to schedule the loads, make the optimization stronger, and compare with current results.

4. Contribution to the WP objectives

The research carried out by ESR15 and ESR14 contributes directly to the objectives of WP5, which focus on advancing green economy models and management systems, and on coordinating research and implementation of BMs within collaborative RES, microgrids, and energy management. Both ESRs have specifically addressed the role of ECs as legal entities capable of developing a range of BMs related to decentralized energy production and consumption. ECs not only generate RES and inject them into the grid, but also provide additional services, including flexibility, e-mobility, and storage. The work of ESR14 and ESR15 consolidates current knowledge on ECs, expands understanding of their BM potential, and proposes pathways to enhance services such as EVCS.

ESR15's contribution focuses on mapping the academic debate and identifying research gaps. Through a bibliometric literature review, ESR15 clarified the evolution of the EC concept, structured existing research areas, and highlighted three major domains: the energy transition, technologies, and models. Within these domains, gaps were identified, particularly in relation to EC BMs. Building on this, ESR15 developed an analytical framework tailored to ECs, structured across five dimensions (value proposition, value creation, main functions, membership, and governance). This framework led to the identification of four archetypes of EC BMs: self-consumption, third-party, aggregator, and integrated services and e-mobility. The framework provides a systematic approach to analysing how ECs create, deliver, and capture value—economic, social, and environmental—and is aligned with WP5's goals of fostering innovative, sustainable BMs for distributed EES. The findings have academic and policy relevance: policymakers may, for instance, see self-consumption as a tool against energy poverty, while the aggregator model can address grid imbalances and flexibility needs. The results also support EC managers and market actors in designing tailored solutions.

ESR14 advanced the WP5 objectives by developing methodologies to optimise COE and GHG emissions, with a specific focus on EVCS as a service for ECs. The first outcome was a techno-economic analysis conducted on a university campus case study, demonstrating how optimisation methods can reduce COE and emissions for end-users.

This provides public and private stakeholders with a framework to assess the feasibility and long-term sustainability of EVCS in community settings. A second outcome expanded this approach to both a university and a building community test case. Here, ESR14 developed a mathematical optimisation model using genetic algorithms and HOMER software to simulate the integration of EVCS, local RES generation, and storage within a VPP framework. The analysis demonstrated improvements in energy management, cost reduction, and emission abatement, while introducing innovative services for EC users. These techno-economic feasibility studies underline the role of RES-powered EVCS as an innovative service that can enhance self-consumption, enable storage and flexibility solutions (including V2G), and reduce carbon emissions. Together, these insights strengthen the evidence base for BM innovation under WP5. Overall, Deliverable D5.3 integrates the work of both ESRs, moving from literature-based insights to validation through techno-economic feasibility studies. It demonstrates how EVCS can evolve into viable services for end-users, especially within ECs, while also creating opportunities for investors and other stakeholders to engage in sustainable energy markets. The results highlight EVCS as a catalyst for innovative BMs and services that advance the growth and sustainability of distributed EES.

5. Conclusions

D5.3 analysed market solutions and BMs to support the growth and sustainability of distributed EES within WP5. The work focused on ECs as key organisational forms to empower citizens and local actors in energy production, consumption, and management. ESR15 mapped the academic debate through a bibliometric review, identifying three main research areas (energy transition, technologies, and models) and highlighting gaps, particularly in EC BMs. Building on this, ESR15 developed an analytical framework that led to four EC BM archetypes (self-consumption, third-party, aggregator, integrated services and e-mobility), clarifying how ECs create, deliver, and capture value. ESR14 complemented this work with techno-economic analyses of RES-powered EVCS, applied to university and community test cases. The studies demonstrated the potential of EVCS to reduce COE and GHG emissions while providing innovative services for EC users. From these results, several lessons can be drawn. First, EC BMs are still low explored in the literature, and the analytical framework developed by ESR15 provides a solid basis for future categorisation and comparative research. Second, the viability of RES-powered EVCS highlights the importance of integrating mobility and building energy systems at community scale, showing that e-mobility can be more than a technological add-on: it can be a central service for ECs. Third, both strands of research demonstrate the value of combining conceptual and techno-economic approaches, bridging theory and practice in the development of innovative BMs. Looking ahead, further research should deepen the empirical validation of EC BM archetypes through surveys, interviews, and case studies across different socio-technical contexts. There is also a need to explore how ECs can integrate new services such as EVCS into viable market models that balance economic sustainability with social inclusion, for instance addressing energy poverty. Finally, future work should examine the role of regulatory frameworks and policy design in scaling up ECs and supporting their integration into broader energy markets. Overall, the lesson learnt is that ECs have the potential to become central actors in the transition toward sustainable and decentralised energy systems. By adopting innovative BMs and integrating services such as EVCS, they can simultaneously enhance local energy independence, deliver environmental benefits, and create new socio-economic opportunities for their members and beyond.

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Chapter 5

Identified enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems

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Coordinator: Bocconi University (UB)

List of abbreviations used in this chapter

ACER	Agency for the Cooperation of Energy Regulators
BMs	Business Models
CECs	Citizen Energy Communities
CNR	Consiglio Nazionale delle Ricerche
DES	Decentralized Energy System
D5.4.	Deliverable 5.4.
ECs	Energy Communities
EED	Energy Efficiency Directive
EES	Electrical Energy System
EPBD	Energy Performance of Buildings
ESR	Early-Stage Researcher
ESS	Energy Storage Systems
ETN	European Training Network
EU	European Union
ECPE	European Center for Power Electronics
EVCSs	Electric Vehicle Charging Stations
FiT	Feed-in Tariffs
GW	Giga Watts
IRP	Individual Research Project
ITN	Innovative Training Network
MSCA	Marie Sklodowska-Curie Actions
NIMBY	Not In My Back Yard
OSS	One-Stop-Shop
PC	Project Coordinator
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REC	Renewable Energy Community
RES	Renewable Energy Sources
SIEM	Siemens
SLR	Systematic Literature Review
SMEs	Small-Medium Enterprises
ST	Search Term
UB	Bocconi University
UNL	Universidade Nova de Lisboa
WP5	Work Package 5

1. Executive summary

Work Package 5 (WP5) "Green Economy Models and Management Systems" aims to coordinate interdisciplinary research and provide guidance for the development, implementation, and replication of innovative Business Models (BMs) that support collaborative renewable energy systems (RES), including Energy Communities (ECs), microgrids, and advanced energy management solutions. This deliverable contributes to WP5 by presenting the outcomes of research carried out by Early Stage Researcher 14 (ESR14) and Early Stage Researcher 15 (ESR15), focusing on the enabling and constraining factors affecting the replicability and scalability of green energy BMs across the European Union (EU). In line with WP5 objectives, the work of ESR14 and ESR15 concentrates on ECs as a key instrument to advance decentralised energy production and energy democratisation under the EU Clean Energy Package. Although ECs have strong transformative potential, they continue to face significant operational, regulatory, financial, and institutional barriers. The research developed within this deliverable provides empirical and analytical evidence to identify, assess, and validate the main barriers and enablers affecting EC development. In this way, it supports WP5's broader ambition of advancing sustainable energy solutions through replicable and adaptable BMs, while also reinforcing WP2, WP3, and WP4 by highlighting cross-cutting factors that can influence the deployment of the technologies addressed in those WPs. The research was articulated in successive phases. ESR15 initiated the work with a cross-country survey on EC ownership models and funding mechanisms, covering seven European countries and showing how governance structures influence access to finance. This analysis also revealed the need to extend the focus beyond financial aspects to capture a broader set of barriers. To address this, ESR14 and ESR15 conducted a comprehensive categorization and validation of barriers using a combination of semi-structured literature reviews and primary data collection. ESR15 applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to analyse over 200 academic and grey literature sources, quantifying the frequency and nature of cited barriers. ESR14 developed and administered a survey involving 122 ECs across the EU, gathering direct stakeholder input on the perceived relevance and severity of identified barriers. Building on this barrier assessment, the research then shifted toward identifying and structuring enabling factors. Through a keyword-based literature review, four key categories of enablers were identified: technical, institutional, social, and economic. These enablers are synthesized and discussed in the context of EC development, offering a structured understanding of what supports EC implementation under varying regulatory and market conditions. The research also includes an applied component that connects BM design to technological innovation. A set of techno-economic feasibility studies was conducted to assess the integration of renewable energy sources (RES) into electric vehicle charging stations (EVCSs). These studies demonstrate that RES-powered EVCSs can enhance energy autonomy, provide storage and flexibility services (including V2G capabilities), and enable economic viability for local actors. These findings underline the enabling role of technology-driven BMs in achieving the goals of ECs and decentralised energy systems and reinforce the replicability goals of WP5. The findings of this deliverable contribute to WP5 by offering a validated typology of EC barriers and enablers, applied insights into financial, regulatory, and technological dimensions of BM replication, a better understanding of how innovative solutions

within electrical energy system (EES) can promote resilient, inclusive, and low-carbon energy systems, and evidence-based policy guidance at both country and EU level.

1.1. Objectives of deliverable

The purpose of this deliverable is to present the progress of WP5 activities, and the research outcomes achieved by the ESRs in the context of Deliverable 5.4, titled “Identified Enablers and Barriers to Foster the Replicability and Transfer of Business Models for Green Energy Systems”. This report focuses on 2 Individual Research Projects (IRPs), namely IRP14 and IRP15. IRP14 explores value chains and market structures emerging under the paradigm of distributed EES, while IRP15 identifies the conditions that facilitate or hinder the transferability of innovative EES. The results included reflect the research achievements reached within the first 46 months of the project. Specifically, the deliverable addresses enablers and barriers that affect the replicability and scalability of BMs in the field of Green Energy Systems. The ESRs are focusing their research on the topic of ECs. Their aim is to analyse the barriers and enablers of ECs that can support the advancement of Green Energy Systems. The deliverable aims to establish a clear link between the research outcomes and the overarching goals of WP5, contributing to the broader understanding of how innovative BMs can be adopted and replicated across different contexts within the green energy system.

1.2. WP5 Objectives and tasks

This deliverable is part of WP5, “Green Economy Models and Management Systems”, which addresses innovative energy management tools and BMs to meet the new challenges posed by the EES. WP5 involves four IRPs, each focusing on distinct topics related to innovative management solutions and BMs. Specifically, IRP12 concentrates to develop sustainable strategies for Net Zero Energy buildings and user energy awareness using smart appliances; IRP13 explores digital twins of prosumers using socioeconomical factors and big data for optimization of customer’s bill savings, and the adoption of concepts of self-consumption and presumption; IRP14 focuses on energy value chains and markets developed with the new paradigm of distributed EES; and IRP15 is dedicated on identifying enablers and barriers to foster the replicability and transfer of BMs for Green Energy Systems. The research outputs aim to enhance understanding and promote the adoption of technological and business solutions that support the sustainable energy transition. WP5 included 5 Tasks:

- Task 5.1: Development of sustainable strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances (UB, UNL).
- Task 5.2: Generation of digital twins of prosumers using socioeconomical factors and big data for Optimization of Customer’s bill savings, (UB-SIEM-UNL).
- Task 5.3: Energy value chains and markets developed with the new paradigm of distributed EES (UB-UNL-CNR).
- Task 5.4: Identifying enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems (UB, UNL, ECPE).
- Task 5.5: Elaboration of partial and final scientific reports (UB).

Tasks 5.1 and 5.2 have been completed and the corresponding deliverables submitted. Tasks 5.3 and 5.4 are ongoing and are scheduled to be finalized by September 2025, remaining on track with the project timeline. This deliverable specifically presents the final insights from Task 5.4, while the main results from Task 5.3 are addressed separately in Deliverable 5.3. Both ESR14 and ESR15 have successfully completed their research activities, fully meeting the objectives outlined in their respective IRPs.

The work carried out in Task 5.4 provides a structured and validated assessment of the barriers and enablers that affect the replicability of green energy BMs in Europe, focusing on EC initiatives. Through mixed-method approaches including systematic literature review (SLR), cross-country surveys, and techno-economic feasibility studies, this research has contributed significant new evidence to inform the design of scalable and context-sensitive BMs. These results directly support WP5's ambitions to inform business strategies, enable effective policy design, and promote sustainable energy innovation across diverse socio-technical contexts.

2. Description

This chapter presents the results of a comprehensive study on the enablers and barriers affecting the replicability and transferability of BMs for Green Energy Systems, with a particular focus on ECs. The aim of the current research work is to analyse the enabling and constraining factors that influence the establishment, development, and scaling of ECs. This study is closely related to the Deliverable 5.3 on market solutions and BMs supporting the development and sustainability of distributed EES. In particular, both deliverables focus on ECs as a strategic pillar of decentralized energy transitions. Moreover, part of the research and analysis included in D5.3 provided background knowledge that informed the formulation of research questions and the design of methodological approaches in the present deliverable (D5.4). The scientific work developed here aligns with the overarching goals of WP5, which promotes green economy models and sustainable management systems. ECs represent a key innovation in this context, enabling citizen-led renewable energy production while delivering environmental, social, and economic benefits. By encouraging collective ownership, energy efficiency, and carbon emissions reduction, ECs embody the core principles of the green economy and energy justice. The results presented in this deliverable have been obtained primarily during the research periods undertaken by ESR14 and ESR15 at Università Bocconi, under the supervision of the Bocconi academic team. However, specific outputs-such as the techno-economic feasibility studies-benefited from the research activities carried out during the secondments completed by ESR14 at NOVA University Lisbon and the University of Extremadura. Similarly, the secondments conducted by ESR15 at the University of Extremadura and Siemens were instrumental in collecting data and deepening the understanding of EC implementation and governance practices. These international research exchanges provided essential empirical and theoretical inputs that strengthened the scientific foundation of this work.

2.1. Scientific Background and summary of the main research outcomes

In 2023, the global renewable power capacity reached 3,870 giga watts (GW), contributing 13% of the world's energy consumption [1]. The EU has advanced the transition from fossil fuels to renewable energy, transforming the energy system from a centralized, vertically integrated model to a liberalized and decentralized one. This shift enables citizens, municipalities, and small-medium enterprises (SMEs) to generate and utilize their own energy, transforming them from passive consumers into prosumers [2]. Studies have placed special emphasis on how ECs can impact and propel the transition to a sustainable energy system. ECs empower citizens and local stakeholders, such as SMEs and local authorities, to collectively produce, consume, and manage energy. The Renewable Energy Community Directive (RED II-EU Directive 2018/2001) and the Internal Energy Market Directive (IEMD- EU Directive 2019/944) have significantly enhanced citizen participation in the energy sector. ECs have the potential to substantially alter the energy market by fostering a more democratic and decentralized energy system (DES) [3]. Approximately 10,000 ECs exist in Europe and have initiated around 22,000 projects, resulting in a total installed capacity of approximately 10 GW [4]. However, this number represents only 1.2% of total renewable power capacity in Europe in 2023 [1]. Numerous barriers affect the setup, development, and expansion of ECs, such as the limited adoption of smart meters, hindering the advancement of EC initiatives in the EU, or the lack of funding that can support the establishment and development of ECs [5].

While numerous studies have explored the barriers faced by EC, there is a notable lack of systematic investigation into the various categories of these barriers. Consequently, the research undertaken by ESR14 and ESR15 aims to identify, categorize, and analyse the barriers that ECs encounter. Additionally, the research focuses on identifying enablers and formulating policy recommendations that can help overcome these barriers. Achieving the research objectives outlined above was not accomplished through a single research project or methodology. Instead, ESR14 and ESR15 developed distinct methodologies, which were implemented during different time periods and in various settings. Nonetheless, all of these efforts contributed to fulfilling the objectives of this deliverable, as outlined earlier (see section 1.1. Objectives of the deliverable).

Specifically, ESR15 carried out a survey, with support from a research team at Bocconi University, focusing on the ownership models and funding mechanisms of ECs. This study, which took place from April to September 2023, aims to analyse how the ownership model of ECs impacts the funding mechanisms utilized and the financial barriers they encounter. This work has been completed and presented as a conference paper at the 16th International Conference on Energy and Climate Change, which occurred in Athens, Greece, in October 2023.

