



D5.6. Final WP5 scientific report

WP5 – Green Economy Models and Management Systems

Author: Bocconi University (UB)

March 2026



SMARTGYSUM project has
been funded by the
European Commission's
Horizon 2020 Programme



SMARTGYsum has been funded by the European Union's Horizon 2020 Programme under the Grant Agreement GA 955614

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Versions:

Version No.	Person in charge	Institution (acronym)	Date	Comments
1	Oleksandr Velihorskyi	CNUT	03.03.2026	First template of the deliverable report
2	Edoardo Croci	UB	18.03.2026	First draft
3	Enrique Romero	UEX	31.03.2026	Approval and PDF creation for uploading



Technical References:

Project Acronym	SmartGYsum
Project Title	Research and Training Network for Smart and Green Energy Systems and Business Models
Project Coordinator (PC)	Enrique Romero (eromero@unex.es) Universidad de Extremadura (UEX)
Project Duration	1 October 2021 – 31 March 2026
Deliverable No.	D5.6
Dissemination Level	Public
Work Package	WP5 – Green Economy Models and Management Systems
Tasks	
Lead Beneficiary	13 – UB
Contributing beneficiary (ies)	UNL, SIEM, UB
Data due of deliverable	31 March 2026
Actual submission date	31 March 2026





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List of abbreviations

AI	Artificial Intelligence
BESS	Battery Energy Storage System
BM	Business Model
CAPEX	Capital Expenditure
CEC	Citizen Energy Community
CGT	Coalitional Game Theory
CHP	Combined Heat and Power
CO ₂	Carbon Dioxide
COE	Cost of Energy
CPLEX	Optimization Solver (IBM ILOG CPLEX)
DER	Distributed Energy Resources
DH	District Heating
Dn	Deliverable (number)
DR	Demand Response
DRL	Deep Reinforcement Learning
DS	Doctoral School
DT	Digital Twin
EC	Energy Community
EED	Energy Efficiency Directive
EES	Electrical Energy System
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
ESR	Early Stage Researcher
ESS	Energy Storage System
ETN	European Training Network
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
FiT	Feed-in Tariff
GA	Grant Agreement
GAMS	General Algebraic Modeling System
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air Conditioning
IEMD	Internal Electricity Market Directive
IoT	Internet of Things
IRP	Individual Research Project
ITN	Innovative Training Network
KKT	Karush-Kuhn-Tucker
LCOH	Levelized Cost of Heat
MILP	Mixed Integer Linear Programming
MCS	Monte Carlo Simulation
MSCA	Marie Skłodowska-Curie Actions
NPV	Net Present Value
NPC	Net Present Cost
NZEB	Net Zero Energy Building
OPEX	Operational Expenditure
OSS	One-Stop-Shop
P2P	Peer-to-Peer
PV	Photovoltaic
REC	Renewable Energy Community
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RTP	Real-Time Pricing
SLR	SCR Self-Consumption Ratio
SME	Systematic Literature Review
SME	Small and Medium-sized Enterprise
SOC	State of Charge
VPP	Virtual Power Plant
WPn	Work Package - number
WT	Wind Turbine



Executive summary

The present deliverable provides the final report about the scientific activities done in WP5, and main result obtained related with the implementation of Individual Research Projects (IRPs) obtained by Early-Stage Researchers (ESRs) in WP5 of the project. The objective of the deliverable is to present the scientific outcomes achieved by ESRs in the reporting period (from M24 to M48, end of the project), and within the overall project duration. In addition, a general evaluation of ESRs research results in relation to WP5 objectives is provided.

The WP5 aims to support and coordinate WP2, WP3, and WP4 in terms of business models research and application in the field of collaborative and distributed renewable generation systems, microgrids, energy management and consumption control systems. Furthermore, WP5 aims to design synergic strategies to demonstrate the benefits of technologies and solutions developed in WP2, WP3, WP4 and provide policy recommendations to drive the energy system transformations. The WP5 entails four IRPs, namely IRP-12, IRP-13, IRP-14 and IRP-15 assigned to four ESRs.

- **ESR-12** focuses on IRP-12 about the “Development of sustainable strategies for Net Zero Energy Buildings and User Energy Awareness using Smart Appliances”.
- **ESR-13** focuses on IRP-13 concerning “Digital twins of prosumers using socio-economic factors and big data for Optimization of Customer’s bill savings and the adoption of concepts of self-consumption and presumption”.
- **ESR-14** focuses on IRP-14 regarding “Energy value chains and markets developed with the new paradigm of distributed EES”.
- **ESR-15** focuses on IRP-15 about “Identifying enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems”.

ESR-12 official date of recruitment was December 15, 2022 and his contract concluded on September 30, 2025. ESR-12 research focused on four pillars: (a) Nearly Zero Energy Buildings (nZEBs), (b) energy flexibility offered by smart appliances, (3) user-centric approach for energy awareness, and (4) collaborative energy ecosystems. ESR-12 worked in NOVA School of Science and Technology (FCT NOVA) at the Universidade NOVA de Lisboa. The ESR-12 research project aimed to enhance buildings sustainability by using smart devices to achieve net zero energy use. The main contribution to WP5 is related to “D5.1 Development of sustainable solutions for Zero Energy Buildings and Energy Awareness using Smart Appliances”. ESR-12 carried out two secondments: one of two months at Università degli Studi di Salerno (USA) in the months Jan-Feb 2024 and one at Consiglio Nazionale delle Ricerche-Istituto di Ingegneria del Mare in the months Sep-Nov 2024 to implement a digital platform for Energy Management System and Smart Buildings / Communities (The first one was postponed due to the residential permits). In terms of publication and academic achievements, ESR-12 has published three articles in academic journals: a) “The Potential of Residential Load Flexibility: An Approach for Assessing Operational Flexibility”, b) “Cooperative Stochastic Energy Management of Networked Energy Hubs Considering Environmental Perspectives”; c) “A two stage probabilistic flexibility management model for aggregated residential buildings”; he has published one conference paper: “Multi-Objective Energy Management of Smart Buildings Through a Bilevel Optimization Approach”; and one book chapter: “Analyzing Value-Sharing Methods in Energy Communities with Coalitional Game Theory”. He also submitted a further paper on an academic journal: “Optimal Clustering Based Energy management of Net Zero Energy Buildings through a Stochastic Hierarchical Approach”.

ESR-13 was recruited on May 09, 2022, at the Research and Training Development Department of Siemens Industry Software SAS in France, and his contract concluded on May 08, 2025. ESR-13 research aimed to improve the understanding of technical, environmental, economic and behavioural factors that compromise the development of innovative models for prosumers participation in the electric grid. The final objective of ESR-13 project was to develop digital models and modelling methods for prosumers considering the interaction and influences of social, economic and environmental factors. ESR-13 has developed a digital model framework for grids that allows the study of technical, social, and economic variables and their impact on the electric systems, as well as two models that demonstrate the effects of social and economic factors in performing prosumers activities. ESR-13 contribution to WP5 is linked to “D.5.2 Validated digital twins of prosumers based on socioeconomic factors”. ESR-13 has performed two secondments: the first at the Universidade NOVA de Lisboa, Portugal (May-June 2023), where two real-cases’ digital twins based on university buildings were developed; the second at Bocconi University (February-April 2025), where he deepened the business models associated with Digital Twins. Regarding academic achievement, the ESR-





13 has published a conference paper, with the title "Multi-factor modelling of electric grids for social and technical impact studies," at the 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG) held in Tallinn, Estonia on 14-16 June 2023.

ESR-14 was officially recruited on September 01, 2022 by the Centre for Research on Geography, Resources, Environment, Energy & Networks (GREEN), Università commerciale Luigi Bocconi, Milan, Italy. ESR-14 research topic aimed to improve innovative service for Energy Communities (ECs) in order to support the implementation of innovative market solutions within the distributed Electrical Energy System (EES). The final research objective of ESR-14 was to propose energy services based on different facilities/technologies for ECs including EV charging station (EVCS) by checking the economic and technical feasibility, market profitability and political/regulatory viability. ESR-14 contribution to WP5 focused on "D5.3 – Report including market solutions and business models to enable the growth and sustainability of distributed EES" and "D5.4 – Identified enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems". ESR-14 has completed his contract and has carried out two secondments including (i) a two-months secondment at Universidade NOVA de Lisboa, where he collected data to design an Electric vehicle charging station (EVCS) for parking lots; ii) a four-months secondment at University of Extremadura, where one conference paper was produced with key collaboration with ESR-03 already presented in IEEE EUROCON-2025 (An IEEE flagship conference). Concerning the academic achievements, ESR-14 has published 2 Journal Articles: a) "Energy-Economic-Environmental (3E) Optimisation of Grid-Connected Electric Vehicle Charging Station for a University Campus in Caparica, Portugal", b) "District Heating Benefits and Economic Assessment Methods: A Systematic Review and the Role of Emerging Technologies"; 2 Book Chapters: a) "A Critical Review of District Heating and District Cooling Socioeconomic and Environmental Benefits", b) "Energy Communities Enablers: Techno-Economic Optimization Analysis of Renewable Energy System for Electric Vehicle charging Station"; 1 Conference Paper: "Techno-Economic Optimization of Electric Vehicle Charging Station with Virtual Power Plant—a University Campus Use Case". In addition, ESR-14 got the "Best Paper Award of the 14th Advanced Doctoral Conference on Computing, Electrical and Industrial Systems (DoCEIS 2023)". Furthermore, he has two papers under development.

ESR-15 was recruited on January 01, 2023 by the Centre for Research on Geography, Resources, Environment, Energy & Networks (GREEN), Università commerciale Luigi Bocconi, Milan, Italy, and his contract finished on December 31, 2025. ESR-15 research was related to IRP-15 since it planned to identify and assess the relevant factors that favour and hinder the diffusion of innovative business models related to sustainable energy systems and energy transition in the EU. ESR-15 focused on Energy Communities (ECs). The main research objectives were: (a) to identify barriers that BMs face, (b) to provide policy solutions to overcome these barriers, and (c) to replicate successful innovative EC BM. ESR-15 main contribution to WP5 was to "identify enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems", and to "D5.3 – Report including market solutions and business models to enable the growth and sustainability of distributed EES". ESR-15 carried out two secondments, one at **Universidad de Extremadura (UEX)** for two months (October 15 to December 15, 2023); the second at Siemens for four months (September 5 to December 20, 2024). Regarding academic achievement, ESR-15 has published two conference contributions: a) "Energy Communities in the EU: Analysis of ownership models and funding mechanisms" at 16th International Scientific Conference Energy and Climate Change- PROMITHEASnet in Athens; b) "Energy Community Business Models Archetypes" at 2025 IEEE 19th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG). He also published one journal paper: "Energy communities – lessons learnt, challenges, and policy recommendations", and one book chapter: "Energy Communities in the EU: An analysis of Ownership, Funding Mechanisms, and Business Models". Furthermore, he has two papers under development and one submitted journal paper.

Objectives of the deliverable

The purpose of this deliverable is to present the results of WP5 activities and the achievements of ESRs involved in WP5. It aims to present the main goals of research projects carried out by ESRs, their scientific outcomes and the connections with WP5 ambitions. Finally, scientific achievements, such as experimental prototypes, publications, and participation in conferences as well as patents and awards are illustrated and listed.





SMARTGYSUM project has been funded by the European Commission's Horizon 2020 Programme

Organisation of the deliverable

This report is organized as follows: First, the evaluation of ESRs activities as well as the overall results of WP5 activities are reported. The in-depth research outcomes and activities of each ESR are presented in section 3, including research goal and achievements obtained in the final reporting period. ESRs contribution to WP5 is also provided and analysed in section 3. Finally, the scientific achievements, in terms of publications and awards, are listed.