Later, ESR14 and ESR15 aimed to deepen the analysis of the barriers encountered by ECs and to develop a research methodology for identifying, categorizing, validating, and evaluating these barriers. First, a semi-structured literature review was conducted to identify and categorize the barriers faced by ECs into different groups. This initial work serves as a foundational stage that supports subsequent research phases. Next, a SLR was performed to validate the barriers identified in the previous stage by examining their frequency in the literature. Finally, a research survey was conducted to collect primary data, through a questionnaire, from ECs to assess the relevance of the barriers identified in the first stage of this research.

This research, which commenced in June 2024, is ongoing, with results obtained but not yet published. Furthermore, the outcomes of the current research are intended to lead to two distinct research papers that will be published as journal articles. Specifically, ESR15, in collaboration with ESR14 and the Bocconi research team, initiates a SLR regarding the barriers ECs faced in September 2024. The objective of this work was to quantify the occurrence of different types of barriers reported in the literature. This work is still in progress; however, preliminary results have been obtained and are presented here (see Section 3.3.2). The final research paper is aimed to be published as a journal article in October 2025. Moreover, ESR14, in collaboration with ESR15 and the Bocconi University team, initiated a survey in October 2024 to collect primary data and assess the relevance of the barriers that EC encounters; this survey is still in progress. In total 122 responses have been collected and analysed, and the results aim to be published as a journal article in October 2025.

The ESR15, in collaboration with other researchers (not related to the SmartGYSum project), conducted a study aimed at assessing the current state of deployment of EC in ten European countries. The study also explored the barriers ECs face in these countries and proposed policies to overcome them. Specifically, ESR15 concentrated the research on Greece, highlighting the main barriers encountered by ECs in that country and suggesting policies to overcome them. This project commenced in December 2024, was completed in April 2025, and was published as a vignette article in the Oxford Open Energy journal in March 2025.

Subsequently, the ESR14, another part of his research, aimed to identify the enablers of ECs, present in the literature, in order to overcome the barriers identified both in the literature and the survey. A semi-SLR was conducted to identify and categorize the enablers of EC. A book chapter is prepared for this work and will soon be submitted for peer review. While this section constitutes the initial phase of categorizing factors that facilitate EC operation and management, this work can be expanded in the future by conducting a survey similar to the one on barriers.

The following sections present in more detail the research methodology as well as the research outcomes of the aforementioned studies. In addition, the subsequent section illustrates how current research contributes to current deliverables and WP5 goals.

2.2. Energy Communities Ownership Model and funding mechanisms

As previously noted, ECs encounter numerous barriers in their establishment and growth [5]. Various scholars have identified financial barriers as a significant challenge that ECs must overcome. These barriers include a lack of long-term funding, initial funding challenges, high institutional costs, and uncertain levels of Feed-in Tariffs (FiT) [5], [6]. One substantial barrier that almost all ECs need to overcome is finding the capital to finance their activities [7]. As Braunholtz-Speight T. et al. [8] stress, EC funding is not about the cost structure or the revenue structure of the business; on the contrary, it refers to “unearned flows of money into community energy groups”. [8]. Thus, the funding mechanism can be described as the “ways by which a supplier makes financial resources available to the organizations that require them. These methods can have a variety of implications for capital recovery, expected returns, ownership rights, and other factors” [9].

EC funding mechanisms can take various forms, which can be categorized into four main types: (i) equity finance, consisting of shares that a community offers in exchange for ownership rights to the community or a project [7]; (ii) debt finance, which refers to the money that an EC borrows from another entity in the form of a loan, requiring repayment over a specified period at an interest rate. While loans allows ECs to operate independently from external influences, it is generally a more costly method of funding a project [10]; (iii) grants, which are funds that an EC can receive without the obligation to repay and can be awarded by the EU, as well as at national, regional, or municipal levels; and (iv) alternative finance, which encompasses crowdfunding and crowd-investment platforms [10].

A key factor affecting how ECs can obtain funding is their ownership model, as the people involved and how the EC is governed greatly impact how they can raise money and support their activities [7]. Furthermore, funding mechanisms, capacity building within ECs, and collaboration with other stakeholders heavily depend on the actors who initiate them. However, there is a lack of academic literature exploring how the ownership model and the initiators of an EC influence the funding mechanisms. In addition, the existing literature lacks an examination of the financial barriers faced by ECs with varying ownership models and actors initiating them. To address this research gap, ESR15 aims to first categorize ECs based on their ownership models and initiators. Second, it seeks to examine the types of funding mechanisms utilized by these ECs. Finally, it intends to investigate the financial barriers encountered by the different ECs.

To define the various ownership models of ECs, ESR15 utilizes four dimensions identified by the International Renewable Energy Agency, namely, (i) membership, which refers to the different types of actors who participate as members, such as citizens, public actors, or private actors; (ii) the level of democratic governance, which refers to the way decisions are made and who has voting rights in the ECs; (iii) the main purpose of the community, which can be economic, environmental, or social; and (iv) the local distribution of benefits, which refers to the extent to which the social, environmental, and economic benefits generated by the EC are distributed locally or not (see Fig. 1). In addition, this study defines the initiators of the EC as any public or private actor, including SMEs, local authorities, or citizens involved in the establishment and setup of the EC.

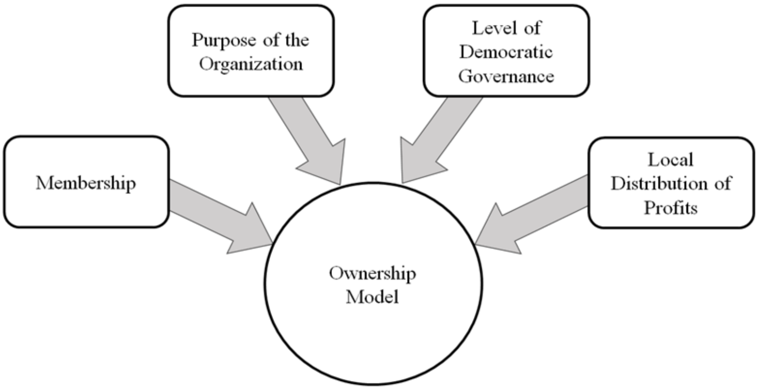

Figure 7: Ownership model dimensions based on International Energy Agency.

To achieve the research aim of the current study, ESR15 conducted a survey using a self-completion questionnaire to gather primary data from ECs. Specifically, the questionnaire is divided into three sections aimed at obtaining data on the characteristics of the ECs in order to analyse their ownership models, funding mechanisms, and financial barriers encountered. It should be noted that the survey considered only ECs that have developed energy generation plants and did not consider other types of activities. The focus only on ECs active in energy production was chosen because the vast majority of ECs are mainly engaged in this activity [11]. Consequently, other activities that could introduce inconsistencies and hinder comparability between the different ECs were deliberately excluded from the analysis.

EC characteristics, ownership model and funding mechanisms

The findings indicated that the predominant characteristics of the ECs are their small size, in terms of number of members, and the primary use of photovoltaic panels for energy generation. Only three communities are categorized as large (500-2000 members) or very large (over 2000 members), while the rest of the ECs have fewer than 500 members. Regarding the year of foundation, the majority of ECs, namely 20 out of 25, were founded from 2017 onwards. Moreover, the predominant number of ECs in the sample are non-profit (16 ECs), with only 6 classified as for-profit ECs, while 3 ECs stated that their primary objectives were non-financial. Regarding the ownership model of the ECs, the analysis revealed that the only variation among the ECs in the sample pertained to their membership. No substantial changes occurred in governance, local profit distribution, or the purpose of the EC. Furthermore, the sample revealed that different actors initiated the ECs. Therefore, this study categorizes the ECs based on two dimensions: the membership and the initiators. Eight separate categories of ECs were delineated (see Tab. 2).

Table 2

Eight Categories of ECs Based on Membership and Initiator Dimensions.

Categories	**Initiators**	**Membership**	**Number of EC in the sample**
1	Citizens	Citizen	4
2	Citizens	Citizens + Private	6
3	Citizens	Citizens + Public	1
4	Citizens	Citizens + Public + Private	7
5	Public	Public	1
6	Public	Public + Citizens	1
7	Private	Citizens	2
8	Citizens + Public + Private	Citizens + Public + Private	3
Total			**25**

Most ECs used a combination of funding mechanisms. Specifically, almost 70% of ECs in the sample relied on debt capital, while 60% stated they relied on equity capital. Furthermore, approximately 40% of the ECs in the study utilized grants or crowdfunding. Regarding the relationship between the categories identified in this study (see Tab. 2) and the funding mechanisms employed, it is noted that ECs initiated by citizens, which include public and/or private actors as members (Tab. 2, categories 2, 3, and 4), are more successful in raising capital through equity or other internal resources compared to ECs that consist solely of citizen members (Tab. 2, category 1). Additionally, this study, similar to others, indicates that both the number of community members and the total capital needed for project funding may influence the choice of funding mechanisms. Specifically, ECs, with investments of more than 200,000 euros in energy generation plants, tend to use debt capital. However, large ECs (more than 2000 members) can use different funding mechanisms, such as green bonds provided to their members, thus reducing the financial risk by depending on debt capital.

EC financial barriers

ECs in the sample encounter financial barriers, particularly in raising capital from both private and public actors. Table 3 summarizes the main barriers that ECs encounter to raise capital and fund their generation plants. The most frequently reported barriers are the lack of grants or subsidies at the national level (barriers 1-3), followed by barriers related to private funding (Tab. 3, barriers 4-6). In contrast, barriers concerning crowdfunding and citizen participation are reported less often (Tab. 3, barriers 7 and 8).

Table 3
Financial barriers EC face

N.	Barriers	Number of ECs reporting impact
1	No subsidies or grants for EC provided at a national level	14
2	Public grants or prizes are not tailored-made for your EC	14
3	Complex bureaucratic processes make it difficult to access public finance	14
4	Private financial institutions or banks do not fund your generation plant because they consider it non-profitable.	11
5	No access to favorable loans, such as soft loans, green loans, etc.	12
6	Unattractive environment for private investors because of the absence of FiT or other pricing mechanisms	8
7	Absence of a legislative framework for the proper functioning of crowdfunding or crowd-investment platforms	7
8	Low participation of people in funding energy generation plants; thus, it isn’t easy to raise capital from equity shares	11

Finally, the current analysis indicates disparities among EC categories regarding the barriers they encounter. Communities created by citizens identify the absence of citizen participation as a barrier (Tab. 2, categories 1, 2, 3, and 4), whereas those initiated by public or private entities do not. Additionally, citizen-initiated ECs that include both public and private members (Tab. 2, categories 2, 3, and 4) can more easily get internal funding through equity than ECs created only for citizens (Tab. 2, category 1). Ultimately, concerning access to public funding sources, it seems that all ECs face obstacles, irrespective of their category. Nonetheless, the restricted sample size of this study needs further investigation to corroborate this pattern.

2.3. Energy Communities barriers analysis

The study mentioned above concentrates exclusively on the financial barriers faced by ECs. However, literature highlights many additional barriers that impact the establishment, growth, and expansion of ECs [12], [13], [14], [15]. Furthermore, the financial barriers discussed above pertain only to ECs that have constructed energy generation plants, omitting other activities such as energy storage, e-mobility, supply, etc. Additionally, the data analysed in this study were limited to just seven EU countries, resulting in a lack of information regarding other national contexts within the EU. Consequently, ESR15 and ESR14 aim to carry out a comprehensive analysis that identifies, categorizes, validates, and assesses all existing barriers, thereby providing a complete picture of all types of barriers. Consequently, a three-step approach was created. The initial stage seeks to identify the primary barriers present in academic papers and policy reports using a semi-structured literature review and desk research. Identified barriers are grouped into categories (economic, institutional, technical and technological, socio-cultural, and behavioural) and then sub-categorized into classes. The second stage seeks to validate the identified barriers and incorporate any additional ones through a SLR utilizing the PRISMA technique. Finally, the third stage aims to evaluate the significance of the barriers identified and validated in the preceding two stages through a survey. To this end, a questionnaire was created and disseminated to ECs throughout the EU.

EC Barriers identification

As already mentioned, the first stage of this research concentrates on the identification and categorization of the different types of barriers. To that end, ESR14 and ESR15 conducted a semi-structured literature review and desk research to identify papers and policy reports addressing EC barriers. The papers and the reports were retrieved from Google Scholar, Scopus, and Web of Science databases using different keywords, based on the diversity of terms used in academic literature concerning the topic of ECs, such as “energy community”, “community energy”, “renewable energy community”, and “citizen energy community” [16]. In addition, keywords similar to “barriers” were used, such as “challenges”, “hindering factors”, and “constraints”. At this stage of the research, only review papers and articles that have conducted a detailed analysis of EC barriers were included to avoid focusing on country-specific barriers. Additionally, searches were limited to “author keywords” to ensure that the papers explicitly address the topic of EC barriers. Finally, only papers published from 2014 onward were considered to ensure the relevance of the barriers identified, as older publications may no longer reflect current policies and energy market conditions. In total, 26 articles were retained and reviewed from the Web of Science and Scopus databases. In addition, six more reports from EU-funded projects were extracted from Google Scholar. Therefore, 32 scientific works were analysed (see Tab. 4).

Table 4. Type of documents and references utilized to identify and develop a categorization of ECs barrier.

Type of documents	Number of documents
Original articles	7
Review Papers	20
Reports	5
	Total=32

After gathering all the papers, they were reviewed, and the barriers were recorded using the NVivo program. The objective at this stage of the research was to identify patterns or themes. Thus, a thematic analysis was conducted to categorize the barriers reported in the literature according to their conceptual similarity. This process led to the development of a three-tier categorization system. First, barriers were grouped into categories that represent higher-order classifications sharing fundamental attributes, e.g., economic barriers. Second, within each category, the barriers were further grouped into classes based on their thematic connections. For instance, under the category of economic barriers, two different classes emerged: the financial barriers and the market barriers (see Tab. 3). Finally, the third level identifies specific and tangible barriers that ECs face in their setup, development, and expansion. In total, 26 barriers, 10 classes, and 4 categories were identified (see Fig. 2).

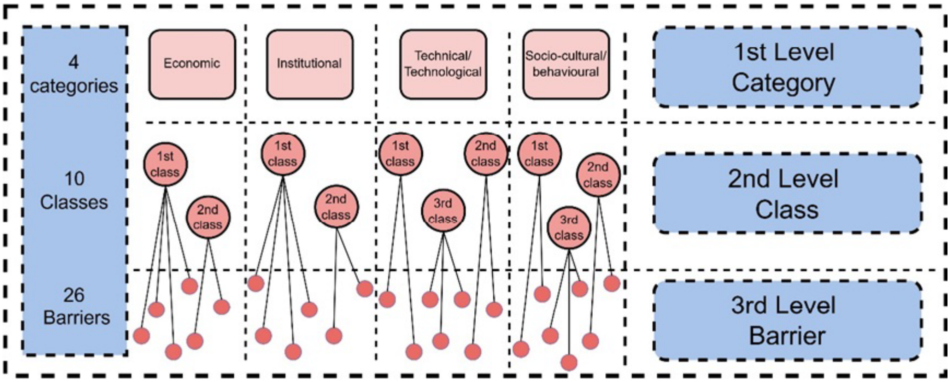

Figure 8: The three level categorization of barriers in current research.

The first category pertains to economic barriers, which refers to difficulties that ECs face in accessing finance and entering the energy market. This category includes two distinct classes: (i) *financial barriers*, which refer to the difficulties that ECs face in securing funding for their activities, and (ii) *market barriers*, which refer to difficulties faced by ECs in acting within the energy market compared to commercial and traditional market players. These challenges can be inherent to ECs characteristics, such as their small size, or caused by asymmetric market dynamics, considering traditional energy players and incumbents.

The second category is the institutional barriers, which are related to political obstruction, conflicting guidelines, lack of policy coordination as well as bureaucratic and administrative issues. Two different classes emerged under this category: (i) *the policy and regulatory barriers*, which refer to either the lack of policies and regulations or the presence of unclear and/or conflicting policies and regulations related to ECs, and

(ii) the administrative and bureaucratic barriers, which refer to complex or slow day-to-day operations that an EC has to perform to function, stemming from administrative or bureaucratic issues.
management of ECs, such as smart meters, smart control systems, digital twins, etc.

Table 5. The barriers, classes and categories of barriers identified in the literature.

Category	**Class**	**Barrier**
Economic	Financial Barriers	Lack of access to traditional finance
		Difficult to access finance from members
		Lack of tailor-made finance options
		Lack of public funds for ECs
	Market Barriers	Lack of a level playing field (i.e. economy of scale)
		Presence of market incumbents
Institutional	Policy and Regulatory Barriers	Absence or lack of a clear and uniform definition for ECs
		Lack of a clear scope of EC's activities
		Lack of policy stability and coherence
	Administrative and Bureaucratic Barriers	Lack of simple and clear administrative procedures
		Slow administrative procedures plants
Technical/Technological	Technical Barriers	Lack of space to build RES
		Lack of technical skills (skilled personnel)
		Lack of technical expertise
	Lack of efficient infrastructures	Lack of efficient and suitable energy infrastructure
		Lack of IT infrastructure
	Lack of enabling technologies	Low diffusion of smart technologies
		Data management issues
		Cybersecurity and protection issues
Socio-cultural and Behavioural	Lack of Knowledge and awareness of ECs	Lack of knowledge regarding the EC concept
		Lack of awareness about ECs' benefits
	Lack of Trust	Lack of trust in private or public actors
		Lack of trust towards peers in the EC
	Lack of Socio-cultural conditions	NIMBY[15] syndrome and local backlash against RES and ECs
		Lack of cooperative tradition in the country or the region your EC is operating
		Lack of Environmental awareness in the country or the region your EC is operating

The third category is the technical and technological barriers and refers to difficulties generated by limited availability and spread of technologies (e.g., smart meters, energy storage, and smart devices), inefficient and old energy infrastructures, and data protection and security issues. This category includes three different classes: (i) *the*

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[15] Not In My Back Yard (NIMBY)

technical barriers, which refer to the lack of land/space to build RES plants/infrastructures or the lack of technical skills to manage ECs; (ii) *the lack of efficient infrastructures*, which refers to the lack of efficient and suitable energy and IT infrastructure; and (iii) *the lack of enabling technologies*, which refers to the lack of specific enabling smart technologies and data processing tools that are necessary for the operation, optimization, and Finally, the last category pertains to the socio-cultural and behavioural barriers, and it refers to barriers that arise from either issues within the broader socio-cultural context in which ECs operate or from a lack of information or awareness among individuals about ECs and energy-related issues in general. Under this category, three classes were identified: (i) *The lack of knowledge and awareness of ECs*, which refers to the lack of understanding and/or awareness among potential EC members about the benefits and opportunities of EC initiatives, which leads to low engagement and hinders the growth of ECs; (ii) *the lack of trust*, which refers to the lack of or low mutual trust among EC members and collaborative actors, reducing citizens' willingness to participate in ECs; and (iii) *the lack of socio-cultural conditions,* which refers to barriers resulting from the lack of socio-cultural conditions necessary for the development of ECs.

EC barrier validation

At this stage, ESR15 seeks to validate the previously presented barriers through a SLR utilizing the PRISMA[16] technique. Identifying relevant keywords is a crucial step in conducting an SLR, as it ensures the inclusion of all academic papers related to the barriers faced by ECs. The most relevant keywords have been identified and are presented in the following table (see Tab. 6).

Table 6. Search terms for the identification of research papers.

Set of keywords for search term (ST)	**Search Term**
ST-1	("Energy communit*" OR "Community energy" OR "Local Energy Communit*" OR "Renewable Energy Communit*" OR "Energy Cooperative*" OR "Citizen Energy Communit*" OR "Renewable Energy Cooperative*" OR "Community Renewable Energy" OR "Smart Energy Communit*" OR "Community Solar" OR "Solar Communit*")
ST-2	("Barrier*" OR "Obstacle*" OR "Challenge*" OR "Hurdle*" OR "Constraint*" OR "Hindering factor*")
Final ST	(ST-1) AND (ST-2)

The PRISMA guidelines involve four phases of decision-making: identification, screening, eligibility, and inclusion. In the identification phase, we identified 848 papers in the WOS database and 749 papers in Scopus using the specified search terms (see Table 6). This resulted in a total of 1,597 papers; however, after removing 560 duplicates, 1,037 unique papers were included in our analysis. During the screening process, we reviewed the titles and abstracts, leading to the exclusion of 545 papers due

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[16] The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique is the structure that is usually applied when reporting systematic literature reviews.

to their irrelevance to the topic under investigation. Consequently, 492 papers remained for full screening. At this stage, we evaluated the remaining papers for eligibility. It was determined that 297 papers were irrelevant, resulting in a final total of 195 papers that were fully reviewed to validate the barriers. To those papers, another 5 reports were added from Google that contain policy reports and had a high relevance to the current research. Thus, a total of 200 papers and reports were reviewed for the validation of the barriers (see Fig. 3).

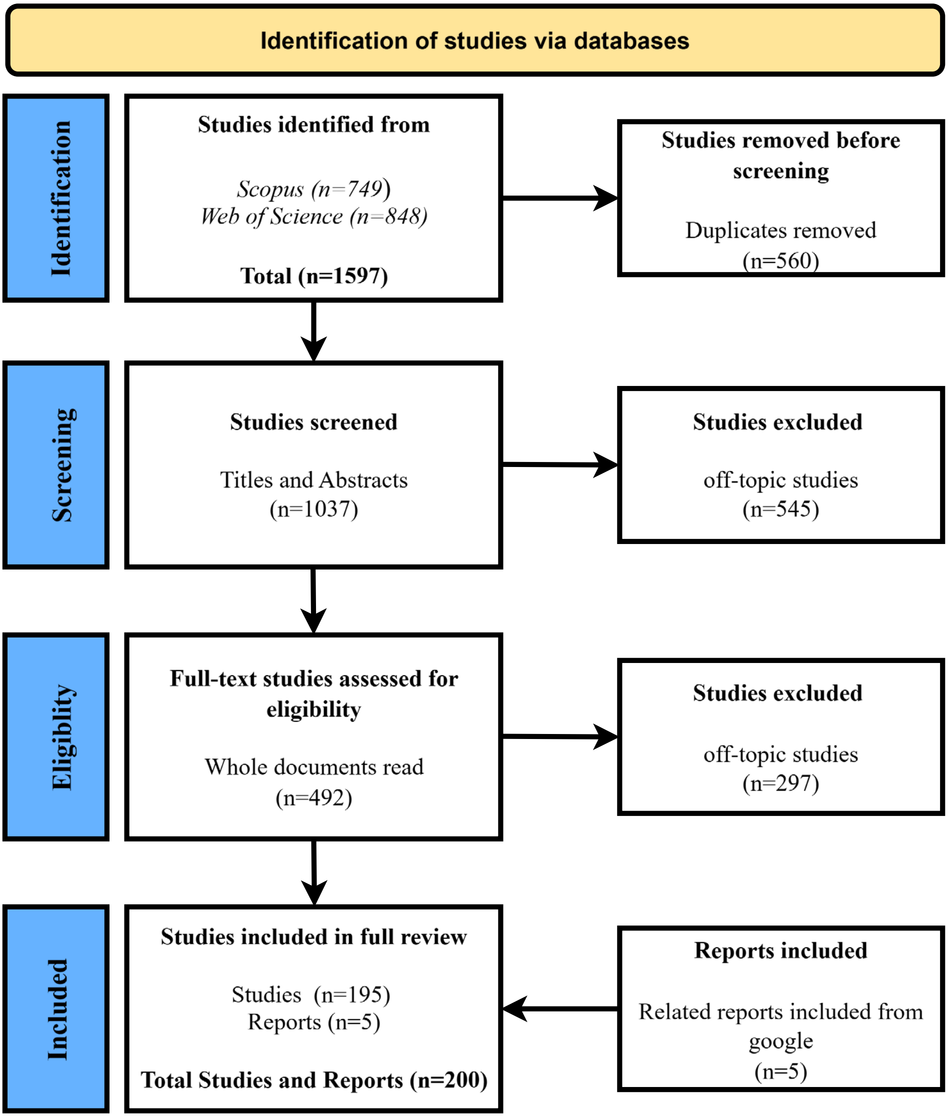

Figure 9: PRISMA diagram of paper selection for the SLR.

After retrieving the final papers for consideration, a content analysis was conducted, categorizing each barrier identified in the literature according to the previously established framework (see Tab. 5). The SLR demonstrates that the literature documents all identified barriers, albeit at varying frequencies. The following section presents a detailed analysis of the barriers and their occurrences in the literature.

Economic barriers

The category of economic barriers further divides into two distinct classes: the financial barriers and the market barriers, as previously mentioned. The SLR reveals that all these barriers appear in literature in varying frequencies.

The financial barriers identified in the literature primarily highlight the lack of tailor-made financial options, which is cited in 65 studies. These barriers refer, among others, to the absence or cancellation of FiT, the unavailability of state bank loans at subsidized interest rates, and the need for targeted tax and fee relief for ECs. Additionally, 54 studies report that the lack of public funding for ECs represents a significant barrier. The last two barriers mentioned, though with varying frequencies, include the lack of access to traditional financing, noted in 45 studies, and the difficulty of accessing finance from members, referenced in 41 studies (see Fig. 4).

Concerning the market barriers, studies have reported the presence of market incumbents more frequently than the lack of a level playing field. Specifically, 63 papers address the issue of market incumbents, whereas 56 papers reference the lack of a level playing field.

Overall, all barriers under this category have been reported with similar frequency, so it cannot be argued that there is significant variation in the frequency of their occurrence in literature. However, it should be noted that the lack of tailored financing options and the presence of market incumbents have been cited more than the other barriers.

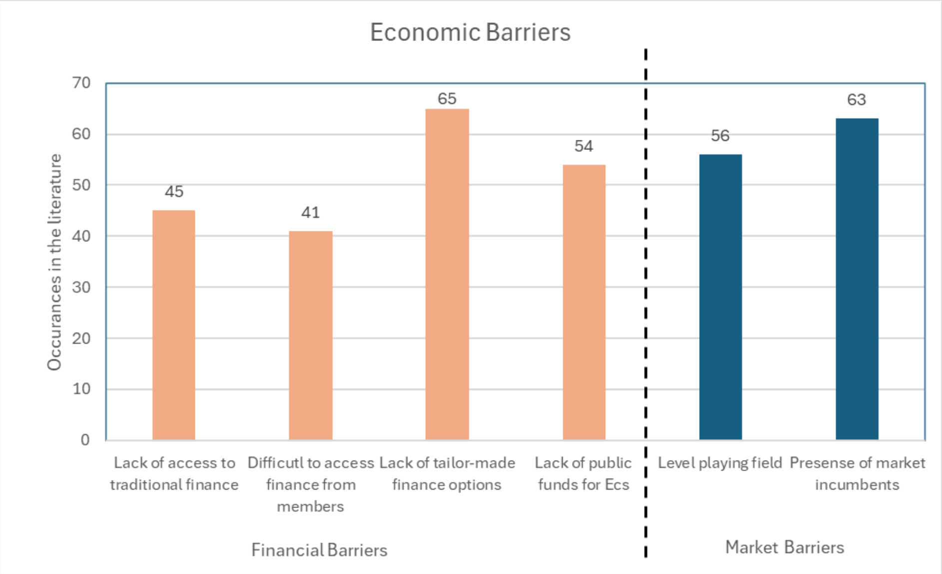

Figure 10: The frequency of occurrence of economic barriers identified in the literature.

Institutional Barriers

The barriers in this category are divided into two classes: policy and regulatory barriers and administrative and bureaucratic barriers. Figure 5 illustrates that all of these barriers have been reported in academic literature with varying frequencies.

Figure 5 illustrates that the lack of policy stability and coherence is cited significantly more often than other barriers, with 76 papers referencing this barrier. This is followed by the lack of clear scope of the EC's activities, mentioned in 38 papers. Lastly, the absence or lack of a clear and uniform definition of ECs is noted in 26 studies.

The barriers related to the second category, specifically administrative and bureaucratic obstacles, are reported with varying frequencies. The lack of simple and clear administrative procedures is cited almost twice as often as the slow administrative procedures; the former is mentioned in 43 studies, while the latter appears in only 27 studies.

Overall, there is a notable variation in the appearance of barriers within this category, with the lack of policy stability and coherence being reported significantly more often than other barriers. The lack of simple and clear administrative procedures is the second most frequently mentioned barrier in this category; however, it is cited much less often. These issues may stem from the fact that EU countries have implemented the EU directives that define ECs, while only a few countries have yet to acknowledge ECs in their national legislation.

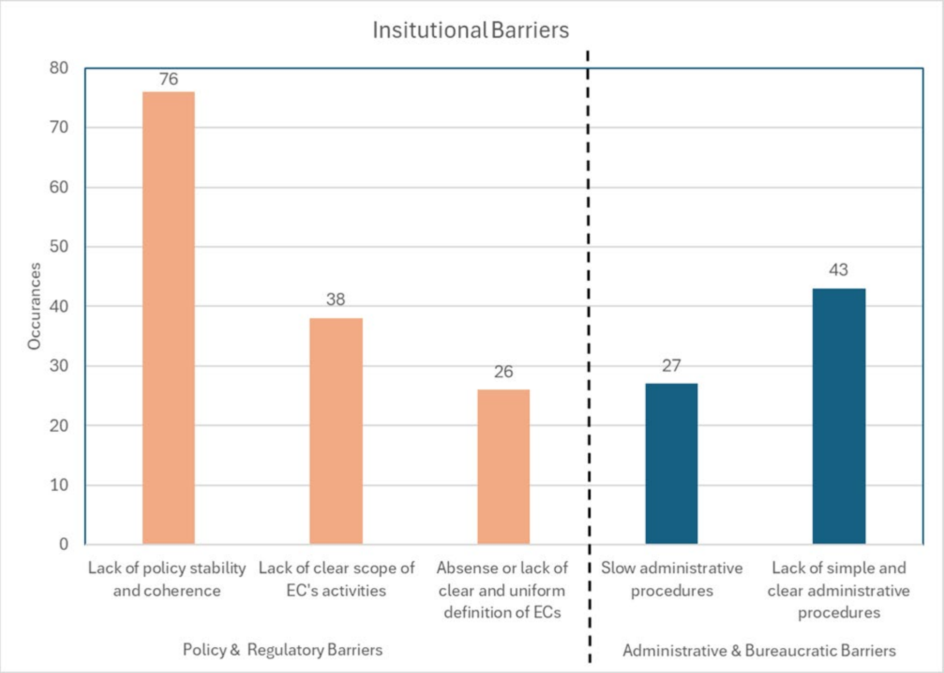

Figure 11: The frequency of occurrence of institutional barriers identified in the literature.

Technical/technological barriers

This category includes three distinct classes of barriers: technical barriers, the lack of enabling technologies, and the lack of efficient infrastructure. While all barriers within each class are present in the literature, there is a significant difference of occurrences noted (see Fig. 6).

The technical barriers class indicates that the lack of technical expertise is the most frequently cited barrier, appearing in 81 studies. Following this, the lack of technical skills is referenced in 66 papers. In contrast, the barrier related to the lack of space for building RES plants is mentioned much less frequently, with only 27 studies citing this issue.

The barriers related to the second class in this category, specifically the lack of enabling technologies, demonstrate some differences in their frequency of occurrence in literature, although not as pronounced as those in the previously mentioned class. The most significant barriers in this class include data management issues, which appear 32 times in the literature. This is followed by the low diffusion of smart technologies and issues related to cybersecurity and protection, which are reported with similar frequencies, 19 times and 18 times, respectively.