General progress of the action

WP5 Objectives and tasks

The WP5 focuses on “Green Economy Models and Management Systems” and aims:

- To coordinate WP2, WP3 and WP4 in terms of business models research, assessment and validating in order to support collaborative and distributed renewable generation systems, microgrids, energy management and consumption control systems.
- To design synergic strategies to demonstrate the benefits of systems and technologies developed in WP2, WP3 and WP4.
- To provide policy recommendations to guide energy system 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).

The following table lists the deliverables included in WP5, the lead beneficiaries and the due date.

Deliverable Number	Deliverable Title	Lead beneficiary	Type	Dissemination level	Due Date
D5.1	Development of sustainable strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances	UB	Report	Public	M30
D5.2	Validated digital twins of prosumers based on socioeconomical factors	UB	Other	Confidential, only for members of the consortium (including the Commission Services)	M30
D5.3	Report including market solutions and business models to enable the growth and sustainability of distributed EES	UB	Report	Public	M45
D5.4	Identified enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems	UB	Report	Public	M45
D5.5	Intermediate WP5 scientific report	UB	Report	Public	M24
D5.6	Final WP5 scientific report	UB	Report	Public	M48

WP5 – Workpackage progress

The ESR progress is evaluated and reported in the following table according to three statuses:

- Inactive status: the ESR left the project or no data are available for the evaluation
- In progress status: the ESR is working on his research topic in line with the WP5 goals, but not all goals have been achieved yet.

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- Complete status: the ESR fulfilled all the project requirements, completing its training and research activities

ESR	Starting date	General evaluation	Status
12	15/12/2022	ESR-12 has achieved its declared research objectives, and the research topic is in line with IRP-12. Since the ESR-12 has been in the project, he has achieved the scientific results and covered his duties in terms of secondment. In terms of publications, ESR-12 has published three journal papers, one conference paper, and one book chapter.	Complete
13	05/09/2022	ESR-13 has achieved its declared research objectives, and the research topic is in line with IRP-13. ESR-13 produced scientific outcomes and fulfilled the goals in terms of secondments. He has published one conference paper. He obtained his PhD during the project.	Complete
14	01/09/2022	ESR-14 has achieved its declared research objectives and the research topic is in line with the IRP-14. Since the ESR-14 has been in the project, he has achieved the scientific results and covered his duties in terms of secondment. In terms of publications, the ESR-14 has published two conference papers, two journal papers, a chapter in a book, and got an award. He is completing two further publications.	Complete
15	01/01/2023	ESR-15 has achieved its declared research objectives and the research topic is in line with the IRP-15. He has achieved the scientific results and covered his duties in terms of secondments. In terms of publications, ESR-15 has published two conference papers, one journal paper, and a chapter in a book. He is completing two further publications.	Complete





WP5 Tasks progress

Task 5.1 – IRP12 “Development of sustainable strategies for Net Zero Energy Buildings and User Energy Awareness using Smart Appliances”

Introduction

ESR-12 was involved in the project in December 2022 (15/12/2022), recruited by Universidade NOVA de Lisboa (Hosting Institution). ESR-12 worked in NOVA School of Science and Technology (FCT NOVA) at the Universidade NOVA de Lisboa. ESR-12 was involved in IRP-12 “Development of sustainable strategies for Net Zero Energy Buildings and User Energy Awareness using Smart Appliances”. The central research topic of IRP-12 is the development of sustainable energy management strategies for Net Zero Energy Buildings (NZEBS) and energy communities, with a particular focus on how energy flexibility can be quantified, activated, coordinated, and shared. The work is rooted in the idea that the value of NZEBs does not lie only in reduced annual energy consumption, but also in their ability to modify their operating profile in response to external signals while preserving acceptable comfort conditions. In practical terms, this means understanding how smart appliances, storage systems, thermal loads, and local generation can be coordinated both within individual NZEBs and across multiple actors. From this perspective, the research addressed four closely connected scientific questions. The first question was how to define and quantify operational flexibility in an NZEB under realistic operating conditions. The second question was how this flexibility could be aggregated and assessed at the level of multiple NZEBs so that an external actor such as an aggregator could estimate ramping potential and support grid operations. The third question concerned how cooperation among heterogeneous prosumers could be organized to improve both economic and environmental performance. This is specifically designed to investigate opportunities for harnessing flexibility within the operation of various entities that have different energy consumption patterns and preferences. The fourth question concerned the post-optimization problem of how cooperative benefits should be redistributed fairly, so that collaboration remains stable and attractive for participating members. These questions are visible both in the thesis narrative and in the sequence of publications that support it. Moreover, the thesis, as part of the scientific dissemination of IRP-12, positions these questions within two interconnected research subareas. One subarea concerns the measurement and exploitation of flexibility in NZEBs, while the other concerns the design of cooperation and value-sharing mechanisms for NZEB communities.

The following activities have been performed by the ESR-12:

- Characterization of energy flexibility in buildings and ECs, taking into consideration user comfort.
- Adaptation of smart appliances to enhance energy flexibility through energy management systems, considering the IoT framework.
- Development of intuitive and interactive interfaces to increase user energy awareness, taking into consideration accessibility criteria.
- Development of integrated strategies to manage building/community flexibility.
- Development of cooperative strategies among EC members and market players to assure grid operation and energy self-consumption.

Scientific outcomes

Within WP5, ESR-12's research was framed around four main pillars: 1) NZEBs, 2) energy flexibility offered by smart appliances, 3) a user-centric approach to energy awareness, and 4) collaborative energy ecosystems. The overall aim was to design energy management strategies capable of improving building sustainability while respecting user comfort and supporting grid operation.

Exploring the capacity for residential load adaptability: a method for evaluating operational flexibility

This work stream addresses the assessment of residential energy flexibility in NZEBs, with particular emphasis on how smart appliances and energy storage systems can support more flexible and sustainable building operation. The work is fully aligned with IRP12, which focuses on the development of sustainable strategies for NZEBs and user energy awareness using smart appliances. The scientific outcomes related to this paper were obtained in the context of ESR-12's research activity at the Universidade NOVA de Lisboa. Therefore, the paper represents one of the first concrete scientific outputs developed within the research environment supporting Task 5.1 of WP5. More specifically, the paper entitled “The Potential of Residential Load Flexibility: An Approach for Assessing Operational Flexibility”





develops a framework to evaluate the flexibility potential of a NZEB under different operating conditions. The study is motivated by the increasing relevance of demand-side flexibility for improving the economic stability and resilience of power systems. Since buildings are recognized as important sources of flexibility, the paper investigates how the characteristics of energy-time curves can be used to quantify operational flexibility in a meaningful and practically useful way.

The study focuses on how the scheduling of shiftable appliances and the operation of an energy storage system can alter the energy exchange pattern between the house and the upstream grid. Rather than assessing flexibility only through isolated metrics, the paper proposes a combined perspective that jointly considers energy, time, and power dimensions. The central research question of the paper is whether there is a meaningful relationship between the geometrical characteristics of energy curves, especially the area under them in energy-time profiles, and the energy flexibility of a consumer. Based on this question, the paper investigates how a flexibility indicator can be defined to accurately represent the flexibility potential of a NZEB under various operational constraints. In parallel, the paper also examines the effects of energy storage systems, user comfort restrictions, and limits on exchanged power capacity on the overall flexibility of residential consumers. This topic is especially relevant for IRP12 because it provides a rigorous and operational way of understanding how smart appliances can increase NZEB flexibility while maintaining user-oriented constraints. It also supports the broader objective of developing energy management strategies for sustainable and grid-responsive NZEBs.

The methodology adopted in the paper is based on a mixed-integer linear programming (MILP) formulation of the NZEB (smart house) energy management problem. The NZEB includes schedulable and non-schedulable loads, as well as an energy storage system. The model is used to determine how shiftable appliances and storage can be operated under different constraints in order to explore the feasible flexibility region of the house. The paper starts from the observation that energy flexibility should be evaluated not only from instantaneous power values, but from the overall energy-time profile of the consumer. For this reason, the methodology studies the energy curves associated with different operating patterns and identifies two extreme behaviors: the maximum forced pattern, in which shiftable loads are supplied as early as possible, and the maximum delayed pattern, in which supply is postponed as much as possible within the operational constraints. The feasible region between these two extreme curves is then interpreted as a representation of the operational flexibility of the smart house. Based on this framework, the authors introduce two indicators. The first is a consumption-style indicator, denoted as φ_{Beh} , which characterizes whether the overall consumption pattern is more forced or delayed relative to a constant-power reference profile. The second is a total flexibility indicator, denoted as Ψ_{Tot} , which measures the area of the feasible region between the maximum forced and maximum delayed energy curves under a given set of constraints. In this way, the methodology provides both a behavioral interpretation of the load pattern and a quantitative measure of overall flexibility. The implementation proceeds through a set of optimization problems and case studies. Different operational conditions are analyzed, including cases with and without energy storage systems, cases with user comfort restrictions, and cases with limits on exchange capacity with the upstream grid. In addition, sensitivity analysis is performed to evaluate how parameters such as the capacity and initial state of charge of the energy storage system affect the resulting flexibility indicators. This implementation structure allows the authors to compare the effect of each constraint or flexibility source on the feasible operational region of the smart house.

The results show that there is indeed a meaningful relation between the area of the energy curve region in the energy-time profile and the operational flexibility of the consumer. This confirms the main hypothesis of the paper and validates the proposed geometric interpretation of flexibility. The simulations demonstrate that the area enclosed by the extreme feasible energy curves can serve as a useful indicator of the number of possible operating states that the NZEB can achieve under a given set of constraints. The paper also shows that considering energy, time, and power simultaneously provides a more accurate representation of flexibility than approaches that treat these metrics separately. In particular, the proposed method captures the interaction and overlap of different operational restrictions, which is important for realistic building operation. This is one of the main methodological advances of the study. With respect to the specific case studies, the results indicate that user comfort restrictions reduce the feasible flexibility region, since they limit the possible scheduling of appliances. Likewise, exchange capacity constraints can reduce the temporal range over which loads can be shifted. At the same time, the deployment of an energy storage system significantly increases flexibility by enlarging the feasible region for energy curve modulation. For example, the simulations reported that deploying the ESS improved the total flexibility indicator in one case from 4.1% to 9.3%, and in another case from 1.8% to 7.0%.

The sensitivity analysis further shows that the flexibility provided by the ESS depends strongly on its capacity and initial state of charge. A larger storage capacity generally leads to higher values of the total flexibility indicator, while the initial SOC affects whether the ESS can support both charging and discharging actions under the selected





operating strategy. These findings are relevant not only for flexibility assessment, but also for the practical sizing and operation of storage systems in NZEBs.

The main conclusion of the paper is that the potential energy flexibility of a NZEB can be meaningfully characterized through the geometrical properties of its energy-time curves. In particular, the area associated with the feasible region between extreme consumption patterns provides a robust basis for defining a total flexibility indicator. This confirms that flexibility is not only a matter of instantaneous power adjustment, but a multidimensional property involving power, energy, and time simultaneously. A second major conclusion is that the proposed indicators are capable of reflecting how real operating conditions affect flexibility. The results show that operational constraints such as comfort preferences and exchange limits reduce the available flexibility, while energy storage systems can substantially enhance it. Moreover, the study concludes that the initial state of charge of the ESS is a critical parameter for exploiting its full flexibility potential. A third important conclusion is that the proposed framework can support the operation of energy management systems by helping determine the flexibility capacity of a NZEB before flexibility activation. In this sense, the work is not only descriptive, but also directly applicable to control and management strategies that aim to improve the interaction between households, aggregators, and grid operators.