The final class of barriers in this category pertains to the lack of efficient infrastructure, and there is a significant discrepancy in the frequency of reported barriers within this class. Specifically, the lack of efficient and suitable energy infrastructure is mentioned three times more frequently than the lack of IT infrastructure, with the former appearing in 58 studies and the latter in only 16.

In conclusion, while all barriers related to technical and technological challenges have been documented in the literature, there is a significant disparity in the frequency with which these barriers are reported. Specifically, the lack of technical expertise, the lack of technical skills, and the lack of efficient and suitable infrastructure are mentioned much more frequently than other barriers.

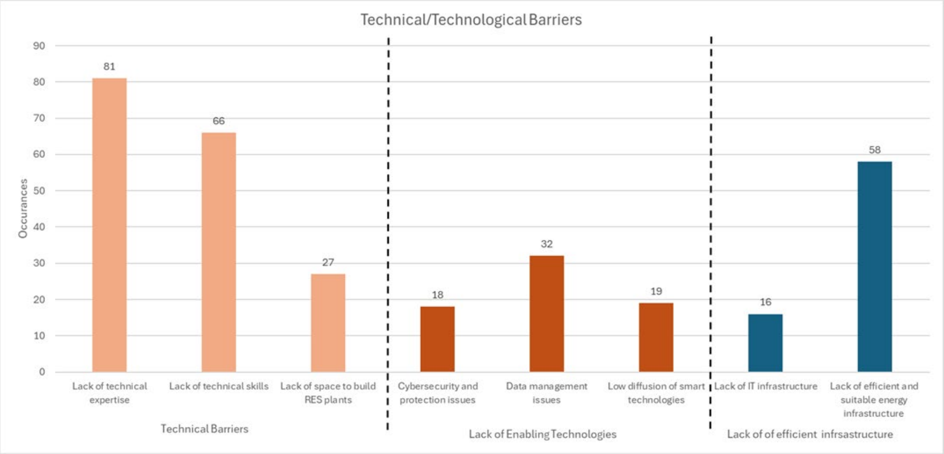

Figure 12: The frequency of occurrence of technical/technological barriers identified in the literature.

Socio-cultural/ behavioural barriers

In the final category of barriers, socio-cultural/behavioural barriers, there is a homogeneity regarding the frequency of barrier occurrences. Specifically, this category encompasses three classes: the lack of trust, the lack of socio-cultural conditions, and the lack of knowledge and awareness of ECs. Each barrier within these classes has been documented in the literature.

The first class, the lack of trust, encompasses both lack of trust towards peers within the EC and lack of trust in private or public entities. Notably, the former has a slightly higher number of citations, with 23 studies compared to the latter's 18 studies.

In the second class in this category, the lack of socio-cultural conditions, it is observed that the barrier of lack of cooperative tradition is cited more frequently than others, with 39 studies reported. Additionally, the NIMBY syndrome and local backlash against RES and ECs are noted, with 32 papers reporting these barriers. Furthermore, the barrier of lack of environmental awareness has been identified in 22 studies.

Finally, concerning the last class within this category, 31 papers have highlighted the barrier of insufficient knowledge regarding the EC concept. This is slightly more than the second barrier, which is the lack of knowledge and awareness about the benefits of EC, as reported in 24 studies.

In general, the differences in the frequency of barriers within this category are not as pronounced when compared to the other categories mentioned earlier. However, the lack of a cooperative tradition is noted more frequently than the others, followed by the NIMBY syndrome and local backlash against RES and ECs, as well as the insufficient knowledge regarding the EC concept.

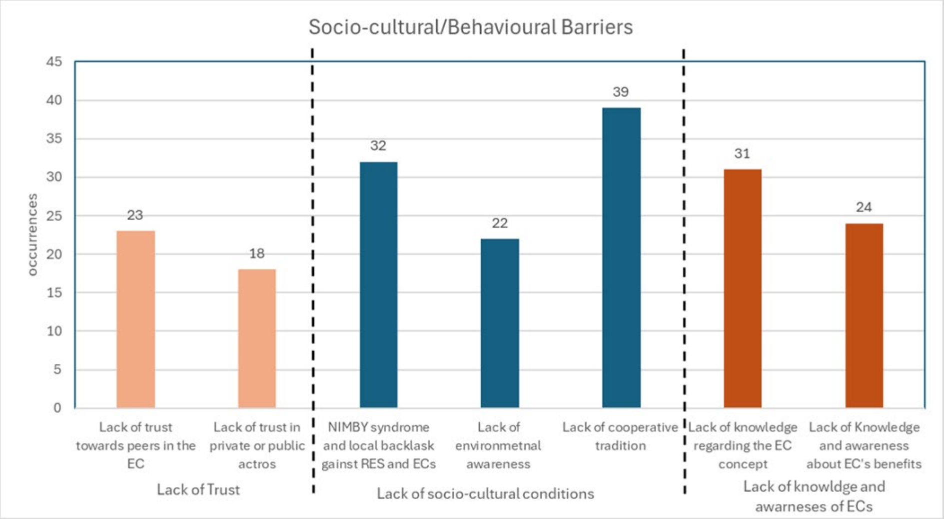

Figure 13: The frequency of occurrence of socio-cultural/behavioural barriers identified in the literature.

In summary, all the barriers are present in the literature, although they appear with varying frequencies. The barriers that appear more often in the literature are the lack of technical expertise, which appears in 81 documents, followed by the lack of policy stability and coherence, which has been cited in 76 documents. Three additional barriers are mentioned in the literature more than 60 times: the lack of technical skills, the absence of customized financial options, and the dominance of market incumbents. All these barriers fall within the first three categories: economic, institutional, and technical/technological. In contrast, barriers classified as socio-cultural and behavioural are less frequently mentioned in the literature.

Table 7. Frequency of occurrence in the literature of barriers faced by ECs.

Barriers	Recurrence
Category: Economic Barriers	
Class: Financial Barriers	
Lack of access to traditional finance	45
Difficult to access finance from members	41
Lack of tailor-made finance options	65
Lack of public funds for ECs	54
Class: Market Barriers	
Lack of a level playing field	56
Presence of market incumbents	63
Category: Institutional barriers	
Class: Policy and regulatory barriers	
Absence or lack of a clear and uniform definition of ECs	26
Lack of a clear scope of EC's activities	38
Lack of policy stability and coherence	76
Class: Administrative and bureaucratic barriers	
Lack of simple and clear administrative procedures	43
Slow administrative procedures	27
Category: Technical/ Technological barriers	
Class: Technical barrier	
Lack of space to build RES plants	27
Lack of technical skills (skilled personnel)	66
Lack of technical expertise	81
Class: Lack of efficient infrastructures	
Lack of efficient and suitable energy infrastructure	58
Lack of IT infrastructure	16
Class: Lack of enabling technologies	
Low diffusion of smart technologies	19
Data management issues	32
Cybersecurity and protection issues	18
Category: Socio-cultural and behavioural barriers	
Class: Lack of knowledge and awareness of ECs	
Lack of knowledge regarding the EC concept	31
Lack of awareness about ECs benefits	24
Class: Lack of trust	
Lack of trust in private or public actors	18
Lack of trust towards peers in the EC	23
Class: Lack of socio-cultural conditions	
NIMBY syndrome and local backlash against RES and ECs	32
Lack of cooperative tradition in the country or the region your EC is operating	39
Lack of environmental awareness in the country or the region your EC is operating	22

The most cited barrier in this latter category is the lack of a cooperative tradition in the country or region where EC operates, having been referenced in 39 documents (See Tab. 4).

Finally, some new barriers appear in the literature review that cannot be assigned to categories presented here. Specifically, five papers in the literature review state that the lack of support from local governments for EC projects is a substantial barrier to their success. Moreover, the literature presents certain barriers that correspond to specific types of EC activities. Specifically, scholars mentioned the environmental barriers, stating that climate change affects natural resources, which in turn can affect the implementation of EC activities that are sensitive to environmental changes, such as energy production by biomass. However, these barriers are related to specific types of activities or have been mentioned only a few times in the literature and are therefore not included in our analysis.

EC barrier assessment

The last step entails the design and launches of a survey addressing EC initiatives located in the EU. The survey aims to gather novel quantitative and qualitative data; therefore, questionnaire consist of 2 thematic blocks: EC characteristics (including location, maturity, number and type of members, activities performed, etc.), and EC barriers: List of barriers, break down into 4 categories (Economic, Institutional, Technical/Technological, and Socio-cultural and Behavioural barriers).

The relevance of Economic, Institutional, Technical/Technological, and Socio-cultural and Behavioural barriers in setting up, developing and operating EC initiatives in the EU. For assessing the barriers, respondents have to rate the relevance of barriers by ranking them from “0” to “5”. Responses marked as “0”, indicating either the absence of a barrier or insufficient knowledge or no relevance by the respondent and “5” means very high relevance. Furthermore, to maintain transparency and analytical consistency, invalid responses have been excluded.

The survey is created using the Qualtrics software and will target “EC representatives”, defined as individuals holding management and/or organizational roles within the EC initiative. In total, 1629 contacts of EC initiatives collected from 19 European countries, both in northern and southern Europe. The survey has been launched in the second half of September 2024. By June 30, 2025, we received more than 153 responses. However, only 122 of these were considered valid for the analysis. However, the survey will remain open to enable a more comprehensive investigation into the relevance of identified barriers. Also, this survey was conducted with five rounds, three rounds of surveys conducted in the “English” language, but to get more responses and assist the respondents to be comfortable with their mother language, it was translated into Italian, French, and Spanish. The overall useful response rate is 122 among 1629, or 7.50%.

Regarding general Characteristics of ECs, the analysis revealed the following:

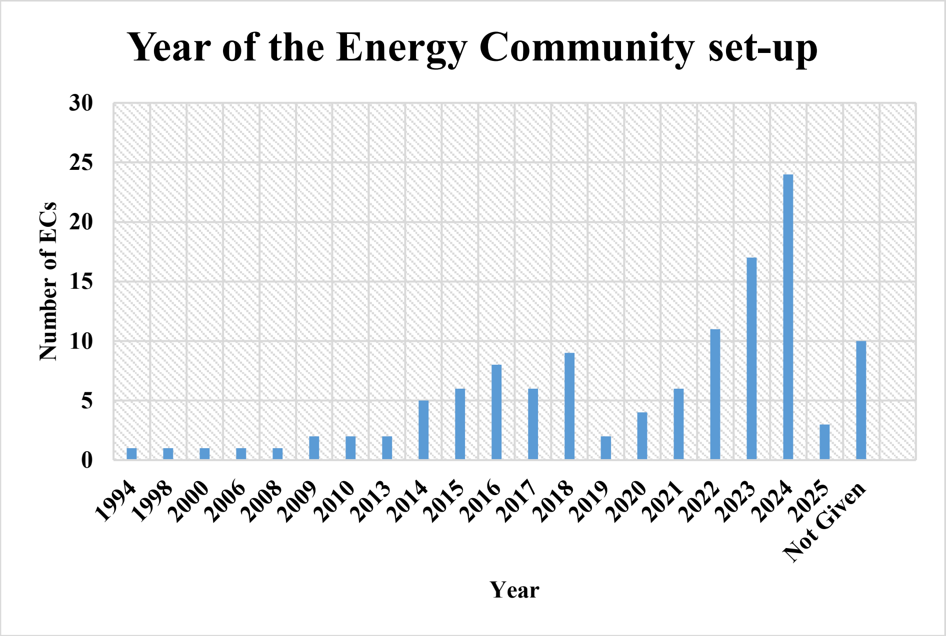

Figure 8: Year of ECs set-up.

Figure 8 shows the distribution of EC establishment years from our dataset. The highest proportion of responses is in the "2024" category (see figure 8). The third largest group indicates that many participants either chose not to disclose this information due to privacy concerns or that the ECs are still being established, so the year of setup cannot be specified yet. The year 2023 has significant activity with 17 ECs, while 2022 has 11 ECs and 2018 recorded 9 ECs. The years 2009, 2010, and 2013 each show two ECs in our survey sample. In contrast, earlier years like 2006, 2008, and before 2000 have minimal activity, with only one EC each.

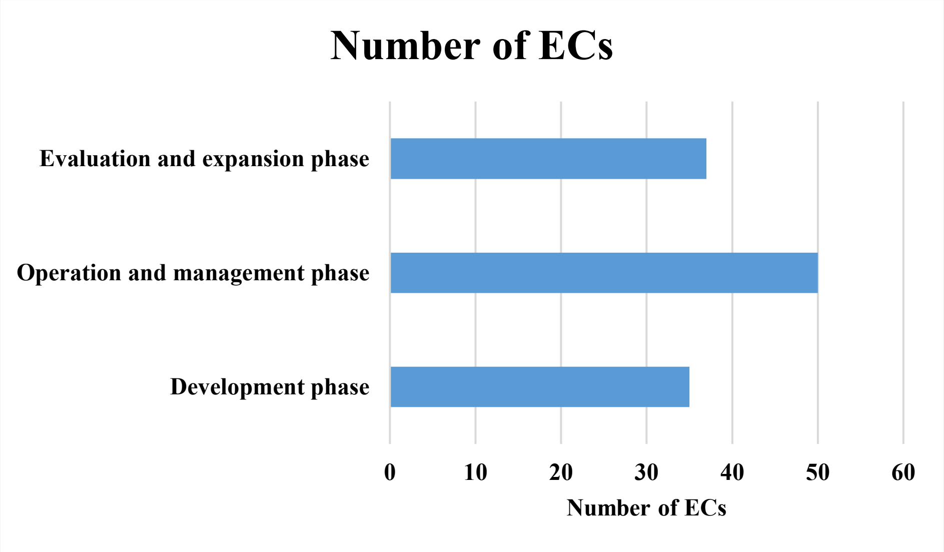

Figure 9: Maturity stages of ECs.

Figure 9 shows the maturity stages of ECs, emphasizing the recent growth of EC initiatives. This trend matches the timeline in Figure 8, which showed increased activity after the publication of EU directives. Specifically, 35 ECs in the dataset are currently in the development stage, indicating ongoing expansion of the EC concept. Additionally, 50 ECs have progressed to the operation and management phase, while 37 ECs are in the evaluation and expansion phase. These findings highlight the dynamic nature of EC establishment and the gradual progress of these initiatives through different stages.

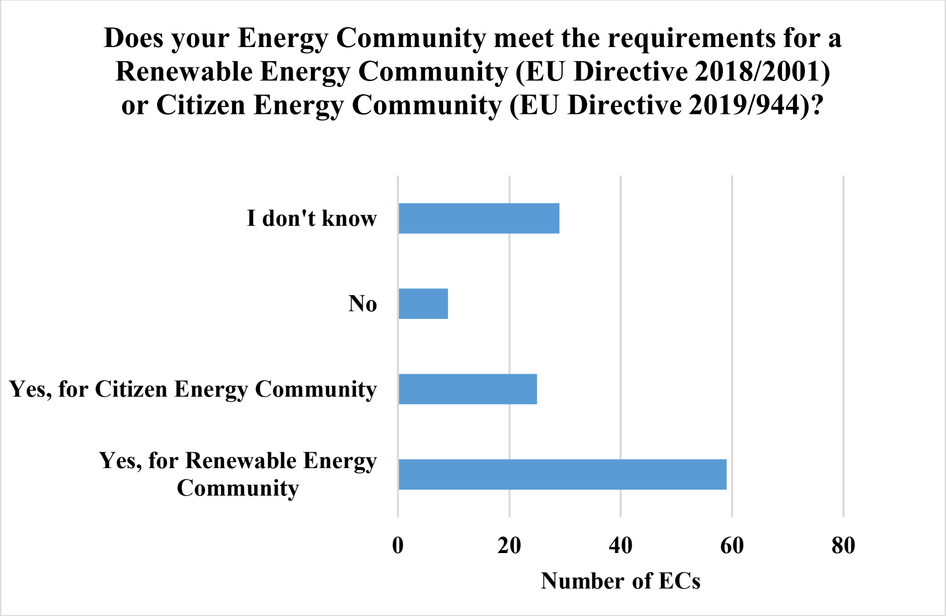

Figure 10: Compliance of ECs with EU REDII and IEMD

Figure 10 shows how ECs comply with EU REDII (Directive 2018/2001) - REC and EU IEMD (Directive 2019/944) - CEC requirements in our sample. Most ECs, specifically 59 out of 122, identify as Renewable Energy Communities (RECs), while 25 ECs see themselves as Citizen Energy Communities (CECs). Notably, 29 ECs chose the option "I don't know", likely reflecting their current development stage and the absence of a finalized strategic plan, which delays choosing a legal form. Additionally, 9 ECs responded "No", possibly because the two EU directives have not been fully integrated into national legislation in some countries. This distribution highlights the dominance of RECs in the dataset and the uncertainties or legislative barriers ECs face in adopting formal classifications.