A two stage probabilistic flexibility management model for aggregated residential buildings

This scientific work stream addresses the probabilistic management of energy flexibility in aggregated residential NZEBs, with a particular focus on how an aggregator can assess and activate the ramping capacity of NZEBs equipped with flexible assets such as energy storage systems, thermal loads, and shiftable appliances. The study is framed within the increasing need for flexible demand-side resources in power systems with high penetration of renewable energy, where variability and uncertainty create challenges for balancing supply and demand and for maintaining grid stability. In this context, the paper proposes a two-stage probabilistic decision-making model that helps quantify and manage the contribution of NZEBs to flexibility services and flexibility markets. The scientific outcomes were obtained in the context of research carried out at the NOVA University Lisbon in collaboration with the University of Salerno. Therefore, the paper constitutes a direct scientific outcome of the SMARTGYSUM research framework and is especially relevant to work concerning energy flexibility, energy management, collaborative energy ecosystems, and demand response. More specifically, the paper entitled "A two-stage probabilistic flexibility management model for aggregated residential buildings" develops a flexibility assessment framework in which NZEBs first optimize their normal daily operation according to electricity prices and then, in a second stage, respond to aggregator requests for energy exchange adjustments. The proposed model is designed to evaluate how much upward or downward ramping capacity can be delivered by a portfolio of residential NZEBs while accounting for uncertainty and occupants' comfort. The overall objective is to help aggregators more accurately assess the technical potential of NZEBs for participation in flexibility-oriented market mechanisms. Rather than treating NZEBs as static loads, the paper models them as active and flexible entities whose energy exchange with the grid can be intentionally modified over time.

The main research questions addressed in the paper can be summarized as follows. First, the paper asks how the ramping flexibility of aggregated residential NZEBs can be quantified accurately in terms of energy, time, and power. Second, it investigates how a building's normal operating plan can be compared with a response plan after an aggregator request, so that the actual flexible capability can be evaluated. Third, it examines how the flexibility assessment can account for uncertainties in demand and PV generation. Fourth, it studies how occupants' comfort and self-reported discomfort can be explicitly incorporated into the optimization process instead of being treated only as an external restriction. Finally, the paper explores how an aggregator can use these building-level responses to construct and manage an aggregated flexibility portfolio for market participation. These questions are clearly reflected in the introduction, the literature review table, and the list of contributions given by the authors. The literature review shows that the paper is positioned against several limitations in previous studies. According to the authors, many existing methods rely on predefined flexibility capacities and prices, deterministic assumptions, or simplified comfort treatment, and often overlook fast-response mechanisms or the joint consideration of energy and time in ramping assessment. The paper therefore aims to fill these gaps through a model that explicitly considers user comfort, flexible assets, and uncertainty.

The methodology adopted in the paper is based on a two-stage probabilistic mixed-integer linear programming (MILP) model for building flexibility management. The paper distinguishes between a normal operation mode and a flexible operation mode. In the first mode, the building optimizes its energy bill according to electricity prices. In the second mode, after a request from the aggregator, the building attempts to alter its energy exchange profile as fast as possible, either by anticipating or delaying its consumption or storage behavior, so that a requested energy adjustment can be achieved. In the first stage, the objective is to minimize the expected electricity cost of the building





over the day. The optimization coordinates power import and export with the grid, PV generation, operation of the energy storage system, scheduling of shiftable appliances, operation of air conditioning, and non-shiftable demand. The model includes power balance constraints, import/export limits, ESS charging and discharging constraints, temperature dynamics for air conditioners, and appliance scheduling rules. Importantly, the model incorporates occupants' comfort by restricting the scheduling of shiftable appliances to acceptable periods and by keeping indoor temperature within predefined limits. In the second stage, the objective changes from cost minimization to the minimization of the required response time δ_{flx} needed for the NZEB to satisfy an aggregator request for an energy exchange increment or decrement. The aggregator sends a request at a certain time interval t_{flx} , and the model computes how quickly the NZEB can modify its net energy exchange profile relative to the normal baseline established in the first stage. Through this design, the paper transforms flexibility assessment into a measurable problem involving a desired energy adjustment over time, from which the NZEB's ramping capability can be inferred. The model explicitly includes uncertainty handling through a scenario-based approach. As described in the paper, the authors generate scenarios for demand and solar irradiance using Monte Carlo Simulation (MCS). Because a large number of scenarios would be computationally burdensome, the paper then applies the k-means clustering algorithm to reduce the scenario set while preserving the diversity and statistical structure of the uncertainties. This scenario preparation process is one of the main methodological contributions of the work. Another important methodological element is the use of a discomfort indicator, which measures the deviation of indoor temperature from the desired set-point. This allows NZEBs to report not only whether they can respond to the aggregator, but also the expected level of discomfort associated with that response. As a result, the aggregator can select NZEBs not only according to ramping performance, but also according to comfort-related priorities. The model is implemented in GAMS and solved with CPLEX, as stated in the simulation section. The reported average processing time is around 2 minutes on an Intel Core i7 with 8 GB RAM. The implementation includes two main case studies: one focused on the response of an individual NZEB to an aggregator request, and another focused on the response of five distinct NZEBs and the resulting aggregated flexibility signal from the aggregator's perspective.

The results demonstrate that the proposed model can effectively quantify the flexibility of residential NZEBs and their aggregated ramping capability. In Case One, the aggregator sends a request at 10:00 asking a building to increase its net exchanged energy by 10 kWh. The model shows that the NZEB can satisfy this request with a minimum expected response time of approximately 45 minutes. The comparison of the first and second stages illustrates how the building changes the scheduling of flexible assets after the request. Under normal operation, shiftable loads are scheduled around lower-price periods, whereas under flexible operation they are advanced immediately to support the aggregator's goal. The results also show that the energy storage system plays a key role in enabling fast response. Before the request, both stages have the same ESS behavior. After the request, however, the ESS operation changes significantly: instead of discharging to maximize economic benefit, it absorbs energy in order to support the desired increase in net exchange. The paper reports that within the first 45 minutes after 10:00, the building imports approximately 10.3 kWh more energy from the grid than in the reference case. This corresponds to an average ramping power of about 13.3 kW, with a computed discomfort indicator of 4.7%. In Case Two, the aggregator sends an 8 kWh increment request to five different NZEBs, denoted B1,...,B5. The results reveal that the NZEBs respond differently due to their different equipment sizes and thermal characteristics. Each building reports its minimum required response time and discomfort index, allowing the aggregator to rank and select NZEBs according to operational priorities. The paper shows, for example, that one building can be excluded because of a slower response time, while another can be excluded because it causes higher discomfort. In this way, the aggregator can refine the portfolio and create a more targeted aggregated flexibility response. The aggregated results further show that the portfolio-level ramping signal can be constructed dynamically by summing the contributions of selected NZEBs over time. The model is not only able to estimate building-level flexibility but also helps an aggregator build an optimized and more reliable flexibility portfolio for external use. The sensitivity analysis provides additional evidence of the model's practical value. The first sensitivity study shows that when the aggregator requests more energy, the building needs more time to respond. The results indicate that for requests below 11 kWh, the building can fulfill the demand within about one hour, while for very large requests above 51 kWh the response time stabilizes at around 11 hours, reflecting the NZEB's physical limit. The second sensitivity study shows that increasing the ESS capacity and the charge/discharge rates reduces the required response time, and that the response time is more sensitive to ESS capacity than to charging/discharging rates.

The main conclusion of the paper is that aggregated residential NZEBs can provide meaningful and quantifiable ramping flexibility when their flexible assets are properly coordinated and when their normal and flexible operating modes are explicitly compared. The two-stage MILP framework enables the aggregator to assess this flexibility more accurately than approaches based only on static or predefined flexibility assumptions. A second major conclusion is





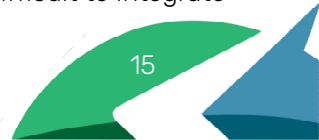
that time is a critical dimension of flexibility assessment. The paper shows that flexibility should not be described only in terms of energy or power, but also in terms of the minimum time needed to implement a requested adjustment. This is especially important for flexibility services intended for intra-day and real-time applications. A third conclusion is that uncertainty and user comfort must be embedded directly into the optimization problem. By treating demand and PV generation probabilistically and by including a discomfort indicator, the model provides a more realistic and user-aware assessment of flexibility. This is particularly relevant for aggregated residential applications, where technical potential alone is not sufficient for reliable activation. Finally, the paper concludes that ESS characteristics strongly influence flexibility performance, and that increased storage capacity can reduce response time significantly. The study therefore provides useful insight for the design and sizing of flexible assets in residential NZEBs and for the operational strategies of aggregators seeking to build reliable flexibility portfolios. Overall, the paper highlights the important role of NZEBs in collaborative energy ecosystems and shows that they can support a more resilient and sustainable energy system when managed appropriately.

Optimal Clustering Based Energy Management of Net Zero Energy Buildings through a Stochastic Hierarchical Approach

This scientific work stream addresses the optimal energy management of Net Zero Energy Buildings (NZEBs) through a two-stage stochastic hierarchical approach. The study is motivated by the growing importance of NZEBs as a pathway to reduce building-sector energy use and carbon emissions while increasing the penetration of on-site renewable generation. The paper starts from the observation that, although NZEBs can annually balance energy consumption with renewable generation, their day-to-day operation remains challenging because of uncertainty in photovoltaic production, variable demand, electricity price signals, and the need to balance economic, technical, and environmental objectives simultaneously. The scientific outcomes reported in this paper were obtained in the research environment of the NOVA University of Lisbon. The paper represents a direct scientific output developed within the SMARTGYSUM framework and is strongly connected to research on NZEBs, energy management systems, energy flexibility, and sustainable NZEB operation.

The main research topic of the paper is the stochastic multi-objective energy management of NZEBs, with particular focus on how an NZEB can simultaneously reduce cost, improve self-consumption, and account for carbon emissions under uncertainty. The paper treats the NZEB not as a passive consumer, but as an active prosumer equipped with photovoltaic generation, schedulable appliances, HVAC systems, and an energy storage system, whose operation can be optimized across day-ahead and real-time stages. The principal research question is how scenario-based two-stage stochastic energy management models can enhance the operational economic performance and self-consumption ratio of NZEBs while also addressing environmental concerns. Around this central question, the paper investigates several related issues. First, it asks how operational cost and self-consumption can be optimized together without collapsing them into a single weighted objective. Second, it examines how uncertainty in PV generation and load can be represented in a tractable way. Third, it studies how carbon pricing and carbon-emission estimation affect operational decisions. Fourth, it explores the influence of ESS characteristics on system performance. The paper also positions itself clearly within the literature. The review shows that many previous models either neglected uncertainty, overlooked environmental concerns, or did not include a proper grid-interaction indicator. Also, it has been argued that although self-sufficiency and self-consumption are often considered, integrated models balancing economic performance, environmental concerns, grid interaction, and uncertainty remain insufficiently developed. This identified gap directly motivates the proposed hierarchical stochastic formulation.

The methodology adopted in the paper is based on a two-stage stochastic programming model combined with a bi-level optimization approach. The first stage corresponds to a day-ahead "here-and-now" decision process, while the second stage corresponds to a real-time "wait-and-see" adjustment process under uncertain scenarios. The first stage handles the day-ahead decisions and the second stage refines the response under scenario realizations, and both are integrated into a two-stage stochastic optimization structure. At the upper level (UL), the model minimizes the operational cost, which includes both the electricity bill and carbon-emission cost, considering power import/export, appliance scheduling, HVAC operation, and ESS management. At the lower level (LL), the model focuses on improving the self-consumption ratio (SCR). This means that the hierarchical structure explicitly prioritizes economic and environmental cost at the upper level while using the lower level to improve technical performance in terms of on-site renewable utilization. Considering the interaction between the two levels, the proposed model considers that ESS decisions in the second stage are refined to maximize self-consumption while remaining coherent with day-ahead binary decisions fixed in the upper level. A notable methodological contribution is the development of a new self-consumption indicator. The traditional SCR formulation is nonlinear and therefore difficult to integrate





into a linear optimization model. To overcome this, the authors propose an equivalent indicator that captures the cumulative alignment between on-site generation and consumption, as well as the worst-case mismatch over the scheduling horizon. A trade-off factor α is introduced so that the decision-maker can tune the relative importance of these two terms. This new indicator enables SCR-oriented optimization inside the stochastic MILP framework. The model also includes detailed constraints for all major facilities. The formulation covers power balance, grid import/export limits, schedulable appliances, HVAC dynamics and comfort limits, and ESS charge/discharge behavior. Schedulable appliances are modeled through a set of alternative power profiles and binary selection variables. HVAC operation is constrained by indoor temperature dynamics and user comfort bounds. The ESS is modeled with charging/discharging power limits, state-of-energy dynamics, efficiency factors, and energy bounds. These formulations show that the model captures both operational realism and tractability. To solve the hierarchical problem, the paper transforms the bilevel structure into a single-level MILP-equivalent formulation. The lower-level problem is replaced through optimality conditions using a primal-dual transformation and equilibrium constraints, and then the resulting nonlinearities are linearized. The paper emphasizes that this approach avoids some nonconvexities associated with traditional KKT treatment while preserving a tractable solution process. For uncertainty modeling, the paper uses Monte Carlo scenario generation followed by k-means clustering for scenario reduction. The simulation section explains that scenario generation and reduction are used to represent uncertain PV generation and demand profiles. The model is implemented in GAMS and solved with CPLEX. Three main case studies are defined. Case 1 minimizes only operational cost. Case 2 focuses only on maximizing the self-consumption indicator. Case 3 combines both objectives in the proposed hierarchical approach, where cost is prioritized in the upper level and self-consumption is optimized in the lower level. This structure allows a direct comparison between single-objective and hierarchical multi-objective operation.

The results show that the proposed hierarchical approach provides the best overall trade-off among cost, self-consumption, and emissions. According to the case comparison, Case 1 achieves the lowest operational cost but the worst SCR, while Case 2 achieves the highest SCR but with much higher operating cost. Case 3 emerges as the most balanced solution. The paper states that, compared with Case 1, Case 3 improves the SCR by about 4%, and compared with Case 2, it reduces operational cost by about 11%. The results section shows that the trade-offs are substantial. Comparing Cases 1 and 2, the paper reports that a 35% increase in cost from about \$7.1 to \$9.6 yields only about 6% improvement in SCR from roughly 0.84 to 0.90. This confirms that optimizing only self-consumption can become economically inefficient. By contrast, Case 3 reaches an SCR of about 0.89, nearly matching the best SCR case while maintaining much lower cost. From the environmental perspective, Case 3 also performs best in terms of carbon emissions. It yields around 6.6 kg of emissions, lower than Case 1 at about 7.9 kg and also lower than Case 2 at about 6.8 kg. This is an important result because it shows that the hierarchical strategy is not only a compromise between cost and SCR, but also the most environmentally attractive of the three tested strategies. The operational schedules explain why these differences occur. In Case 1, the building relies heavily on grid imports, especially around noon, because the optimization follows the best economic opportunities from the price signal. In Case 2, the ESS operates more intensely to store solar generation at midday and use it later, which maximizes self-consumption but neglects some economic opportunities. Case 3 adopts a more moderate and balanced strategy, combining PV utilization, battery operation, and controlled grid exchange. The paper describes this as a compromise that reduces grid dependency and improves environmental sustainability while still controlling cost. The schedulable appliance results further reinforce this interpretation. The paper explains that Case 1 aligns appliance operation mainly with low-price intervals, even if that increases grid dependency. Case 2 schedules appliances more strongly during periods of high PV generation, thus improving self-consumption but increasing cost. Case 3 moderately aligns with both price and PV availability, thereby producing a practical compromise between economic efficiency and renewable self-use. Another important set of results concerns carbon-emission estimation and carbon tariffs. The paper compares three operation modes: O1, which ignores carbon intensity; O2, which assumes a fixed conservative carbon intensity; and O3, which uses an hourly carbon intensity factor. The results show that ignoring carbon emissions underestimates environmental impact, while using a fixed high carbon factor can overestimate it and lead to less efficient grid exchanges. The hourly-based factor in O3 provides a more realistic basis for balancing emissions and cost. The paper reports that, relative to O1, the operational cost under O2 increases by about 25% and 100% under carbon tariffs of 0.05 and 0.20 \$/kg, respectively, while O3 leads to smaller increases of about 6% and 18% under the same tariff levels. The paper also includes a sensitivity analysis of ESS characteristics. The results show that increasing ESS capacity reduces operational cost regardless of charging/discharging rates, and that cost is more sensitive to ESS capacity than to rate variations. For example, with a 2 kWh ESS and lower charging/discharging rates, cost is around \$10, while for a 10 kWh ESS it drops to around \$7.7–\$8 depending on the charging/discharging rate. Based on these trends, the paper concludes that increasing storage capacity should generally be prioritized over merely increasing power rate when aiming to improve economic performance.





The main conclusion of the paper is that a two-stage stochastic hierarchical energy management model can provide a more balanced and practical operational strategy for NZEBs than single-objective deterministic approaches. By jointly considering operational cost, self-consumption, and carbon emissions, the model is able to deliver a compromise solution that is economically reasonable, environmentally better, and technically more aligned with the NZEB concept. A second major conclusion is that hierarchical optimization is particularly suitable for NZEB energy management because it allows objective prioritization. The study shows that simply minimizing cost leads to strong dependence on external grid resources, while maximizing self-consumption alone can become economically inefficient. The proposed bilevel structure allows cost to remain the priority while still improving self-consumption in a meaningful way. A third conclusion is that precise carbon-emission estimation matters. The simulations emphasize that an hourly-based carbon intensity factor provides a more realistic and operationally useful representation than either ignoring emissions or assuming a fixed emission factor. This result is especially relevant for future policy and tariff design, since the model shows that poorly designed carbon tariffs or inaccurate emission assumptions can distort operational decisions. A fourth conclusion is that ESS characteristics are critical for NZEB performance. The sensitivity analysis shows that storage capacity has a stronger influence on operational cost than charging/discharging power rates. This finding provides useful guidance for the design of cost-efficient ESS configurations in NZEB applications. Overall, the paper concludes that the proposed model improves the economic, environmental, and technical performance of NZEB operation, and that the resulting framework is a strong basis for more sustainable integration of NZEBs into future energy systems with high renewable penetration.

Multi-Objective Energy Management of Smart Buildings Through a Bilevel Optimization Approach

This scientific work stream focuses on the multi-objective energy management of smart NZEBs through a bilevel optimization approach. The study addresses the challenge of operating smart NZEBs in a way that not only minimizes electricity costs but also improves the characteristics of the power exchanged with the utility grid. This issue is increasingly relevant in modern power systems, where high load variability, peak demand periods, and the growing penetration of distributed energy resources require NZEBs to behave as more flexible and grid-supportive energy actors. In this context, the paper proposes an optimization-based framework that coordinates building loads, photovoltaic generation, heating and cooling demand, and an energy storage system in order to balance economic and technical objectives simultaneously. The scientific outcomes reported in this paper were obtained in the research environment of the NOVA University of Lisbon. The paper constitutes a direct scientific output developed within the SMARTGYSUM framework and contributes to the research activities related to smart NZEBs, energy management systems, flexibility, and grid interaction. More specifically, the paper entitled "Multi-objective energy management of smart buildings through a bilevel optimization approach" develops a hierarchical decision-making framework for smart building operation.

Unlike approaches that optimize only electricity cost or only technical indicators, this paper studies how both goals can be addressed together through a bilevel structure. The key research questions addressed in the paper can be summarized as follows. First, the study asks whether a smart building energy management system can minimize electricity bills while simultaneously improving the exchanged power profile with the utility grid. Second, it investigates whether a bilevel optimization framework can better represent the hierarchical interaction between the building EMS and the ESS than a conventional single-level model. Third, it examines how the ESS can be operated not only for economic arbitrage but also for peak shaving and valley filling, thereby producing benefits for both the building and the grid. Fourth, the paper explores whether these improvements can be achieved without compromising user comfort. The paper also identifies a gap in prior literature. Specifically, many earlier studies focused either on peak shaving and valley filling only, or on technical improvements that may compromise cost and user comfort. In response, this study proposes a framework that combines economic optimization, load scheduling, thermal comfort, and exchanged-profile improvement in a unified exact-solving approach.

The methodology adopted in the paper is based on a bilevel optimization model. At the upper level, the building energy management system acts as the leader and seeks to minimize total operating cost, including electricity purchasing cost and ESS operation and maintenance cost. At the lower level, the ESS acts as the follower and seeks to minimize the difference between the upper and lower bounds of the power exchanged with the grid, which effectively means flattening the exchanged power profile. This hierarchical formulation allows the economic objective and the technical grid-support objective to be coordinated rather than treated independently. The upper-level model includes several NZEB operation constraints. These cover grid import and export limits, ESS charging and discharging status, schedulable appliance operation, and HVAC thermal comfort constraints. The paper models schedulable appliances such as dishwashers and washing machines using predefined power profiles and window restrictions reflecting user comfort. It also models indoor temperature dynamics, upper and lower comfort limits, and set-point deviations for





HVAC operation. In this way, the framework explicitly represents the key flexible and comfort-sensitive elements of NZEB operation. The lower-level model represents the ESS behavior. Its objective is to minimize the range between the upper and lower bounds of net exchanged power, thereby smoothing the building-grid interaction. The lower level includes power balance constraints, ESS charging/discharging power limits, state-of-energy dynamics, and minimum and maximum state-of-energy constraints. According to the model description, this means that the ESS is not operated only to follow price signals, but also to reshape the building's exchange profile from the perspective of the grid. To solve the bilevel problem, the paper applies Karush-Kuhn-Tucker (KKT) conditions and duality assumptions to replace the follower problem and transform the model into a single-level nonlinear problem, which is then linearized using the big-M method. The conversion process is illustrated in the paper, where the bilevel structure is transformed into a tractable optimization model. This is an important methodological contribution because it enables exact solution of the hierarchical problem with reasonable computational effort. The simulation model is implemented in GAMS and solved using CPLEX. The case study assumes a smart building with three apartments, each equipped with a dishwasher and washing machine that can be scheduled by the EMS. The building is also equipped with 25 kW of PV generation and an ESS with 40 kWh capacity and 25 kW charge/discharge rate. A 15-minute time resolution is used over one day, and the electricity tariff follows a real-time pricing (RTP) signal. The demand profiles, PV generation, and electricity price are illustrated in the charts on pages 4–5, while the NZEB thermal and appliance scheduling assumptions are explained in the simulation section. Two case studies are examined. In Case One, the optimization focuses only on operating cost. In Case Two, the proposed bilevel framework is implemented, where the upper level minimizes operation cost and the lower level improves the exchanged power profile. This comparative structure allows the authors to evaluate the added value of the proposed method relative to a more conventional energy management approach.

The results show that the proposed strategy improves the technical characteristics of power exchange with the grid without increasing operating cost. The second case presents a flatter profile from the utility grid's perspective, which indicates that the proposed strategy successfully supports both peak shaving and valley filling. This is one of the main practical outcomes of the study, since it shows that grid-supportive behavior can be achieved without sacrificing the building's economic objective. The ESS state-of-charge trajectories shown in Figure 6 on page 4 provide further insight into this effect. In both cases, the ESS generally follows the electricity price signal, charging during low-price intervals and discharging during high-price periods. However, in the bilevel case, the ESS also anticipates charging around 5:00 and discharging around 10:00, which helps flatten the exchanged power profile. This shows that the lower-level decision-making mechanism effectively modifies ESS operation to achieve better technical performance while remaining aligned with the upper-level cost objective. The optimal power balance for the second case is presented in Figure 7 on page 4, where the contributions of imported power, exported power, discharge, charge, air conditioning, non-shiftable loads, and PV generation can be seen throughout the day. The figure shows that schedulable loads are shifted to relatively low-price periods within user-defined operating windows and that PV generation supplies a significant share of demand when available. This confirms that the proposed framework effectively coordinates building flexibility resources at the operational level. The sensitivity analysis further validates the model. The results show that increasing either the ESS capacity or the charge/discharge rate reduces the NZEB's operation cost in both cases. However, the operation cost is more sensitive to ESS capacity than to charging/discharging rate. The same figure also shows that the peak-to-valley ratio is consistently improved in the second case across all tested ESS parameter variations. This demonstrates that the proposed strategy remains effective under different storage configurations and therefore has good robustness.