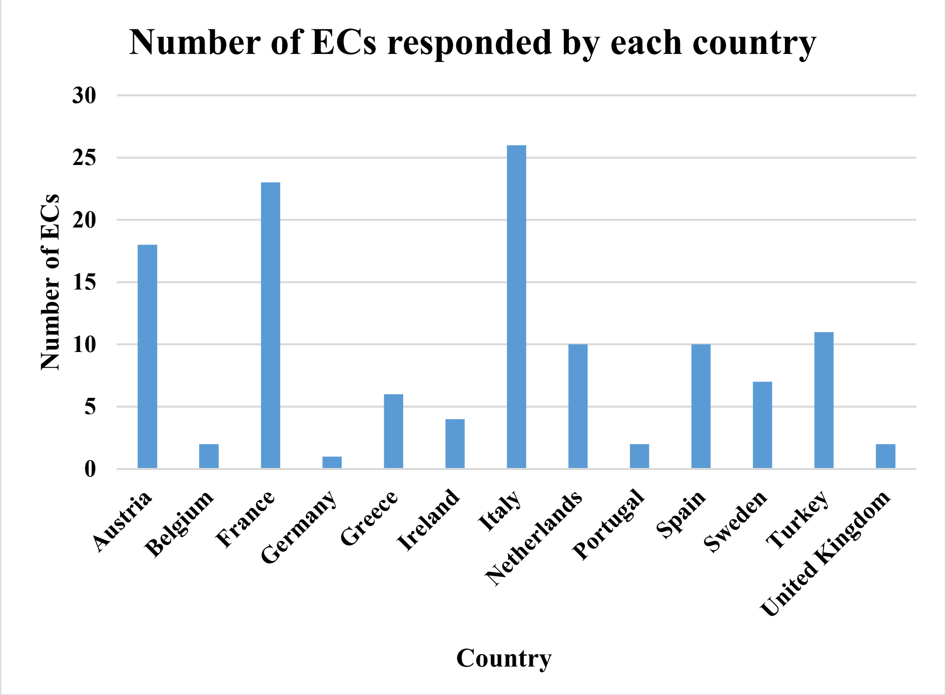

Figure 11: Geographical distribution of ECs.

The geographical distribution of ECs in our survey shows that Italy (26 ECs), France (23 ECs), and Austria (18 ECs) have the highest numbers of ECs. Turkey has 11 ECs, while Sweden accounts for 7 ECs in our analysis. The Netherlands and Spain each report 10 ECs. Additionally, Greece has 6 ECs, while Belgium, Portugal, and the United Kingdom each have 2 ECs, and Germany has 1 EC. The lack of data from other regions, such as Eastern Europe, may indicate either a smaller presence of ECs in our current database or limited survey participation. To address this gap and better understand how barriers differ across countries, another round of survey distribution will be conducted, focusing specifically on countries that were underrepresented in this initial phase.

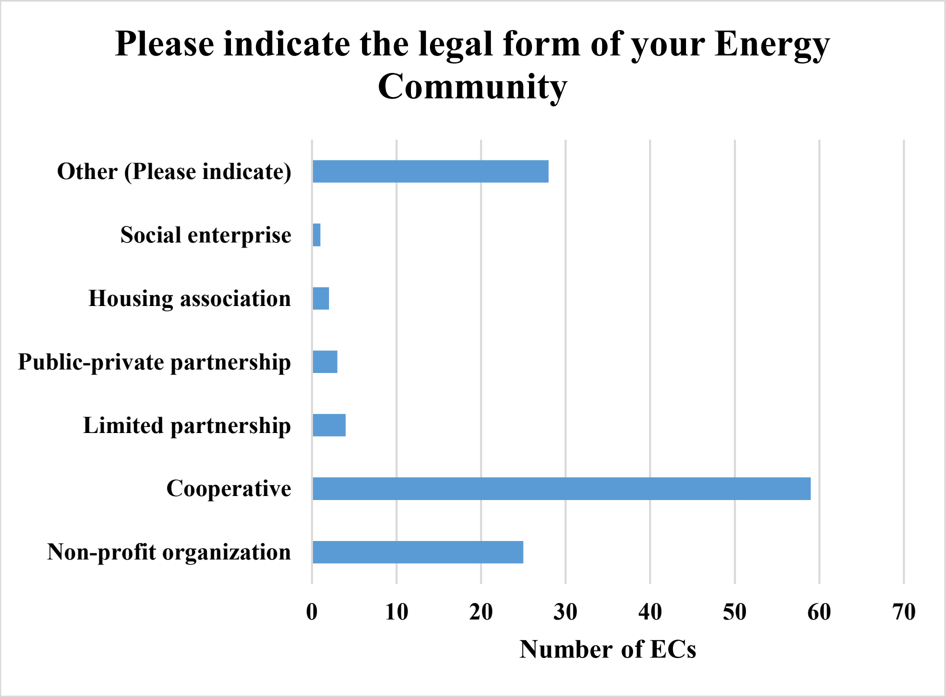

Figure 12: Legal forms of ECs.

Figure 12 shows the legal forms of the surveyed ECs. About 59 ECs follow the “Cooperative” legal form, which is the most common. The “Others” category, including various unspecified legal forms, comes next with around 28 ECs. The large number of unspecified legal forms is due to many ECs still being in the development phase and not yet having a set legal form. Non-profit organizations make up roughly 25 ECs. Other legal forms, such as limited partnerships (4 ECs), public-private partnerships (3 ECs), housing associations (2 ECs), and social enterprises (1 EC), are less common. These findings show a strong preference for cooperative models among ECs, emphasizing shared ownership and collaborative governance.

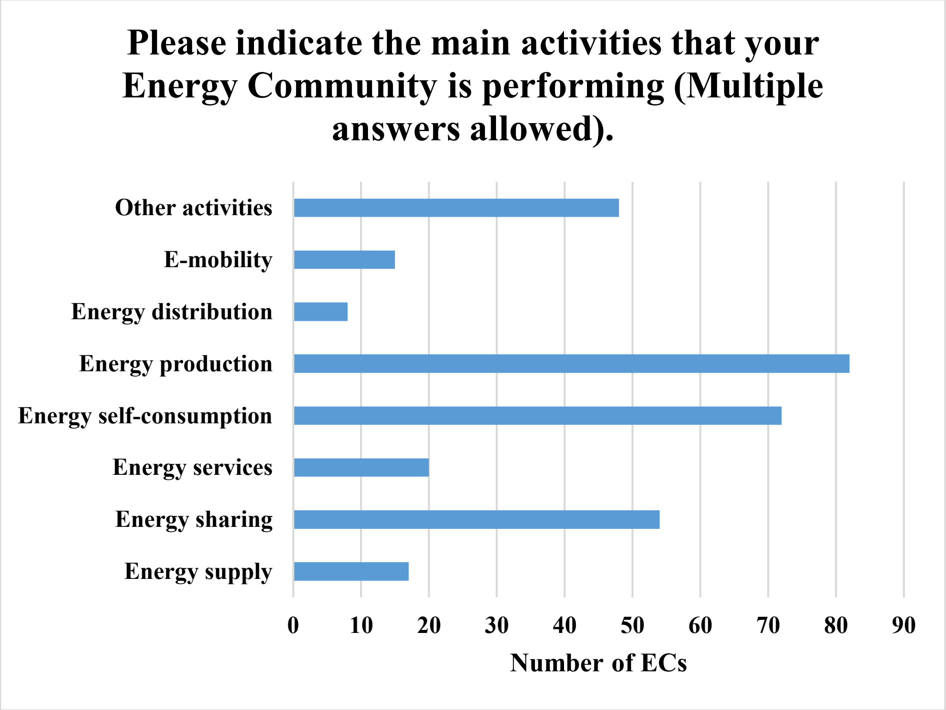

Figure 13: Main activities performed by ECs.

Figure 13 shows the main activities performed by ECs. The most common activity is energy production, with about 82 ECs involved in this area among the respondents. Energy self-consumption is next, with over 72 ECs participating. Energy sharing and energy services are also significant, with 54 and 20 ECs, respectively. Other activities like energy supply (17 ECs), e-mobility (15 ECs), and energy distribution (8 ECs) are less common, each involving fewer than 18 ECs. These results emphasize the key role of energy production and self-consumption in the operations of ECs.

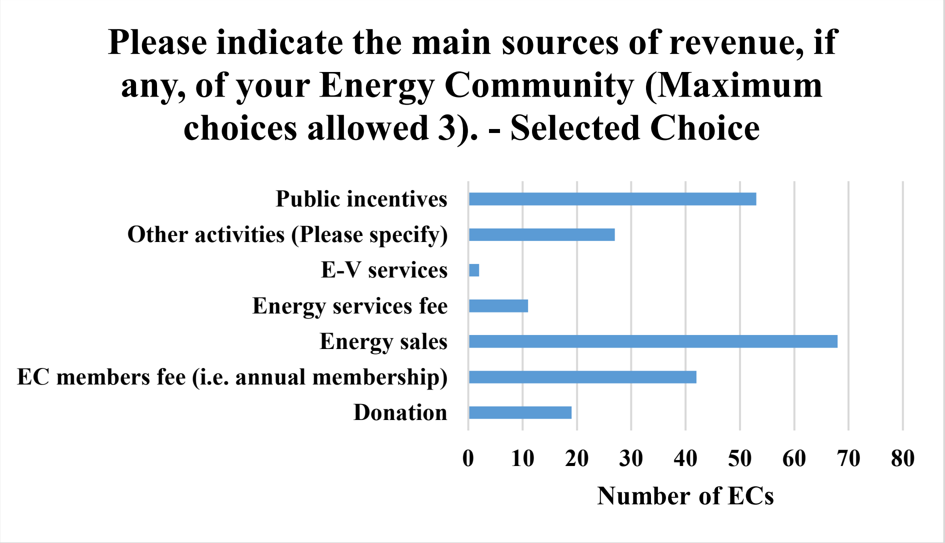

Figure 14: Main source of revenue of ECs.

Figure 14 highlights the main revenue sources for ECs in our sample. The leading source is “energy sales”, chosen by 68 respondents, followed by “public incentives”, selected in 53 cases. “Membership fees” contribute to the revenue of about 42 ECs, while “other activities” and “Donations” account for significant but smaller sources, involving roughly 27 and 19 ECs, respectively. “Energy services fees” (11 ECs) and “E-V services” (2 ECs) are minor income sources. These findings suggest that ECs mainly depend on market-based income (through energy sales) and government support (via public incentives) to operate.

After reviewing the data, it is clear that the barriers identified in this survey were considered relevant by respondent EC. Survey participants evaluated the barriers differently, with some finding them very important and others considering them less significant. In the following sections, we present and analyse them.

Economic barriers

The first Economic barriers considered refer to Financial barriers. Over 122 answers received, and 121 responses were considered for this barrier class. Four distinct barriers are analysed: “Lack of public funds for ECs”, “Lack of tailor-made finance options”, “Difficult to access finance from members”, and “Lack of access to traditional finance”.

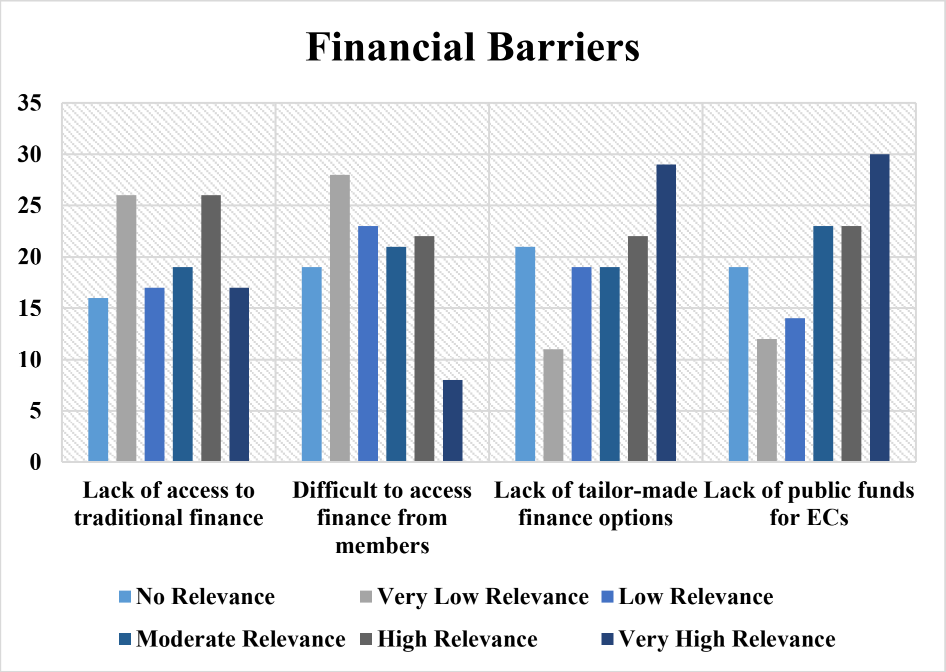

Figure 15: Financial barriers.

The findings show that the "Lack of public funds for ECs" is the most commonly identified barrier with very high relevance. Public funds are often essential for covering initial capital costs, especially in community-driven renewable energy projects that usually need significant upfront investment. The absence of adequate public financial support, ECs are forced to depend on private investments or member contributions, which can be insufficient or unsustainable. The high relevance of this barrier is also linked to the results reported in figure 15 on primary revenue sources, which indicates that most ECs in our sample depend on public incentives.

This barrier is closely followed by the "Lack of tailor-made finance options", highlighting how important funding availability and customized financial mechanisms are for the development of ECs. 29 EC respondents also rated these barriers as very highly relevant, reinforcing their role as major challenges to the growth of ECs. This barrier is especially critical for small projects, where it's even more difficult to secure enough funding from members because there are not financial options specifically designed to meet the unique needs of small ECs, which often find it less attractive to pursue traditional funding.

In contrast, "Difficult to access finance from members" and "Lack of access to traditional finance" are more often linked to very low relevance rankings. The former is especially common in low-income or economically disadvantaged areas, where community-driven projects can provide the most benefits but are less likely to receive sufficient financial support from members. This situation is also connected to the niche nature of ECs, which mainly remain accessible to high-income citizens with strong environmental commitments. This contrasts with the goals of ECs as outlined by the EU in its descriptions of RECs and CECs, which highlight the aim to fight energy poverty and promote open participation for all citizens in energy democratization. The last barrier is strongly related to the perceived high risk by financial institutions when investing in ECs, due to their smaller scale, limited credit history, and dependence on community involvement. These factors can lead to unfavourable loan terms or even outright rejection of loan applications. Furthermore, the complexity of energy market regulations and the need for specialized knowledge in evaluating renewable energy projects can further discourage traditional financial institutions from working with ECs. This analysis highlights the vital need to address financial barriers, especially through public funding and customized financial solutions, to support ECs. Overcoming these barriers requires a multi-layered approach that includes policy changes, innovative financing methods, and greater awareness among financial institutions. Public funding programs, such as grants or subsidies, can help reduce the initial cost burden, while developing tailored financial products like green loans or community bonds can improve access to capital.

The second Economic barriers considered refer to Market barriers. Over 122 answers were received, 121 responses were considered for this barrier class.

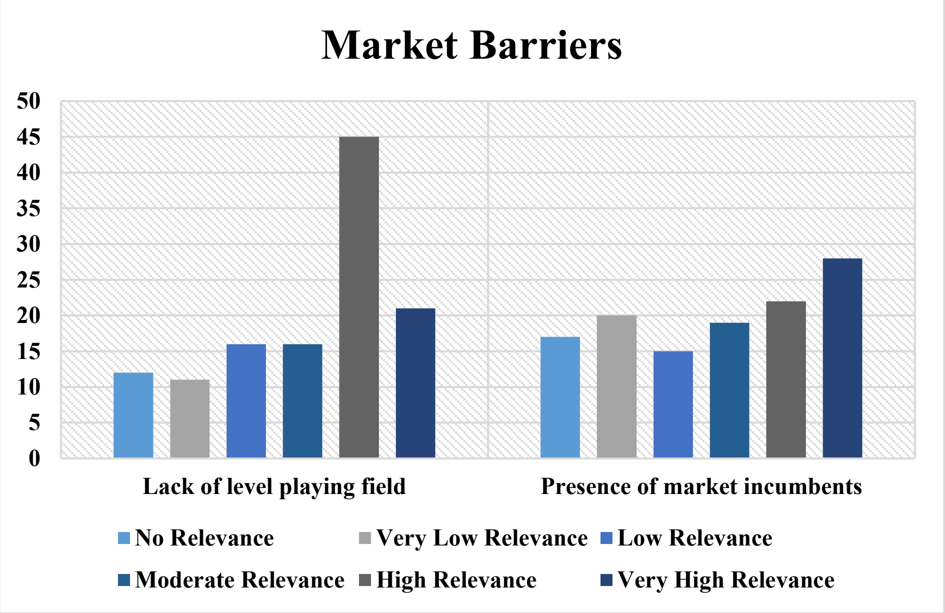

Figure 16: Market barriers.

The graph 16 illustrates the perceived relevance of market barriers focusing on two specific obstacles: the “Presence of market incumbents” and the “Lack of a level playing field”.

The “Lack of a level playing field” is widely seen as a major obstacle, with most respondents rating it as having “High Relevance”. This shows that many believe the current market setup is unfairly tilted, favouring energy providers over community-based projects. For instance, large energy companies often have better access to resources like financing, infrastructure, or regulatory support, which ECs usually lack. Additionally, administrative processes such as permitting, grid access, and regulatory compliance tend to be more complicated and expensive for ECs, putting them at a disadvantage. These structural inequalities restrict ECs ability to grow and compete effectively, especially in markets dominated by traditional energy providers.

On the other hand, the "Presence of market incumbents" shows a more diverse distribution across relevance categories, with responses ranging from "Very Low Relevance" to "Very High Relevance". While some respondents view incumbent actors as a major challenge due to their dominance, others view their impact as less critical, indicating that the barrier depends on the context and varies by region or project. In competitive markets with policies that support renewable energy, market incumbents may be less problematic, as ECs are allowed space to innovate and grow. Conversely, in markets where a few companies control energy production and distribution, market incumbents are more likely to pose significant challenges for ECs.

To overcome these obstacles, policymakers could implement measures to promote fairer competition and lower market entry barriers for ECs. Additionally, encouraging collaboration between ECs and larger energy providers could help foster competition and create opportunities for knowledge-sharing and innovation.

Institutional barriers

The first Institutional barrier considered refers to Policy and regulatory barriers. Over 122 answers were received, 121 responses were considered for this barrier class.

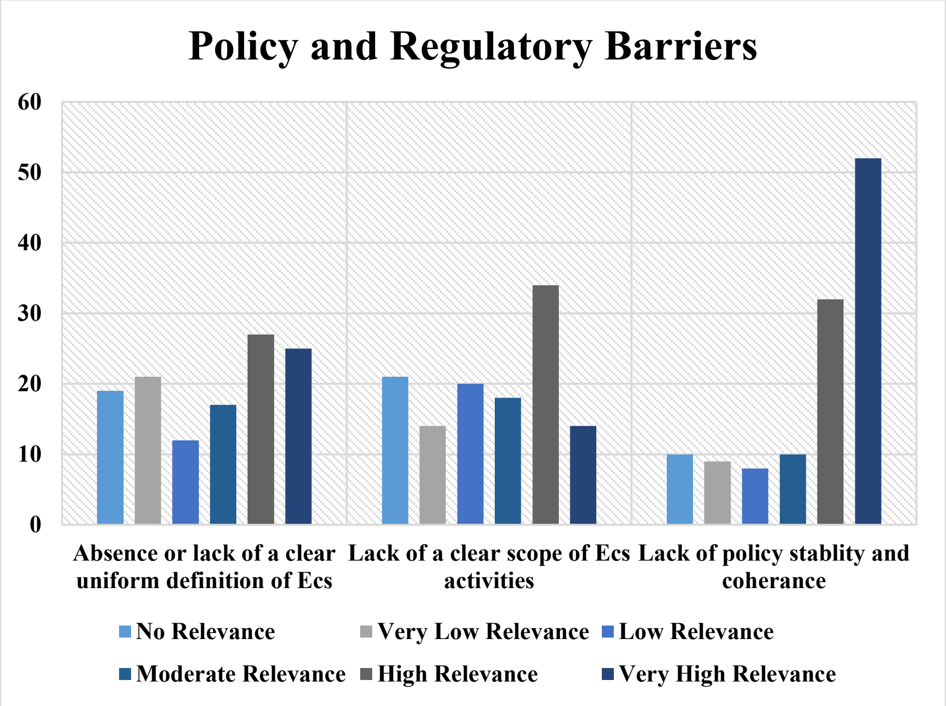

Figure 17: Policy and regulatory barriers.

The graph presents the perceived relevance of policy and regulatory barriers affecting the development and functioning of ECs. Three specific barriers are evaluated: "Lack of policy stability and coherence", "Lack of a clear scope of ECs' activities", and "Absence or lack of a clear and uniform definition of ECs".

The “Lack of policy stability and coherence” emerges as the most significant barrier, with the highest number of respondents (from 52 ECs) identifying it as “Very High Relevance”. This reflects widespread concerns about the unpredictability or inconsistency of regulatory frameworks that govern ECs. Unstable or incoherent policies may discourage investments, delay project implementation, and create uncertainty about long-term viability (also in terms of incentives, see the Italian Premium tariff assured till 2027). For instance, frequent changes to energy policies can undermine trust and confidence in the system, making it challenging for ECs to plan and execute their projects effectively.

The “Lack of a clear scope of ECs activities” is also a highly ranked barrier, with many respondents perceiving it as “High Relevance” (from 34 ECs). This indicates that there is confusion or ambiguity about what activities ECs are allowed to undertake under current regulations. For example, some ECs may wish to expand their roles beyond renewable energy production to include energy efficiency services or sharing services (i.e., EV-charges or EVs sharing), but unclear rules can restrict such initiatives.

The “Absence or lack of a clear and uniform definition of ECs” is another key issue, although it is slightly less often rated as “Very High Relevance” compared to other barriers. It is important to point out that this barrier has been addressed in many countries, such as Italy and France, where clear laws defining ECs have been established in line with EU directives. However, in many other countries, full transposition of these directives is still in progress, leading to a blurred understanding of the EC concept. This lack of consistency can also make it harder for ECs to collaborate across regions or expand.

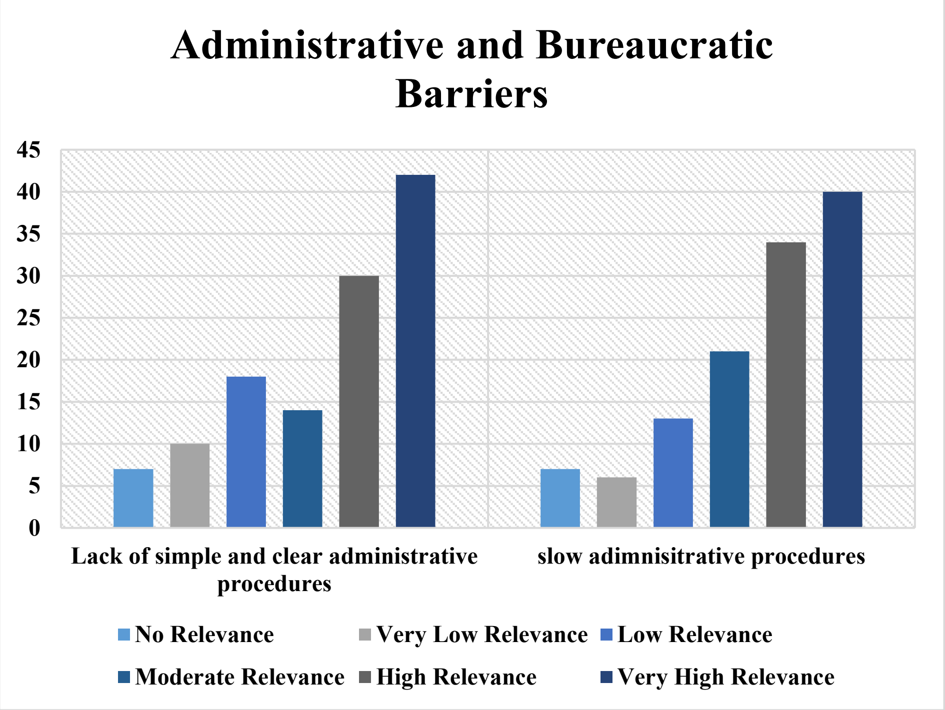

Figure 18: Administrative and bureaucratic barriers.

The distribution of responses emphasizes the importance of respondents' locations. For example, ECs operating in countries with advanced energy policies may face fewer issues related to policy stability or definitions (such as the Netherlands, Belgium, and the UK in our sample), while those in emerging markets might face significant obstacles. Additional analysis is necessary to better understand how the maturity of policy frameworks influences this barrier, as our sample size is too small to establish clear correlations.

The second Institutional barriers considered refer to Administrative and bureaucratic barriers. Over 122 answers were received, 121 responses were considered for this barrier class.

The graph presents the perceived relevance of administrative and bureaucratic barriers affecting ECs, specifically focusing on "Slow administrative procedures" and the "Lack of simple and clear administrative procedures".

The "Slow administrative procedures" barrier is the most critical issue, with the most respondents rating it as "Very High Relevance". This shows that delays in processing permits, licenses, and other administrative requirements are a major obstacle for ECs. Such delays can significantly delay project timelines, raise costs, and discourage stakeholders from participating in or starting EC projects. For instance, long approval processes for renewable energy installations or grid connection agreements can cause missed opportunities to implement energy projects on time. When the timeframe for obtaining public finance is also tight (see the Italian time limits for accessing PNRR funds for ECs), a slow administrative system can completely prevent starting an EC, impacting its ability to access public funds. This barrier is also linked to the "Lack of policy stability and coherence" mentioned above.

The "Lack of simple and clear administrative procedures" also received significant recognition as a major barrier, with many respondents rating it as "Very High Relevance". This issue points to the complexity and opacity of the regulatory environment, which often demands specialized knowledge. For ECs, especially smaller initiatives, unclear administrative requirements can add extra burdens, raising the risk of errors or compliance issues. For example, vague project approval guidelines or differences between local and national regulations can make administrative processes more complicated, discouraging potential EC participants. This barrier is particularly important in the context of home energy renovations. A solution proposed by the European Commission, as outlined in Directive 2018/844/EU on the Energy Performance of Buildings (EPBD), Directive 2018/2002/EU on Energy Efficiency (EED), and the strategy "Renovation Wave for Europe" (COM (2020)662), is the One-Stop-Shop (OSS). This model offers a centralized physical or virtual location, or both, where customers can access multiple products and services in one place [17]. A similar approach is now being used to promote, support, and guide ECs by pooling expertise and knowledge to reduce the time and effort required by non-experts. In fact, through the recast of EPBD (Directive (EU) 2024/1275), Member states are required to provide information, technical assistance, and training to all relevant actors, including ECs, following an integrated and multi-service OSS concept. Other solutions to overcome this barrier include introducing standardized guidelines, reducing paperwork, and using digital platforms to speed up processes.

It is important to highlight that at the EU level, many initiatives and support services for ECs have been implemented in recent years to overcome barriers. These services aim to inform, support, and empower citizens, local authorities, and businesses to establish EC initiatives. The most notable initiative was the Energy Communities Repository (which ended in 2024), which collected EC experiences across the EU and provided comprehensive analysis of policy, governance systems, investments, and impacts. Another key service is the Rural Energy Community Advisory Hub, designed to accelerate the development of sustainable EC projects in rural areas of the EU. The hub identifies best practices and offers technical assistance and networking opportunities to support local authorities, businesses, farmers, and citizens in setting up their own rural ECs. The Support Service for Citizen-led Renovation is an EU Commission initiative aimed at empowering ECs to lead energy-saving renovation projects. By assisting selected pilot projects to overcome financial, legal, technical, and informational barriers, this service promotes the delivery of future-proof residential buildings and encourages citizen participation in the energy transition. Additionally, the European Energy Communities Facility in 2024, with a budget of €7 million, aims to support the development of at least 140 local projects focused on business plans. The first call for grant support is expected in 2025, providing financial resources to strengthen citizen-driven energy initiatives.

Technical/Technological barriers

The first class of barriers considered under this category refer to technical barriers. Over 122 answers were received, 121 responses were considered for this barrier class. The graph illustrates the perceived relevance of technical barriers impacting ECs, focusing on three specific challenges: “Lack of technical expertise”, “Lack of technical skills (skilled personnel)”, and “Lack of space to build RES plants”.

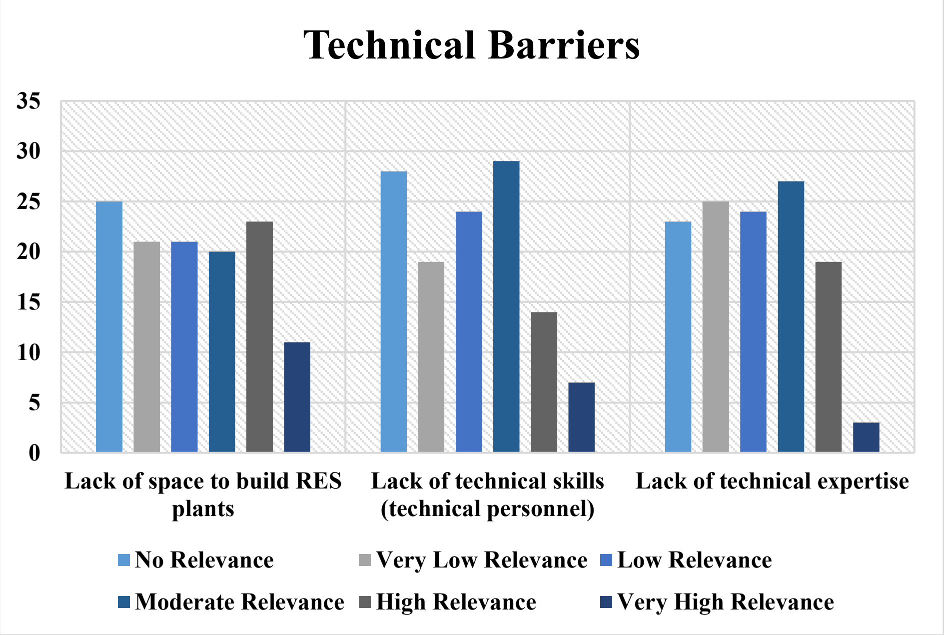

Figure 19: Technical barriers.

The “Lack of technical expertise” is rated as having “Moderate Relevance” by 27 respondents, while the majority of the 72 participants in the survey considered it to be of even lower importance. This suggests that, in many cases, ECs have access to sufficient general knowledge or external technical guidance to support their activities. However, for a smaller number of respondents, this barrier is of high to very high relevance, possibly reflecting differences in local contexts or the complexity of administrative procedures required to access funds or licenses. In fact, this barrier is closely related to the institutional one called "Lack of simple and clear administrative procedures", since when administrative procedures are unclear and complicated, the importance of technical skills to navigate this complexity increases.