The main conclusion of the paper is that a bilevel energy management strategy can improve the interaction between smart NZEBs and the utility grid while preserving economic optimality. By assigning the operation-cost objective to the upper-level EMS and the exchanged-profile smoothing objective to the lower-level ESS, the framework achieves both economic and technical benefits simultaneously.

A second important conclusion is that the proposed strategy is effective for both peak shaving and valley filling. The case study results show that the exchanged power profile becomes flatter in the bilevel case, with no increase in total operating cost. This suggests that smart NZEBs can support grid flexibility services without needing to sacrifice their own economic objectives. A third conclusion is that the ESS is a central enabling technology for this multi-objective strategy. The results indicate that appropriate coordination of ESS charging and discharging behavior can improve grid-side technical indicators while also preserving price-responsive economic scheduling. The sensitivity analysis further shows that ESS capacity is especially influential in improving performance. Finally, the paper concludes that the use of complementarity theory and linearization makes the proposed framework computationally practical. The reported solving time is less than two minutes, which shows as a solid basis for practical implementation. The conclusions section also notes future research directions, such as incorporating additional user load types, comfort aspects, and alternative electricity tariffs like time-of-use pricing.





Cooperative Stochastic Energy Management of Networked Energy Hubs Considering Environmental Perspectives

This scientific work stream focuses on the cooperative stochastic energy management of networked energy hubs (NEHs) while explicitly considering both economic and environmental perspectives. The study is situated within the broader transition toward integrated, flexible, and low-carbon energy systems, where different energy carriers such as electricity and gas are jointly managed through interconnected energy hubs. In this context, the paper addresses the need for advanced operational strategies capable of coordinating multiple hubs, integrating renewable energy sources, managing storage systems, and handling uncertainty in electricity prices and photovoltaic generation. The scientific outcomes reported in this paper were obtained in the research environment of the NOVA University Lisbon. More specifically, the paper entitled “Cooperative stochastic energy management of networked energy hubs considering environmental perspectives” develops a cooperative optimization framework for interconnected energy hubs that exchange energy and share resources. The study is motivated by the observation that traditional deterministic or non-cooperative methods are often insufficient to capture the uncertainty of renewable generation and energy prices, while also failing to ensure fair benefit allocation among cooperating entities. Therefore, the paper proposes a stochastic cluster-based optimization framework that combines cooperation, uncertainty modeling, demand response, storage, and emission-aware scheduling into a unified decision-making model. Moreover, it extends the energy management problem of NZEBs by considering thermal loads as well as electrical ones. Accordingly, it investigates the potential flexibility that could be harnessed through the use of various energy converters and storage systems.

In the study, each energy hub is modeled as a multi-carrier system capable of supplying electrical, heating, and cooling loads by combining several technologies, including photovoltaic units, combined heat and power units, boilers, electric chillers, absorption chillers, electricity storage, heat storage, and ice storage. The paper then extends this concept by interconnecting several hubs into a networked energy hub architecture so that they can cooperate and exchange resources. The structure of the proposed EH illustrates how electricity, heat, cooling, storage, and demand response are coordinated inside each hub. The main research questions addressed in the paper can be summarized as follows. First, the study asks whether cooperation among energy hubs (including residential, commercial, and industrial types) can reduce operating costs and carbon emissions compared with autonomous operation. Second, it investigates how uncertainties in PV generation and electricity price can be incorporated into the scheduling problem in a realistic but computationally tractable way. Third, it examines how the benefits of cooperation can be fairly allocated among participating hubs. Finally, it evaluates the role of energy storage systems and demand response programs in improving the techno-economic and environmental performance of the networked system. These questions are explicitly reflected in the literature gap analysis and in the stated contributions of the paper. The paper positions itself against several research gaps found in earlier literature. Accordingly, previous works often neglected one or more of the following aspects: uncertainty management, fair cost allocation, environmental concerns, cooling storage, thermal demand response, or full cooperation among hubs (exchanging power and heat simultaneously). The paper therefore proposes a framework intended to fill these gaps simultaneously.

The methodology adopted in the paper is based on a cooperative stochastic mixed-integer linear programming (MILP) model for the optimal operation of networked energy hubs. The objective function minimizes the total expected cost of the system, including energy purchasing cost, operational and maintenance costs, and CO₂ emission treatment cost. In this way, the model embeds environmental concerns directly into the economic scheduling framework rather than treating them as an external post-processing measure. The methodological structure has several main components. First, the paper formulates the energy balance constraints for electricity, heat, and cooling across each energy hub. This is relevant to IRP 12, as it considers various types of NZEB loads, including electrical and thermal ones. These constraints ensure that the various loads are supplied through a combination of local generation, storage, purchased energy, and exchange with other hubs. The formulation includes detailed operational models for CHP units, boilers, electric chillers, absorption chillers, PV generation, and electricity, heat, and ice storage systems. This allows the framework to represent the multi-energy nature of each hub in a physically meaningful way. Second, the model includes demand response programs (DRPs) for both electrical and thermal loads. The paper formulates upward and downward load shifting variables together with constraints ensuring that total shifted demand remains balanced over the optimization horizon. This means the model does not merely curtail demand, but reschedules part of it in time to exploit flexibility. The inclusion of both electrical and thermal DR is one of the aspects that distinguishes the paper from some previous approaches. Third, the paper develops a stochastic uncertainty-handling framework. To represent uncertainty in solar irradiance/PV output and electricity prices, the authors first apply Monte Carlo Simulation (MCS) to generate scenarios. Because the large number of scenarios would increase computational burden, they then use the k-means clustering algorithm as a scenario reduction technique. The study generated 1000



scenarios for solar irradiance and electricity price and then reduced them to four clusters for each uncertainty source, with associated probabilities. Fourth, the paper adopts a cooperative game theory approach for benefit allocation. Specifically, it uses the Shapley value to allocate the gains of cooperation among participating energy hubs according to their contribution and performance. This is an important methodological addition because it ensures that the economic benefit of coalition formation is not only optimized at the system level but also distributed in a rational and fair manner among participants. The implementation of the methodology is tested through a 6-bus networked energy hub system with three hubs located at buses 2, 4, and 6. The system architecture shows a networked energy hub manager that coordinates the three hubs. The authors define three main case studies: autonomous operation without cooperation, cooperative operation with electricity exchange only, and cooperative operation with both electricity and heat exchange. The model is implemented in GAMS and solved with CPLEX, using technical and operational data. The results clearly show that cooperation improves both economic and environmental performance. In the autonomous base case, each energy hub optimizes its operation independently. In the cooperative cases, hubs form coalitions and share their resources. The best-performing configuration is the full coalition in Case 3, where hubs exchange both electricity and heat. In that case, the total operating cost decreases from 6120.2 \$ in the non-cooperative case to 5934.5 \$, corresponding to an improvement of about 3.0%. The paper also shows that the benefits of cooperation vary depending on the coalition structure. For example, under Case 2, where only electricity exchange is allowed, the total reduction is smaller, while under Case 3 the possibility of exchanging both heat and electricity creates more operational flexibility and leads to greater savings. The full coalition C2,4,6 is particularly advantageous because the hubs can exploit complementary resource profiles and better coordinate their facilities. From an environmental point of view, cooperation also reduces CO₂ emissions. In the base case, total emissions are 20,509.6 kg, whereas in the full cooperative configuration of Case 3 they decrease to 20,145.9 kg, a reduction of about 1.8%. The paper emphasizes that this result is important because the optimization model includes emission treatment cost and therefore internalizes environmental impact within the operational decision process. The study further demonstrates the importance of proper uncertainty modeling. The results across different scenario clusters show that the optimal operating cost varies significantly with the realizations of PV generation and electricity prices. Based on this, the authors conclude that a simplified deterministic formulation would not be sufficiently accurate for this problem, because it could lead to suboptimal or unreliable scheduling decisions. The optimal scheduling results shown in Figures 7–9 on pages 11–13 provide further insight into system operation. The electrical scheduling results indicate that CHP units supply a major share of demand, while storage systems shift energy from lower-price to higher-price periods. The thermal scheduling results show that, in cooperative operation, hubs may exchange heat rather than relying only on their local storage, which improves cost efficiency. The cooling scheduling results show that absorption chillers, electric chillers, and ice storage jointly support the cooling demand, and that the cooperative mode increases the operational flexibility of these assets, particularly in the third hub. The sensitivity analysis studies how increasing the participation ratio of demand response programs affects both cost and emissions. The results show that higher participation in both electric and thermal DR generally reduces operating costs, but electrical DR is more effective than thermal DR in reducing both cost and emissions. The analysis also indicates that, under cooperative operation, the relationships are more stable and nearly linear, while in autonomous operation thermal DR can sometimes lead to more irregular emission behavior because the optimization remains primarily cost-driven. The main conclusion of the paper is that cooperation among networked energy hubs, comprising various types of energy prosumers, namely residential, industrial, and commercial ones, is beneficial from both economic and environmental perspectives. By forming coalitions and sharing electricity and heat resources, the hubs can reduce total operating cost and CO₂ emissions compared with autonomous scheduling. The most effective configuration is the one allowing simultaneous exchange of both electricity and heat, since this maximizes the operational flexibility available to the network. A second key conclusion is that uncertainty modeling is essential for realistic energy management of networked energy hubs. The variability of PV generation and electricity prices significantly affects scheduling outcomes, and therefore stochastic scenario-based approaches are more appropriate than purely deterministic methods. The proposed combination of Monte Carlo simulation and k-means clustering offers a practical compromise between modeling realism and computational tractability. A third important conclusion is that fair allocation mechanisms are necessary for sustainable cooperation. The use of the Shapley value ensures that the gains from coalition formation are distributed according to the contribution and efficiency of each hub, which can support long-term willingness to cooperate among participants. This is especially relevant if the framework is later extended to larger-scale systems or real market settings. Finally, the paper concludes that energy storage systems and demand response programs enhance the flexibility and performance of the hubs, and that emission-aware scheduling can be integrated directly into the operational optimization model. Overall, the study provides a comprehensive and scalable cooperative management strategy for future multi-energy systems. The authors





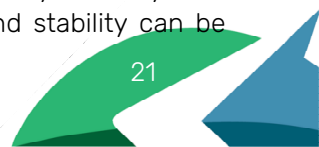
summarize that the proposed framework reduces total cost by around 3% and emissions by around 1.8%, while also highlighting the need for future multi-criteria decision-making models in coalition selection.

Analyzing Value-Sharing Methods in Energy Communities with Coalitional Game Theory

This scientific work stream addresses the application of Coalitional Game Theory (CGT) to value-sharing in Energy Communities (ECs). The study is motivated by the growing importance of collaboration in decentralized energy systems, where multiple actors such as consumers, prosumers, storage owners, aggregators, and local communities need mechanisms to cooperate and share benefits fairly. Moreover, considering the possibility of cooperation among NZEBs, there is a need to analyze the possible outcome distribution methods for sustaining their cooperation. The paper starts from the observation that the success of collaboration in ECs depends not only on technical coordination, but also on the existence of fair, stable, and transparent value-sharing methods that reflect the contributions of participants. The scientific outcomes reported in this paper were obtained in the research environment of the NOVA University Lisbon. The paper represents a direct scientific output developed within the SMARTGYSUM framework and contributes to research on collaborative energy ecosystems, human-centric systems, and fair cooperation mechanisms in ECs. More specifically, the paper entitled "Analyzing Value-Sharing Methods in Energy Communities with Coalitional Game Theory" provides a structured review of recent developments in CGT and their application to ECs.

The main research topic of the paper is the analysis and characterization of value-sharing methods in cooperative games for Energy Communities. The paper investigates how the benefits or costs of cooperation can be distributed among EC members in a way that is fair, stable, and suitable for practical implementation. This topic is highly relevant because ECs involve multiple stakeholders with different objectives, and collaboration can only be sustainable if participants perceive the allocation of gains as legitimate and advantageous. Research questions include: Which value-sharing methods have been employed in EC contexts? What are the main properties of these methods from the perspective of Game Theory? How can these methods be classified or characterized based on foundational GT principles? What are the advantages and disadvantages of implementing these methods? These questions shape the structure of the chapter and clarify that the work is not proposing a single new algorithm, but rather building a conceptual and analytical framework for understanding the suitability of different CGT-based methods in EC applications. The paper also frames the problem within the broader transformation of power systems. It explains that conventional centralized planning and control approaches are increasingly inadequate for decentralized systems characterized by many interacting players. In this setting, ECs emerge as collective and citizen-driven structures that require methods capable of representing cooperation, resource sharing, local markets, and benefit redistribution. The chapter therefore positions CGT as a promising framework for modeling these interactions and for supporting collaborative business and operational models in ECs. Another important dimension of the paper is its connection to human-centric systems. Fair-sharing mechanisms are not only mathematical tools, but also instruments for supporting well-being, participation, autonomy, and long-term engagement of community members. This is especially important because ECs are not merely technical systems; they are socio-technical structures in which fairness and inclusiveness play a central role.

The methodology adopted in the paper is a structured literature review with conceptual analysis, grounded in the theoretical foundations of Game Theory and focused specifically on cooperative approaches. Literature exploration was based on a Systematic Literature Review (SLR) strategy using the Scopus database. The search relied on the co-occurrence of the terms "cooperative AND game" and "energy AND communit*", restricted to English-language papers, and limited to "Article" and "Conference paper" sources. The search period was set between 2014 and 2024, although some older foundational references were also used to explain key theoretical concepts. The review scope was further narrowed to studies dealing with operation and planning issues in ECs, and only papers in the subject areas of Engineering and Energy were considered. This gives the chapter a clear methodological boundary and ensures that the analysis remains focused on value-sharing methods that are relevant to real EC design and management problems. After defining the review scope, the paper develops a theoretical background on ECs and Game Theory. It explains the distinction between non-cooperative and cooperative games, then zooms in on cooperative and coalitional approaches. A classification of games is provided, and the place of cooperative approaches within the broader GT landscape is described. The chapter then discusses three forms of coalitional games—canonical coalitional games, coalition formation games, and coalitional graph games—together with bargaining games. This theoretical layer is important because it provides the conceptual basis for later comparing allocation methods. A central methodological contribution of the paper is the characterization of value-sharing methods through axioms and desirable properties. The chapter reviews several axioms used to evaluate cooperative allocation methods, including efficiency, symmetry, dummy player, additivity, null player, continuity, linearity, and independence of irrelevant alternatives. The paper argues that properties such as fairness and stability can be





understood through these axioms, which then serve as criteria for comparing methods. The paper then analyzes the main sharing methods used in cooperative games: the Core, Shapley Value, Nucleolus, MCRS, Banzhaf Value, and hybrid approaches. For each method, the chapter explains the basic principle, mathematical formulation, and main strengths and weaknesses. For example, the Core is associated with coalition stability, the Shapley value with fairness and marginal contribution, the Nucleolus with reducing dissatisfaction among coalitions, and hybrid approaches with attempts to balance fairness, stability, happiness, and scalability. After the methodological and theoretical foundation, the paper reviews the application of cooperative games in ECs. The main application domains of value-sharing methods include sharing resources, sharing benefits, allocating cost, allocating emission, allocating loss, and scheduling appliances. This overview is useful because it shows that value-sharing in ECs is not restricted to financial benefits only, but extends to technical and environmental quantities as well. Finally, the paper discusses future opportunities. Gaps are identified, such as the lack of research on multi-to-multi collaboration, the difficulty of guaranteeing a non-empty core, the challenge of choosing among different sharing rules depending on the priorities of a real application, and the need to address uncertainty more explicitly.

Since this paper is a review and conceptual analysis rather than a simulation paper, its main results are analytical rather than numerical. The first important result is that the paper shows that CGT has been widely applied in ECs mainly for redistribution problems, especially for sharing benefits and costs, but also for allocating emissions, losses, and operational scheduling outcomes. A second major result is the identification of the relative strengths and limitations of the main sharing methods. The paper concludes that the Shapley value is widely used because of its fairness properties, especially symmetry, dummy-player treatment, and additivity. However, it also points out that Shapley-based approaches can face substantial computational complexity, especially in large communities, and may implicitly favor the formation of grand coalitions even when these are not always the best real-world option. The chapter also shows that the Core is particularly valuable when stability is the main concern, because it guarantees that no subset of players has an incentive to leave the coalition if a feasible allocation exists. At the same time, the paper notes that the Core often does not yield a unique solution, which can limit its practical usefulness when a single clear allocation rule is needed. Similarly, the Nucleolus is presented as a method that focuses on minimizing coalition dissatisfaction and can improve fairness and stability, but its applicability depends on the existence of a non-empty core and may involve numerical difficulties. Another significant result is the paper's finding that hybrid approaches are becoming increasingly relevant. Researchers are combining classical methods such as Shapley, Core, and Nucleolus in order to mitigate their individual weaknesses and achieve a better balance among fairness, stability, and scalability. This is one of the main trends identified by the review. The chapter also identifies several limitations in the current literature. One of the main findings is that most existing EC studies model collaboration in relatively simple forms, usually bilateral or unilateral structures, while real ECs often involve richer multi-to-multi interactions across different levels of the energy system. Another key result is that many studies still rely on deterministic interaction models, despite the importance of uncertainty associated with renewable generation, demand variability, and market conditions. These limitations are explicitly discussed in the future opportunities section.

The main conclusion of the paper is that Coalitional Game Theory provides a valuable and increasingly relevant framework for analyzing collaboration and value-sharing in Energy Communities, but the choice of a sharing method must depend on the priorities and structure of the specific application. The chapter makes it clear that there is no universally superior method: different approaches emphasize different properties such as fairness, stability, coalition satisfaction, or computational tractability. A second major conclusion is that fair value-sharing is essential for the sustainability of collaboration in ECs. Technical cooperation alone is not enough; participants must also perceive the allocation of costs and benefits as legitimate and beneficial. This is why axioms such as efficiency, symmetry, and additivity, together with stability-related concepts such as the Core, are so important in EC design. A third conclusion is that current EC research often oversimplifies cooperation structures and ignores uncertainty, which limits the realism of many models. The chapter therefore calls for future work on more complex multi-actor collaboration patterns and on methods that explicitly address variability and uncertainty in renewable-based systems. A fourth conclusion is that hybrid and context-dependent approaches are likely to be the most promising path forward. Because no single classical sharing rule can simultaneously guarantee uniqueness, fairness, stability, computational efficiency, and applicability under all conditions, future research should focus on developing tailored or combined approaches for specific EC use cases. Overall, the paper concludes that CGT is a strong conceptual and analytical basis for the design of collaborative ECs, but that practical deployment requires careful attention to coalition structure, uncertainty, computational burden, and the socio-technical priorities of the community.





Contribution to the WP objectives

ESR-12 contributed to WP5 by developing advanced, sustainable, and user-centric energy management strategies for Net Zero Energy Buildings (NZEBs) and Energy Communities (ECs). The research focused on creating techno-economically viable solutions that account for real operational constraints and uncertainties, ensuring practical applicability. A key achievement was the design and validation of optimization-based frameworks (e.g., MILP and stochastic models) for managing flexible resources such as appliances, HVAC systems, storage, and renewable generation. The work introduced novel indicators to quantify building flexibility while explicitly incorporating user comfort, enabling realistic demand-side management strategies. ESR-12 also advanced aggregator-oriented approaches by modeling coordination among multiple NZEBs and assessing their collective flexibility for participation in energy and ancillary service markets.

Several contributions addressed uncertainty-aware energy management, integrating economic objectives with environmental considerations such as carbon emissions and pricing. The research further explored hierarchical and bilevel optimization methods to improve grid interaction through peak shaving, valley filling, and enhanced self-consumption.

Beyond individual buildings, ESR-12 extended the analysis to multi-energy systems and energy hubs, demonstrating the benefits of coordinated operation across electricity, heating, cooling, and gas networks. Cooperative frameworks based on game theory were developed to ensure fair value sharing and stable collaboration within ECs.

Overall, ESR-12 provided a comprehensive set of validated tools and strategies that support flexible, low-carbon, and economically sustainable energy systems, while enabling NZEBs and ECs to actively participate in future energy markets.

Scientific achievements

Publication

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
1.	The Potential of Residential Load Flexibility: An Approach for Assessing Operational Flexibility	Journal	Published	https://doi.org/10.1016/j.jjepes.2024.109918
2.	Cooperative Stochastic Energy Management of Networked Energy Hubs Considering Environmental Perspectives.	Journal	Published	https://doi.org/10.1016/j.egy.2024.07.015
3.	Multi-Objective Energy Management of Smart Buildings Through a Bilevel Optimization Approach	Conference	Published	https://doi.org/10.1109/CPE-POWERENG60842.2024.10643759
4.	Analyzing Value-Sharing Methods in Energy Communities with Coalitional Game Theory	Book chapter	Published	https://doi.org/10.1007/978-3-031-63851-0_3
5.	A two stage probabilistic flexibility management model for aggregated residential buildings	Journal	Published	https://doi.org/10.1016/j.enbuild.2025.115404
6.	Optimal Clustering Based Energy management of Net Zero Energy Buildings	Journal	Submitted	n.a.





SMARTGYSUM project has been funded by the European Commission's Horizon 2020 Programme

	through a Stochastic Hierarchical Approach			
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Task 5.2 – IRP13 “Generation of digital twins of prosumers using socioeconomical factors and big data for Optimization of Customer’s bill savings”

Introduction

This chapter presents a synthesis of the scientific work undertaken during the preparation of the doctoral thesis of ESR 13. The research is situated within the broader context of the energy transition, characterised by the increasing integration of decentralised energy resources, the emergence of prosumers, and the need for advanced digital tools capable of capturing the complex interactions between technical, economic, and behavioural dimensions of energy systems.

The scientific outcomes presented in this work were obtained through a multi-institutional and interdisciplinary research process conducted over the course of the doctoral programme. This process combined experimental work, modelling, and conceptual development across several academic and industrial environments, each contributing to specific aspects of the overall research framework on digital twins of prosumers.

Firstly, the contributions related to the development of the NOVA digital twin, including the pseudo-envelope approach for modelling buildings under conditions of data scarcity, were carried out at NOVA University of Lisbon, within the Faculty of Science and Technology. These outcomes were achieved during a two-month secondment, complemented by continuous collaboration with the hosting research group. This research context enabled the exploration of simplified yet robust modelling strategies capable of operating under limited data availability, a key challenge in real-world digital twin deployment.

Secondly, the scientific contributions concerning the UTBM digital twin were developed at the hydrogen platform of the Université de Technologie de Belfort-Montbéliard (UTBM). These results were obtained during multiple research visits to the institution, allowing access to a complex multi-energy system integrating hydrogen technologies, photovoltaic generation, and electric mobility infrastructure. This environment provided the experimental basis for the development and validation of a high-fidelity digital twin incorporating electrical and hydrogen subsystems.