The "Lack of technical skills (skilled personnel)" is more evenly spread across the relevance categories, with many respondents rating it as "Moderate Relevance". This highlights the difficulty of finding adequately trained personnel to manage EC operations, including maintenance or energy management. For ECs in less developed areas or those operating on a small scale, the availability of skilled workers might be limited, affecting their ability to implement and maintain EC initiatives. To deal with this barrier, it is crucial to rely on external experts and managers (maybe by setting up a collaboration with third parties) who can provide technologies, maintenance services, or advanced energy management platforms to improve energy production and use. These types of services offered by utilities and energy providers are increasing in the EU.

The "Lack of space to build RES plants" appears as a minor barrier, indicating that space constraints are generally not a significant issue for most ECs. However, for some respondents, this barrier is highly or very highly relevant, likely due to specific geographic or regulatory factors. For example, densely populated urban areas or regions with strict land-use policies may struggle to allocate space for renewable energy projects like solar panels or wind turbines. This challenge can limit the growth of ECs, especially in areas with high energy demand but limited physical space.

The second Technical/Technological barrier considered relates to the Lack of efficient infrastructures. Over 122 responses were received, and 121 responses were included in this barrier category. The graph illustrates the perceived relevance of infrastructure-related barriers to ECs, specifically focusing on the "Lack of IT infrastructure" and the "Lack of efficient and suitable energy infrastructure".

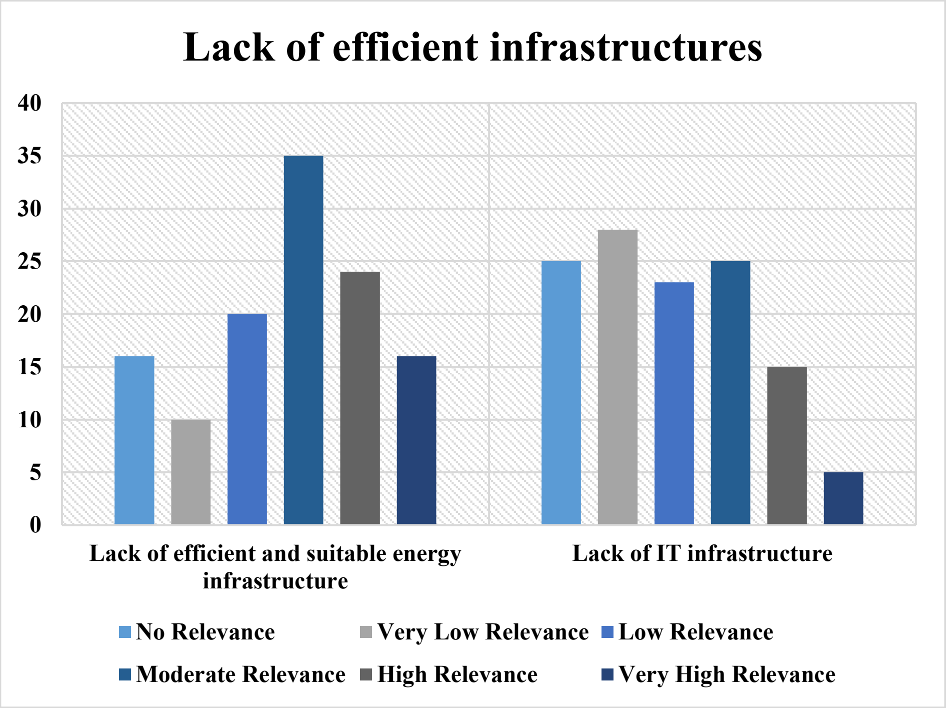

Figure 20: Lack of efficient infrastructures.

The lack of efficient and suitable energy infrastructure emerges as a critical challenge. This obstacle is especially significant for ECs, where grid access may be limited due to management issues or grid saturation. A large percentage of respondents rated this barrier as "Moderate Relevance" (35 respondents) or higher, highlighting its impact on ECs ability to implement renewable energy projects. For instance, overloaded grids or outdated infrastructure can delay the integration of decentralized energy systems, restricting both scalability and operational efficiency. Addressing this issue requires investments in modernizing the grid, expanding capacity to support RES, and implementing advanced grid management systems to reduce bottlenecks and inefficiencies.

The "Lack of IT infrastructure" is rated predominantly as "Very Low Relevance". However, advanced energy management systems, such as digital monitoring platforms, depend on strong IT infrastructure to ensure accurate data flow and optimal decision-making. In areas with limited digital connectivity or outdated IT systems, ECs may encounter operational difficulties, such as delays in responding to system issues. The last Technical/Technological barrier considered refers to Lack of enabling technologies. Over 122 responses were received, with 121 considered for this barrier class.

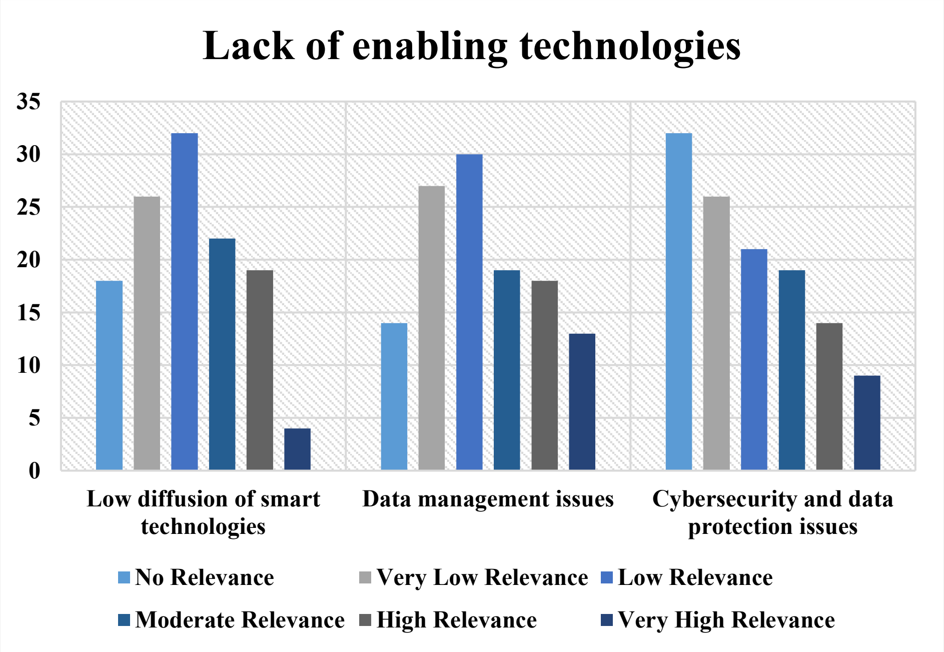

Figure 21: Lack of enabling technologies.

The graph emphasizes the importance of technological barriers faced by ECs, especially the “Low diffusion of smart technologies”, “Cybersecurity and data protection issues”, and “Data management issues”. Among these, the “Low diffusion of smart technologies” is seen as the most significant barrier. This highlights the slow adoption of key technologies, such as smart meters and automated control systems, which are vital for optimizing energy management. Smart meters can deliver near real-time feedback on energy use, helping consumers better manage their consumption, save energy, and reduce their bill, for example, by adjusting their energy usage based on different energy prices throughout the day. According to the EU Agency for the Cooperation of Energy Regulators (ACER, 2023), only 54% of European households had an electricity smart meter by the end of 2022, with over 80% penetration in 13 EU countries at that time.

In contrast, “Cybersecurity and data protection issues” are rated as less critical overall but remain a major concern for some ECs, especially those relying on advanced digital platforms for energy management. These systems are vulnerable to data breaches or system attacks, which could disrupt operations and increase members’ fears.

“Data management issues”, related to the challenges of data collection, processing, and use, vary in importance. They are particularly relevant for ECs aiming to implement advanced data-driven solutions, such as demand-response systems or predictive analytics. Poor data quality, fragmented datasets, and the lack of proper digital tools impede ECs’ ability to make informed decisions and optimize energy use.

Socio-cultural and behavioural barriers

The first Socio-cultural and behavioural barrier considered refer to Lack of knowledge and awareness of EC. Over 122 answers received, 120 responses were considered for this barrier class. The graph highlights the relevance of barriers related to knowledge and awareness about ECs. It examines two specific challenges: the "Lack of awareness about EC's benefits" and the "Lack of knowledge regarding the EC concept".

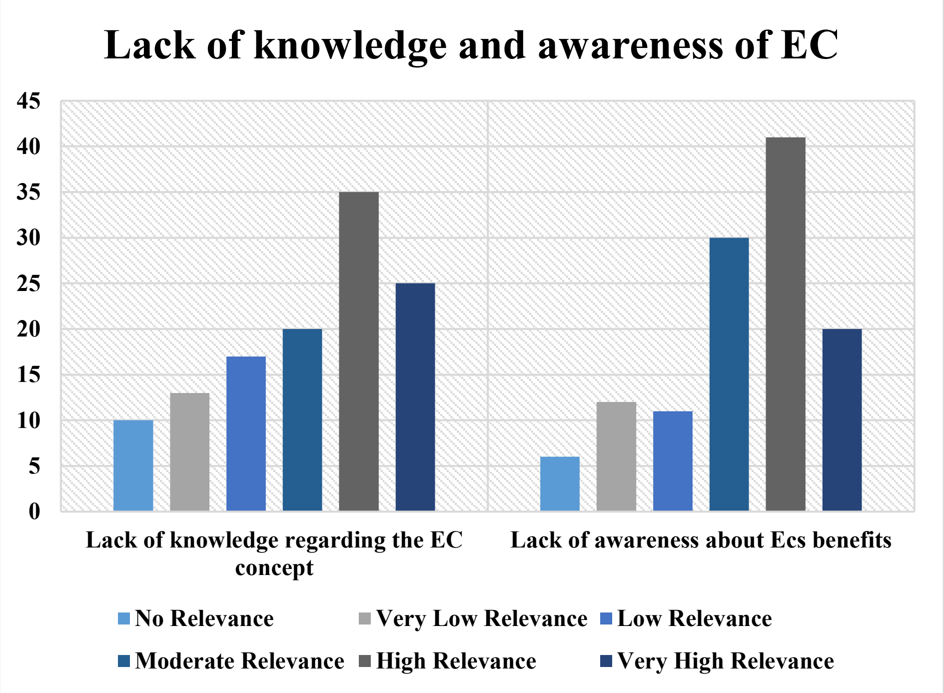

Figure 22: Lack of knowledge and awareness of EC.

The graph highlights the relevance of barriers related to knowledge and awareness about ECs. It examines two specific challenges: the "Lack of awareness about EC's benefits" and the "Lack of knowledge regarding the EC concept".

The "Lack of awareness about EC's benefits" is identified as a significant barrier, with many respondents assigning it "High Relevance" (35 respondents) or "Very High Relevance" (25 respondents). This finding underscores the challenge of communicating the advantages of ECs, such as economic savings, environmental benefits, and community empowerment. Many potential participants and stakeholders may be unaware of how ECs operate or the direct and indirect benefits they offer. The lack of understanding can limit people's engagement, reduce support for ECs, and diminish participation in renewable energy initiatives. As seen before, an EC requires effort (economic resources, time, and commitments) from its members. Thus, well understanding the benefits generated by being part of one of those initiatives can make a difference in scaling up and rolling out EC initiatives around Europe. In countries where there is a strong and maybe historical background on environmental matters, this barrier appears less prominent than in other countries where economic disadvantages and crises limit the commitments of citizens toward environmental issues. However, EC can contribute to fighting energy poverty and become a driver for low-income people who face economic limitations. This opportunity, for reasons that intercept financial and market barriers, along with institutional ones, might be lost.

Similarly, the "Lack of knowledge regarding the EC concept" is also perceived as highly relevant by respondents. This indicates that beyond the benefits, a fundamental understanding of what ECs are and how they function is often missing among potential members and stakeholders. Misunderstandings about what an EC is, requires, and provides can create resistance, particularly in regions where ECs are a relatively new concept.

Addressing these barriers requires a concerted effort to improve information, education, and awareness about ECs. Public awareness campaigns can play a key role in highlighting the benefits of ECs, particularly their potential to reduce energy costs, enhance sustainability, and foster public-private partnerships and collaboration among local stakeholders and community engagement in energy transition. It is crucial to increase awareness also in terms of EC operational structures, legal aspects, and technical and administrative requirements towards citizens, local stakeholders, and even public authorities at the local level that might lack knowledge about this topic. This is particularly crucial to avoid rebound effects within institutional and technical barriers as seen before.

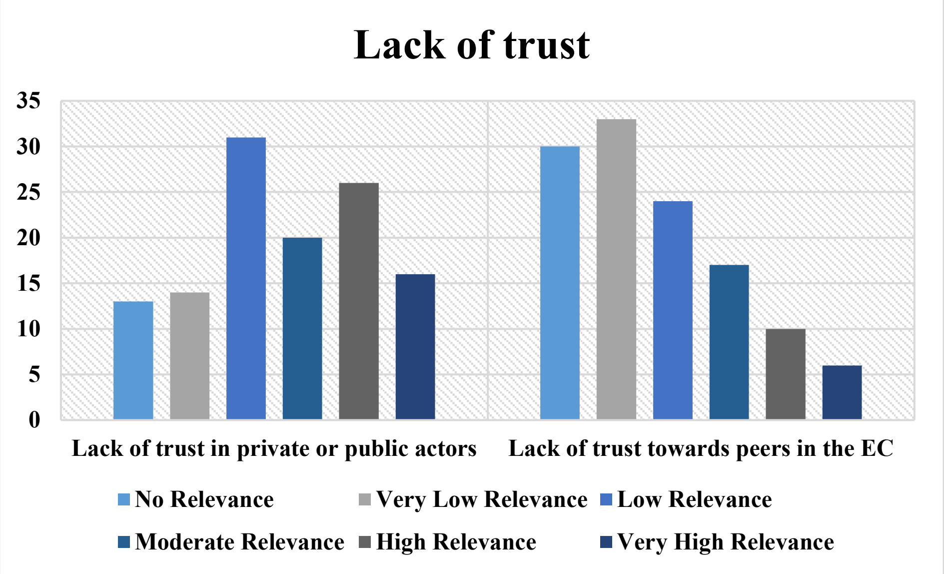

Figure 23: Lack of trust.

The second Socio-cultural and behavioral barrier considered refer to Lack of trust. Over 122 answers were received, and 120 responses were considered for this barrier class. The graph examines trust-related barriers to ECs, focusing on “Lack of trust towards peers in the EC” and “Lack of trust in private or public actors”.

The “Lack of trust in private or public actors” emerges as a major barrier. This reflects a perception that external stakeholders, such as private companies, local authorities, or national governments, may not act in the best interests of ECs or their members. Concerns about profit motives, mismanagement, or lack of transparency in regulatory and operational processes contribute to this distrust. For example, ECs may hesitate to collaborate with energy utilities or public authorities if they believe their interests will be overlooked or dismissed. Trust in public actors is essential for ECs to access regulatory support and funding. However, as previously noted, public authorities at the local level are often unaware of ECs and unable to offer proper support or enhance these initiatives, leading to feelings of exclusion and isolation among EC members. Conversely, trust in private actors is vital for partnerships involving technology providers or investors, which can significantly reduce technical and technological barriers.

In contrast, the "Lack of trust towards peers in the EC" is generally rated as "No Relevance" or "Very Low Relevance" by most respondents. This suggests that EC members largely trust each other, likely due to shared goals and a collective interest in the community's success. However, internal conflicts, unequal contributions of resources and revenues, and differing priorities can weaken trust and disrupt collaboration within ECs. Mechanisms such as transparent governance structures and regular communication can strengthen cohesion. Building trust also involves demonstrating competence. Members need confidence that the EC has technical, administrative, and financial expertise to meet its goals. Training programs, external advisory support, and partnerships with experienced organizations can enhance the EC's capabilities and reassure members of its potential for success. This is especially important to lower financial barriers like "Difficult to access finance from members", as many ECs, particularly small-scale initiatives, rely heavily on member funding to operate. Lack of trust could hinder their willingness to invest capital, worsening access to credit issues.