Thirdly, the conceptualisation of business models for prosumer digital twins, including the identification of value sources and monetisation pathways, was conducted during a three-month secondment at Bocconi University (UB) – GREEN research centre in Milan. This phase of the research focused on the economic and organisational dimensions of digital twin deployment, addressing the gap between technical feasibility and commercial viability in prosumer-oriented energy systems.

Finally, the contributions related to grid modelling using Simcenter Amesim, as well as the implementation of digital twins within this simulation environment, were carried out at the Research and Development department of Siemens Digital Industries in Lyon, which served as the primary hosting institution. This industrial setting enabled the integration of advanced multi-physics modelling tools and facilitated the development of scalable and interoperable digital twin architectures aligned with industry standards and practices.

Overall, the scientific work presented emerges from the combination of these complementary research environments, integrating academic and industrial perspectives. This distributed research context has been instrumental in addressing the multifaceted challenges associated with digital twins of prosumers, encompassing technical modelling, data integration under real-world constraints, and the development of viable business models.

Scientific outcomes

The central research topic of this work concerns the design, implementation, and evaluation of digital twins (DTs) tailored to energy prosumers, with particular emphasis on integrating technical, socio-economic, and behavioural dimensions within a unified modelling and optimisation framework. This topic is situated at the intersection of energy systems engineering, data-driven modelling, and business model innovation, addressing the growing need for tools capable of managing decentralised and prosumer-driven energy systems.

The research is motivated by three key gaps identified in the literature: (i) the limited integration of socio-economic and behavioural factors within energy-focused digital twins; (ii) the challenges associated with modelling systems under conditions of incomplete or disjointed datasets; and (iii) the lack of clearly defined and validated business models for prosumer-oriented digital twin applications. These gaps highlight the necessity for a multidisciplinary approach capable of bridging physical system modelling with data analytics and economic value creation.

Accordingly, the primary research question guiding this work is formulated as follows: How can digital twins be designed and implemented to reflect the technical, economic, and social dimensions of prosumers in order to support energy optimisation and enable viable business models?

To operationalise this overarching question, several sub-research questions are defined:





1. *Technical dimension:* How can multi-energy systems (including electrical, thermal, and hydrogen subsystems) be accurately modelled within a digital twin framework using real-world and incomplete datasets?
2. *Data and modelling dimension:* How can digital twins be developed and calibrated under conditions of data scarcity, inconsistency, or fragmentation, particularly in building-level applications?
3. *Socio-behavioural dimension:* How can user behaviour, occupancy patterns, and socio-economic factors be incorporated into digital twin models to improve their predictive and optimisation capabilities?
4. *Optimisation and control dimension:* How can digital twins be used to optimise energy consumption, self-consumption, and operational strategies in prosumer systems under dynamic pricing and environmental conditions?
5. *Economic and business model dimension:* What are the key value streams and business models that can emerge from the deployment of digital twins for prosumers, and under what conditions are they economically viable?
6. *Scalability and implementation dimension:* How can the proposed digital twin framework be generalised and transferred across different scales and contexts, from individual buildings to complex multi-energy systems?

Overall, these research questions structure the scientific investigation by linking modelling challenges with practical implementation constraints and economic considerations. They reflect the core ambition of the work: to move beyond purely technical digital twin implementations and towards integrated socio-technical systems capable of supporting both operational optimisation and sustainable business value creation in prosumer-driven energy ecosystems.

The methodological framework adopted in this research is grounded in a multidisciplinary approach that integrates physical modelling, data analytics, socio-economic representation, and optimisation techniques within a unified DT architecture for prosumer systems. The objective is to construct a multifactor DT capable of reflecting the complexity of real-world energy systems, where technical, behavioural, economic, and regulatory dimensions interact dynamically.

The proposed DT framework is structured around a multi-layered architecture inspired by established conceptualisations of digital twins, notably the integration of physical and virtual systems interconnected through data flows. In this work, the DT is extended to explicitly incorporate multiple contextual domains, resulting in a multifactor architecture composed of the following core components:

- *Physical layer:* This layer represents the real-world energy system, including buildings, energy assets (e.g., photovoltaic systems, batteries, hydrogen technologies), and user interactions. Data acquisition is enabled through sensors, smart meters, and existing infrastructure, capturing environmental, technical, and operational variables.
- *Virtual layer:* The virtual representation is developed using a combination of physics-based and data-driven models. Implemented primarily in Simcenter Amesim, the models capture multi-energy interactions (electrical, thermal, and hydrogen) and allow simulation of system behaviour under varying operational and environmental conditions.
- *Data layer:* This layer ensures the continuous exchange between the physical and virtual systems. It includes preprocessing, cleaning, and integration of heterogeneous datasets, such as weather data, energy consumption, generation profiles, and occupancy-derived indicators. Particular emphasis is placed on handling disjointed and incomplete datasets, through interpolation, calibration, and the introduction of proxy variables (e.g., access-based occupancy estimation).
- *Service and optimisation layer:* This component operationalises the DT by enabling scenario analysis, optimisation, and decision support. Genetic algorithms are employed for parameter calibration and optimisation of control strategies, including demand response, peak shaving, and self-consumption maximisation.
- *Security and privacy layer (transversal):* A dedicated cybersecurity and privacy layer is incorporated as a transversal element across all components. This layer governs data access, ensures compliance with regulatory frameworks (e.g., data protection requirements), and mitigates risks associated with data exchange between stakeholders. It is particularly critical given the sensitivity of behavioural and consumption data in prosumer environments.

A distinguishing feature of the methodology is the explicit consideration of the broader ecosystem in which the DT operates. The model is not limited to technical representation but is embedded within five interacting domains:

- *Technical domain:* modelling of system components, simulation fidelity, and platform implementation.
- *Economic domain:* integration of tariffs, pricing mechanisms, and cost structures influencing optimisation objectives.



- *Social domain*: representation of user behaviour, occupancy patterns, and interaction with energy systems.
- *Legal and regulatory domain*: constraints related to data governance, operational limits, and compliance.
- *Environmental domain*: incorporation of weather data and sustainability considerations affecting system performance.

These domains interact with two primary agents: the user (prosumer) and the developer/operator of the digital twin. The methodology accounts for their roles, data access rights, and influence on system behaviour, thereby framing the DT as a socio-technical system rather than a purely engineering artefact.

A key methodological contribution lies in addressing the challenge of limited or fragmented data availability. Two complementary strategies are adopted:

- *Pseudo-envelope modelling approach*. For the NOVA case study, simplified thermal models are developed to approximate building behaviour without requiring detailed architectural or material data. This approach enables scalable DT deployment in data-scarce environments.
- *Data-driven calibration and proxy variables*. Occupancy is modelled using anonymised access control data, serving as a proxy for human presence. This allows the integration of behavioural dynamics into the DT despite the absence of direct measurements.

The implementation of the DT follows a structured pipeline of data collection and preprocessing, model development, calibration and validation, scenario definition, simulation and analysis, and integration into a DT framework.

In summary, the methodology advances the state of the art by proposing a comprehensive, multifactor digital twin framework that explicitly integrates technical, socio-economic, and regulatory dimensions. It provides a structured approach to implementing digital twins in real-world prosumer contexts, particularly under constraints of data availability and system complexity.

The results obtained in this research demonstrate the feasibility and effectiveness of the proposed multifactor digital twin framework in modelling, analysing, and optimising prosumer energy systems under real-world constraints. Across the different case studies and scenarios, the developed digital twins show a strong capacity to reproduce system behaviour, support decision-making, and generate actionable insights despite limitations in data availability and system complexity.

In the case of the NOVA digital twin, the results highlight the robustness of the pseudo-envelope modelling approach under conditions of data scarcity. The calibration process, supported by optimisation algorithms, significantly improved the agreement between simulated and measured energy consumption profiles. This demonstrates that simplified modelling techniques, when combined with data-driven calibration, can achieve sufficient accuracy for operational analysis. Scenario simulations further showed that the digital twin could effectively evaluate demand-side management strategies, including peak reduction and tariff-based optimisation, leading to measurable reductions in energy costs while maintaining acceptable comfort conditions. These findings validate the methodological choice of combining simplified physical models with optimisation techniques in environments where detailed building data is unavailable.

For the UTBM digital twin, the results illustrate the capability of the framework to handle complex multi-energy systems integrating electrical and hydrogen subsystems. The simulations captured the dynamic interactions between photovoltaic generation, hydrogen production and storage, fuel cell operation, and electric mobility demand. Scenario analyses revealed that the coordinated operation of these subsystems can enhance energy flexibility and reduce dependency on grid imports, particularly during periods of high electricity prices. However, the results also indicate that the economic viability of hydrogen-based strategies is highly sensitive to system efficiencies and tariff structures, underlining the importance of integrating economic parameters within the digital twin. The model's ability to simulate these interactions provides a valuable tool for assessing the conditions under which such technologies contribute positively to prosumer systems.

A key outcome across both case studies is the successful integration of behavioural and socio-technical factors into the modelling framework. The use of occupancy estimation based on access data enabled the digital twins to capture correlations between human presence and energy consumption. This integration improved the predictive capability of the models and allowed for more realistic scenario evaluations, particularly in strategies involving load shifting and demand response. The results confirm that incorporating behavioural proxies, even when indirect, enhances the relevance and applicability of digital twin models in real-world contexts.

Additionally, the implementation of the modelling framework in Simcenter Amesim, including the development of grid and network modelling components, proved effective for simulating interconnected energy systems. The platform supported the integration of multiple subsystems and facilitated scenario-based analyses, demonstrating its suitability for digital twin applications in prosumer environments. The interoperability and modularity of the developed models further support their scalability and reuse in different contexts.



Overall, the results validate the proposed methodological approach by demonstrating that digital twins can operate reliably under imperfect data conditions, capture multi-domain interactions, and support optimisation of energy systems. They also show that the value of such systems extends beyond technical performance, providing insights into economic trade-offs and user behaviour that are essential for the development of viable prosumer-oriented solutions.

Conclusions

The scientific work developed for IRP-13 demonstrates that digital twins (DTs) constitute a viable and effective approach for modelling, analysing, and optimising prosumer energy systems, even under the constraints imposed by real-world data environments. A key conclusion is that high-fidelity and operationally useful DTs can be developed despite incomplete, disjointed, or imperfect datasets, provided that appropriate modelling strategies are employed. This finding is particularly relevant for practical deployments, where ideal data conditions are rarely available.

The research further establishes that the integration of technical, socio-economic, and behavioural dimensions within a unified DT framework is not only feasible but also essential for capturing the true dynamics of prosumer systems. By embedding factors such as user behaviour, tariff structures, and regulatory constraints into the modelling process, the developed DTs provide a more comprehensive and realistic representation of energy systems. This integration enhances both the explanatory and predictive capabilities of the models, offering deeper insights into the interactions between human activity and technical infrastructure.

From an applied perspective, the results confirm that DTs unlock multiple layers of value for prosumers. At the operational level, the simulations demonstrate measurable reductions in grid imports and associated energy costs through optimised control strategies and improved self-consumption. In terms of flexibility, the DTs enable the identification and quantification of demand-shifting opportunities and peak reduction potential, thereby supporting participation in demand response and flexibility markets.

The analysis of hydrogen-integrated systems provides further insights into the role of emerging technologies within prosumer contexts. The results indicate that hydrogen can contribute meaningfully to system flexibility and energy management under specific conditions, particularly when aligned with favourable policy frameworks and economic signals. This highlights the importance of coupling technical modelling with economic and regulatory considerations when evaluating multi-energy solutions.

Moreover, the DT framework developed in this work functions as a powerful decision-support tool. By enabling scenario-based analyses, it supports stakeholders in exploring alternative operational strategies, assessing trade-offs, and making informed decisions under uncertainty. This reinforces the role of DTs as not only analytical tools but also enablers of strategic planning in decentralised energy systems.