The final socio-cultural and behavioural barrier concerns the "Lack of socio-cultural conditions". Over 122 responses were received, with 120 responses considered relevant to this barrier. The graph explores socio-cultural challenges, focusing on three main issues: "Lack of environmental awareness in the country or region where the EC operates", "Lack of cooperative tradition in the country or region", and "NIMBY syndrome and local backlash against RES and ECs".

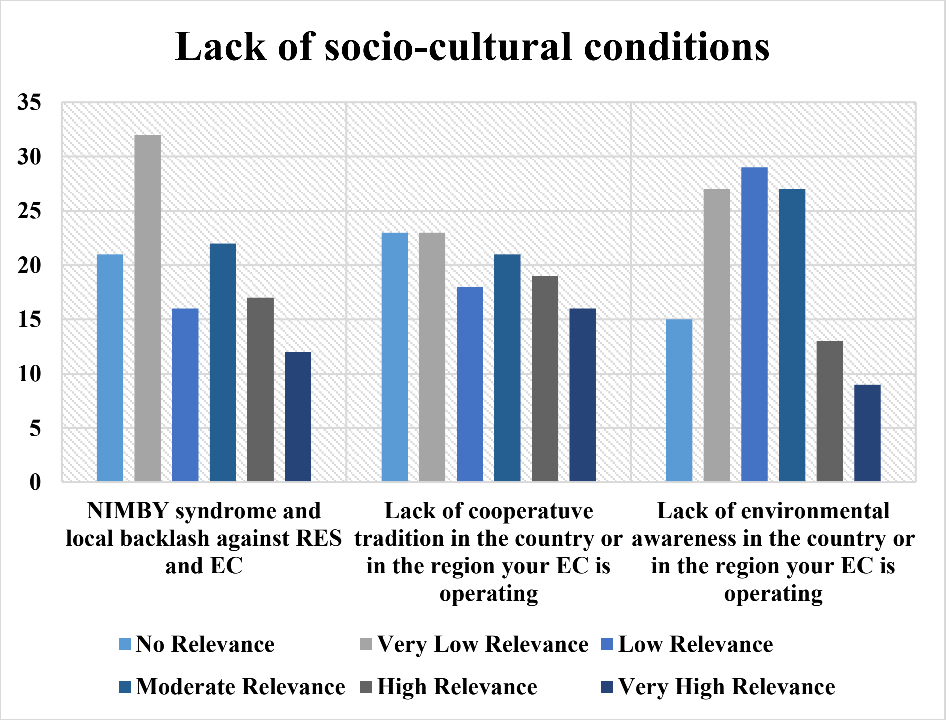

Figure 24: Lack of socio-cultural conditions.

The graph examines socio-cultural barriers by focusing on three main challenges: “Lack of environmental awareness in the country or region where the EC is operating”, “Lack of cooperative tradition in the country or region”, and “NIMBY syndrome and local backlash against RES and ECs”.

The “Lack of environmental awareness” emerges as a significant obstacle, with many respondents rating it as “Very Low Relevance”, “Low Relevance”, and “Moderate Relevance”. This emphasizes how important environmental awareness is in gaining support for ECs. In areas where awareness of environmental issues like climate change and renewable energy is low, people may lack motivation to engage with or support EC initiatives. Without understanding the long-term benefits, ECs may find it hard to involve stakeholders and citizens. This lack of awareness not only reduces participation but may also fuel scepticism or opposition to change.

The “Lack of cooperative tradition” is another key barrier. While not seen as critical everywhere, it can have a major impact in certain contexts. Cooperative traditions, which involve collaborative decision-making, resource-sharing, and mutual support, are essential for the success of ECs. In countries or regions with weak or no such traditions, communities might struggle to build the social bonds and organizational structures needed to sustain ECs. Conversely, countries with a history of collective practices, like cooperatives and associations, like Scandinavian countries, tend to accept and understand the benefits of community-driven initiatives like ECs more easily.

The “NIMBY syndrome” and local resistance against RES and ECs is mostly rated as “Very Low Relevance”. This phenomenon reflects opposition to renewable energy infrastructure, like wind turbines or solar farms, due to perceived local inconveniences or aesthetic concerns. Overcoming this barrier requires careful planning and active community engagement. Involving residents early in the planning process and listening to their feedback can help reduce opposition. Transparent communication about the benefits of ECs, along with efforts to address specific local concerns, can foster trust and lessen resistance. Offering incentives, such as discounted energy rates or direct financial benefits to affected communities, can also help garner support.

Summary of the most encountered barriers by ECs from our survey

Looking at all barriers, we can make a list of the most relevant barriers across technical, regulatory, financial, and socio-cultural categories of barriers according to our sample of respondents. Based on this analysis, the ten most relevant barriers are:

1. Lack of policy stability and coherence
2. Lack of simple and clear administrative procedures
3. Slow administrative procedures
4. Lack of public funds for ECs
5. Lack of tailor-made finance options
6. Lack of a clear scope of ECs activities
7. Lack of awareness about EC’s benefits
8. Lack of knowledge regarding the EC concept
9. Presence of market incumbents
10. Lack of level playing field

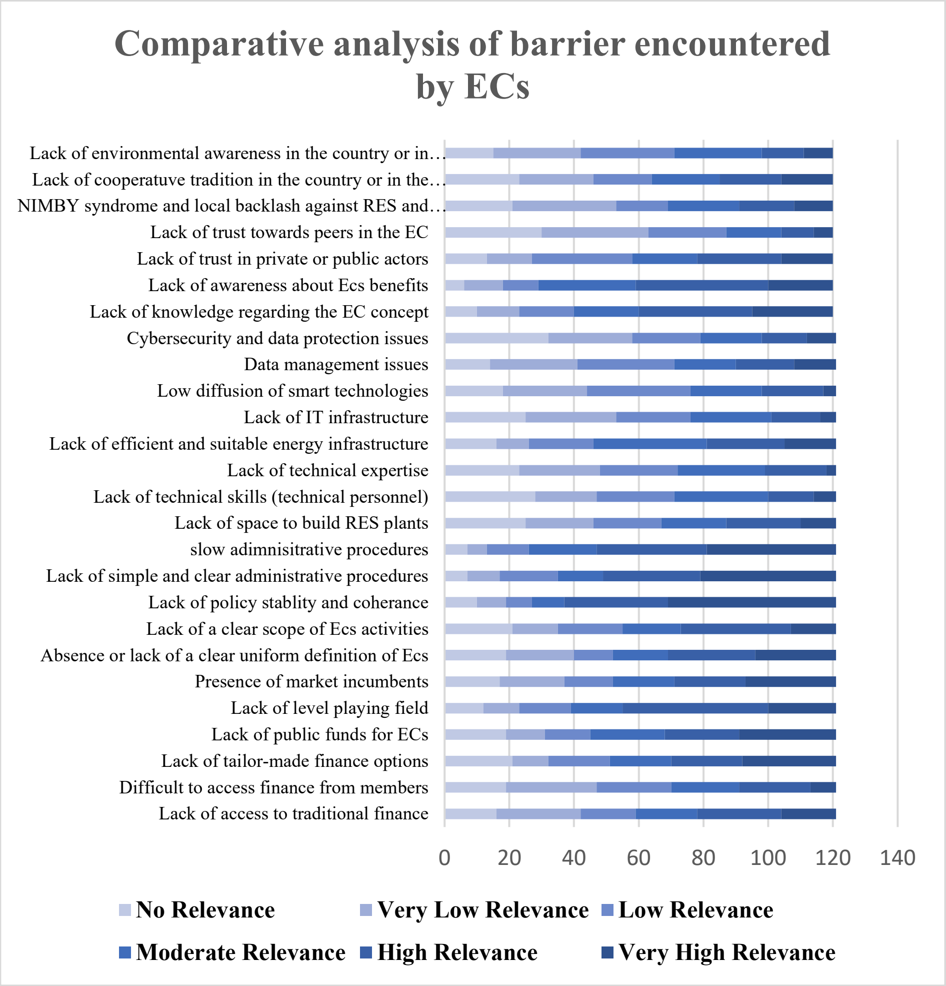

Figure 25: Comparative analysis of barriers.

2.4. Energy Communities enablers

There are several types of enablers of ECs, including technical, institutional, social, and economic. A technical enabler is a technological solution, including both hardware (equipment) and software, that enhances operations and management while reducing project costs, including EC projects. A social enabler is a combination of personal behaviours (traits of EC members), policies, and awareness that promotes participation (interaction among EC members) to achieve social goals. Economic enablers are mechanisms, policies, and support systems that promote the economic growth of projects. Institutional enablers can positively influence an organization, institution, or community, helping end users (EC members) access services.

Key EC enablers assessment by Literature

To identify the key enablers of ECs in the literature, a traditional literature review process is conducted by searching Google Scholar with two keywords, namely “energy communities" and "enabler". After analysing current literature found that Economic enablers are (a) access to financial support including subsidies or grants, (b) a cooperation bank that facilitates low-interest loans, (c) crowdfunding which helps ECs by allowing members to choose and support projects that need funding from a social or local standpoint), and (d) self-ownership for locally produced energy [18]. Moreover, institutional enablers are (a) a liberalized market enables direct energy trading, encourages the involvement of prosumers, promotes the integration of RES, and developing economies of ECs with competitive markets, (b) a stable regulatory framework for ECs, (c) CO_2 taxation assist emerging economies by increasing fossil fuel prices, making RES more competitive, and enhancing the self-consumption of ECs, (d) reduced installation cost of RES than traditional energy, and (e) state financial support or debt securities. Social enablers are (a) trust, and community-based networks, (b) values including self-ownership of RES and RES-based energy production locally either onsite or through VPP, [22], and (c) Social learning [19]. Technical enablers are (a) DES which can work as an enabler to promote a sustainable and resilient energy future by generating energy at its point of use, reducing reliance on centralized grids, and improving grid flexibility and local energy security [20], (b) RES technology options available, (c) Smart meters which are essential tools for a modern energy system, changing utilities and consumers by increasing grid efficiency and providing innovative services such as real-time consumption data, dynamic pricing, and more accurate billing, (d) net metering, and virtual net-metering, (e) blockchain which is a popular option as a security enabler [21] that can be integrated with ECs [22], (f) Virtual Power Plants have developed into advanced facilitators of various energy assets which can be considered as enabler [23]), (g) microgrid facilitating peer-to-peer [18], and (h) EVCSs where EV can play as energy storage and EVCS can sellback energy during RES generation [24]. Figure 2 illustrates the enablers of ECs.

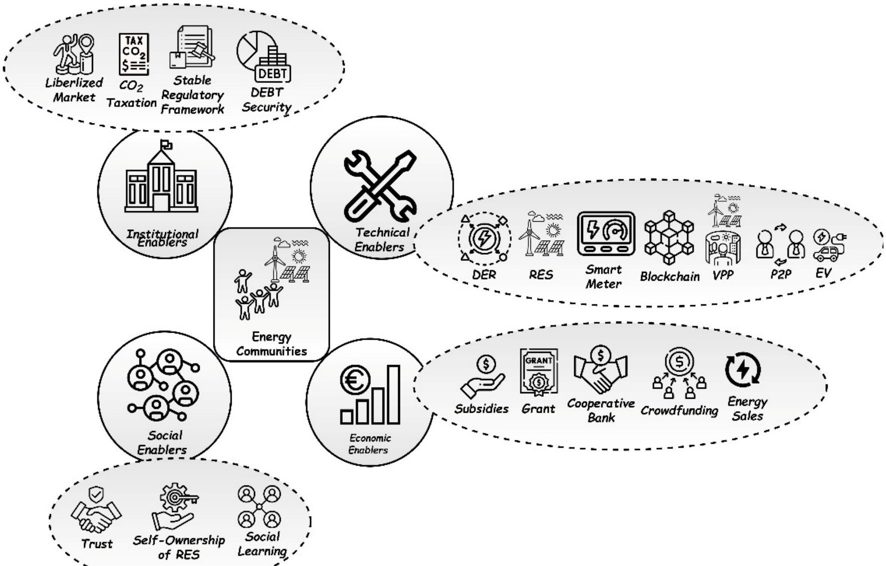

Figure 26: Comparative analysis of enablers.

2.5. Contribution to the WP objectives

The research conducted by ESR15 and ESR14 contributes directly to the overarching objectives of WP5, which focuses on developing green economy models and management systems to support the transformation of the energy system. This deliverable corresponds to Task 5.4 under WP5, which aims to identify the enablers and barriers that influence the replicability and transferability of BMs for green energy systems. The research focuses specifically on ECs, which represent a citizen-led, decentralized approach to energy production and management. ECs are instrumental in advancing WP5's objectives by enabling distributed renewable energy generation, fostering prosumer engagement, and supporting flexible demand-side energy strategies. The studies presented here offer valuable empirical and analytical insights into the challenges and opportunities facing ECs across Europe. ESR15's initial work investigated how different EC ownership models affect funding mechanisms and access to capital. The results showed that ownership structure plays a significant role in determining financial barriers and opportunities. ECs initiated and managed solely by citizens often struggle to raise internal funds, while those involving a broader coalition of actors face fewer financial constraints. This analysis supports WP5's first and third objectives by offering a categorization of EC types and suggesting policy pathways to facilitate capital access for underfunded ownership models. Furthermore, the SLRs and survey research conducted by ESR14 and ESR15 contribute to the WP's goals. The development of a validated typology of barriers-categorized into regulatory, technical, financial, and social domains-offers a comprehensive understanding of the constraints ECs face. ESR15's use of the PRISMA methodology to identify the most frequently cited barriers in the literature, coupled with ESR14's survey collecting primary data from 122 ECs, provides robust evidence to inform targeted policy actions. In addition to identifying barriers, the research also addresses enabling conditions. A literature-based mapping exercise identified four main categories of enablers-technical, institutional, economic, and social. These enablers were linked to the practical implementation of ECs and aligned with WP5's aim of promoting sustainable, inclusive, and replicable energy solutions. These insights are valuable for future BM development under WP5.

3. Conclusions

The current report provides information regarding the research outcomes of IRP14 and IRP15 in relation to D5.4, focusing on enablers and barriers to foster the replicability and transfer of BMs for green energy systems. In this context, ESR14 and ESR15 concentrate ECs, which are legal entities established to empower local stakeholders, including citizens, SMEs, and local authorities, to produce, consume, and manage their energy. The aim of the research presented here was to examine the various barriers that ECs encounter, as well as to explore the enablers that can help overcome these barriers, thus contributing to the objective of WP5 and the current deliverable.

ESR14 and ESR15 collaborate to achieve the above-mentioned objective but also develop research strategies independently. Specifically, ESR15 conducted a survey to analyse how the ownership model of ECs impacts the funding mechanisms they employ, as well as to identify the financial barriers faced by these ECs. In this work, ESR15 developed a questionnaire and gathered primary data related to the general characteristics of ECs, as well as data regarding the ownership model, funding mechanisms, and main financial barriers they face.

Nevertheless, ESR14 and ESR15 aim to extend the analysis of barriers. They are trying to identify, analyse, validate, and assess all possible types of barriers that ECs face. Hence, a semi-structured literature review was conducted to identify and categorize all different types of barriers faced by ECs. These barriers were later validated through a SLR carried out by ESR15 with the support of ESR14. Finally, a questionnaire was developed by ESR14 with the support of ESR15 to collect primary data from ECs in Europe and assess the relevance of the barriers.

Finally, in the current report, the results of studies conducted by ESR14 and ESR15 regarding the enablers of ECs were presented. ESR14 specifically performs a literature review and compiles all of the research on the enablers that can facilitate the establishment, growth, and expansion of ECs. ESR15, which focuses on Greece, aims to provide tailored policy recommendations that address the reported policy barriers hindering the development of ECs in the country.

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