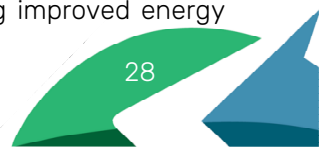
In terms of concrete scientific contributions, three main achievements can be identified. First, the development and validation of a grid modelling library, integrated within the simulation environment, provides a robust foundation for representing network interactions within DTs. Second, the successful implementation of digital twins under conditions of data scarcity, across different energy domains (electrical, thermal, and hydrogen), demonstrates the scalability and adaptability of the proposed methodology. Third, the introduction of a parametrised occupancy modelling algorithm for entrance-controlled buildings offers a novel approach to incorporating behavioural dynamics into DTs when direct measurement is unavailable.

In summary, this research advances the state of the art by demonstrating that multifactor digital twins can bridge the gap between technical modelling and real-world applicability. By integrating socio-economic factors, addressing data limitations, and enabling value-driven applications, DTs emerge as key tools for supporting energy optimisation, enhancing system flexibility, and facilitating the development of viable business models in prosumer-driven energy systems.

Contribution to the WP objectives

The scientific work developed constitutes a direct contribution to Work Package 5 (WP5), whose overarching objective is to coordinate and synthesise the technical developments from preceding work packages (WP2, WP3, and WP4) into coherent, validated business models and operational strategies for distributed and prosumer-driven energy systems. Within this context, the research provides both methodological and applied contributions that support the integration, evaluation, and valorisation of multi-energy systems.

Firstly, the research directly addresses the design of synergistic strategies by enabling scenario-based simulations in which multiple subsystems operate in a coordinated manner. The results obtained from both the NOVA and UTBM case studies demonstrate that the joint optimisation of distributed resources—such as photovoltaic generation, storage systems, and hydrogen technologies—can yield enhanced performance compared to isolated operation. These findings provide quantitative evidence of the benefits of system coordination, including improved energy





efficiency, increased flexibility, and reduced operational costs. The ability of the digital twin to simulate such coordinated strategies supports WP5 objectives by offering a robust tool for demonstrating the added value of integrated energy solutions.

Secondly, the work contributes to the research and formulation of policy-relevant insights by explicitly incorporating regulatory and economic parameters into the digital twin framework. By analysing the impact of tariff structures, pricing mechanisms, and policy conditions on system performance, the research highlights the critical role of policy design in enabling or constraining the value creation potential of prosumer systems. In particular, the evaluation of hydrogen integration and flexibility services illustrates how economic viability is strongly dependent on regulatory frameworks, thereby informing the development of policy packages aimed at accelerating the energy transition.

In addition, the business model conceptualisation developed during the course of this research aligns closely with the objectives of WP5. By identifying value streams such as energy cost savings, flexibility provision, and enhanced self-consumption, the work provides a structured basis for understanding how digital twins can support economically viable and scalable prosumer solutions. These insights contribute to bridging the gap between technical feasibility and market implementation, which is central to the objectives of WP5.

The contribution of IRP-13 to Work Package 5 lies in its ability to operationalise the coordination between technological development and economic validation. By combining advanced modelling, real-world data integration, and business model analysis within a single framework, the research supports the demonstration of synergistic benefits across distributed energy systems and provides evidence-based guidance for both system design and policy development.

Scientific achievements

Publication

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
	Multi-factor modelling of electric grids for social and technical impact studies, Tallinn, Estonia, 2023, pp. 1-6,	Conference	Published	https://doi.org/10.1109/CPE-POWERENG58103.2023.10227407



Task 5.3 – IRP14 “Energy value chains and markets developed with the new paradigm of distributed EES”

Introduction

ESR-14 research activities have been conducted for 36 months since his recruitment by Università Commerciale Luigi Bocconi (Hosting Institution) in September 2022. ESR-14 worked in the Centre for Research on Geography, Resources, Environment, Energy & Networks (GREEN), Università Commerciale Luigi Bocconi. ESR-14 also completed his first secondment at the Universidade NOVA de Lisboa (two months, June–July, 2023) and his second secondment at the University of Extremadura (four months, November 2024–February 2025). ESR-14 worked on the IRP-14 “Energy value chains and markets developed with the new paradigm of distributed EES”. ESR-14 research topic aims at improving the effectiveness of flexibility service for Energy Communities (EC). According to FEDARENE “Energy communities are initiatives led by citizens, allowing them to take control of their energy production and consumption”. ECs can play a pivotal role in enhancing RES generation and consumption and increasing energy security for the EU member states. Moreover, the EC is one of the crucial disruptive innovations within the Electric Energy System (EES). ECs can provide different services to their members such as energy generation, energy storage, EV charging station (EVCS) and toward energy market players as new energy service which is considered a key aspect of managing energy flow among users within ECs. Innovative services are intended as the ability of power systems to cope with renewable energy variability and uncertainty through peak demand shifting to avoid overloads and reduce electrical grid stress. Within this research framework, ESR-14 explored and investigated energy services' technical and business feasibility and barriers, Furthermore, he explored ECs literature review to find enablers, then validated those enablers with feasibility studies. The final research objective was to propose energy services based on different technologies and solution and check their economic feasibility and market profitability, which next are validated by executing techno-economic-environmental analysis. Besides the profit obtained from these services, ESR-14 focused on low-income families to tackle energy poverty, considering it as a value proposition in EC BM and evaluating different revenue streams and investment strategies.

In detail, ESR-14 goals were:

- Assessing policy and regulations framework of ECs (REC–Renewable Energy Communities & CEC–Citizen Energy Communities).
- Reviewing market players and stakeholders of the energy value chain and ECs in different EU contexts.
- Assessing and categorizing existing barriers of ECs reviewing current literature and comparing them by conducting a survey.
- Analysing barriers and enablers which will assist in scaling up opportunities for ECs.
- Developing new feasible and sustainable energy services and BMs for ECs.
- Delivering policy recommendations to support ECs.

The final beneficiaries will be ECs members, and EES stakeholders, including energy suppliers, DSO, municipalities, EV charger providers, aggregators, investors, etc. The main innovation of this work is to explore the innovative services capacity based on different innovative technologies (EV charging station). Also, this research will utilize real data obtained from various ECs through collected survey and provide them with feasible combination of solutions and services. This work will assist investors in understanding their profitability before investing in the EC.

1.1.1. Scientific outcomes

1. Systematic Literature Review of District Heating System

District heating (DH) is a key driver for decarbonizing the heating sector and improving energy efficiency, especially given the high proportion of energy consumption in buildings. A systematic literature review has been conducted and published as a journal article where 123 studies identify four categories of benefits: energy system, environmental, end-user, and social. However, the economic and social impacts have not yet been fully explored in the literature. While methods such as Net Present Value (NPV), Avoided Cost, and Levelized Cost of Heat (LCOH) are commonly





used, the monetization of DH benefits is limited and lacks standardization. Emerging technologies, such as Artificial Intelligence (AI), IoT, Digital Twins, and Cyber-Physical Systems, are transforming DH into smart and flexible energy networks. Despite its strong adoption in Europe and China, further development of harmonized economic frameworks and interdisciplinary research is needed to fully realize the potential of DH and support policy and investment decisions.

2. Barriers analysis of ECs: A survey within ECs

ESR-14 and ESR-15 conducted a literature review on the topic “barriers of ECs” and discovered barriers hindering EC development in the EU. Barriers were categorized in this research into: financial, administrative and legal, technological and social. Based on this work, key barriers include: a) difficulties in finding investors for small scale ECs, b) the absence of a definition of the term “proximity” in the regulatory framework of ECs in the EU which creates confusion, and c) inefficient energy infrastructures.

ESR-14 and ESR-15 also designed and launched, with key support of Bocconi University’s research team, a survey addressing EC initiatives located in the EU. The survey aimed to gather novel quantitative and qualitative data. The questionnaire consisted of 2 thematic blocks: EC characteristics (including location, maturity, number and type of members, activities performed, etc.), and EC barriers, where a list of barriers in setting up, developing and operating EC initiatives in the EU was provided, broken down into 4 categories (Economic, Institutional, Technical/Technological, and Socio-cultural and Behavioural barriers). Questionnaire participants were asked to assess the relevance of barriers, by ranking them from “0” to “5”. Responses marked as “0” indicated either the absence of a barrier or insufficient knowledge or no relevance by the respondent and “5” meant very high relevance. To maintain transparency and analytical consistency, invalid responses have been excluded.

The survey was created using the Qualtrics software and targeted “EC representatives”, defined as individuals holding management and/or organizational roles within the EC initiative. In total, 1629 contacts of EC initiatives were 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, more than 153 responses were received, of which 122 were considered valid for the analysis. It was decided to leave the survey open, to enable a more comprehensive investigation into the relevance of identified barriers. Also, the survey was conducted with five rounds: three rounds of surveys were conducted in “English” language. To get more responses and assist the respondents to be comfortable with their mother language, the questionnaire was translated and provided as well into Italian, French, and Spanish. The overall useful response rate was 122 among 1629 contacts, or 7.50%.

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

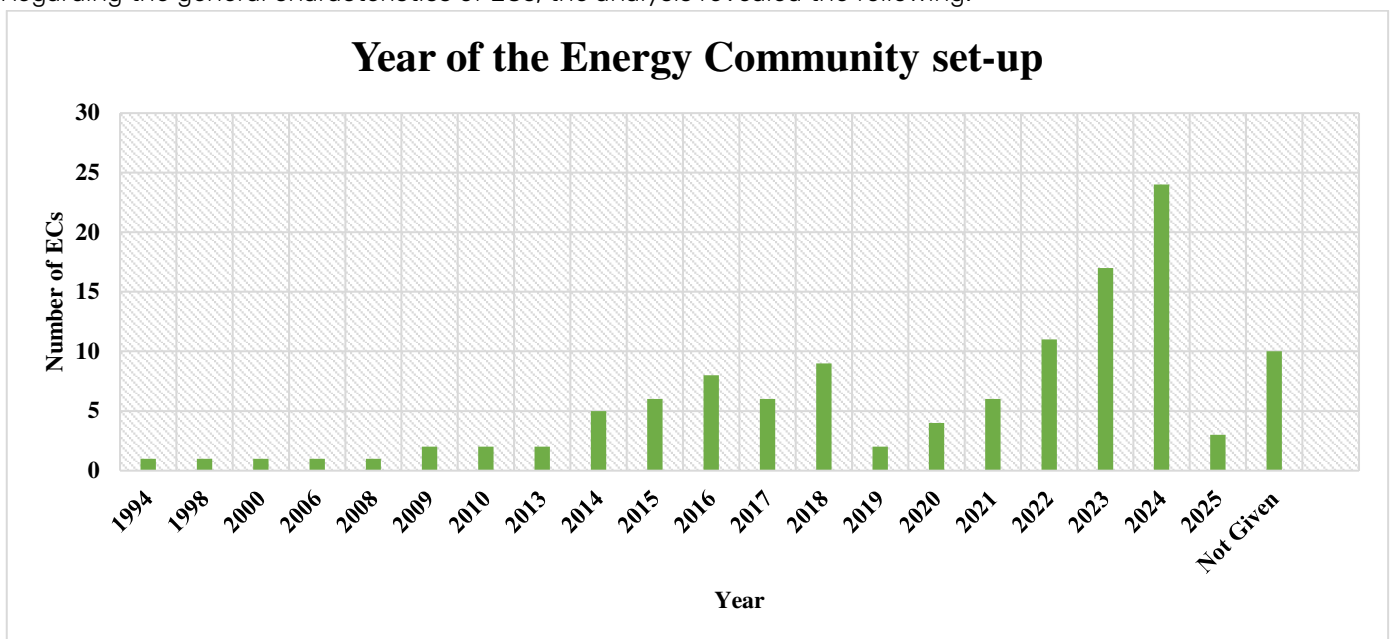


Figure 1: Year of ECs set-up.

Figure 1 shows the distribution of EC establishment years from the dataset. The highest proportion of responses is in the year “2024”.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 also a significant number of responses 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 number of responses, with only one EC each.

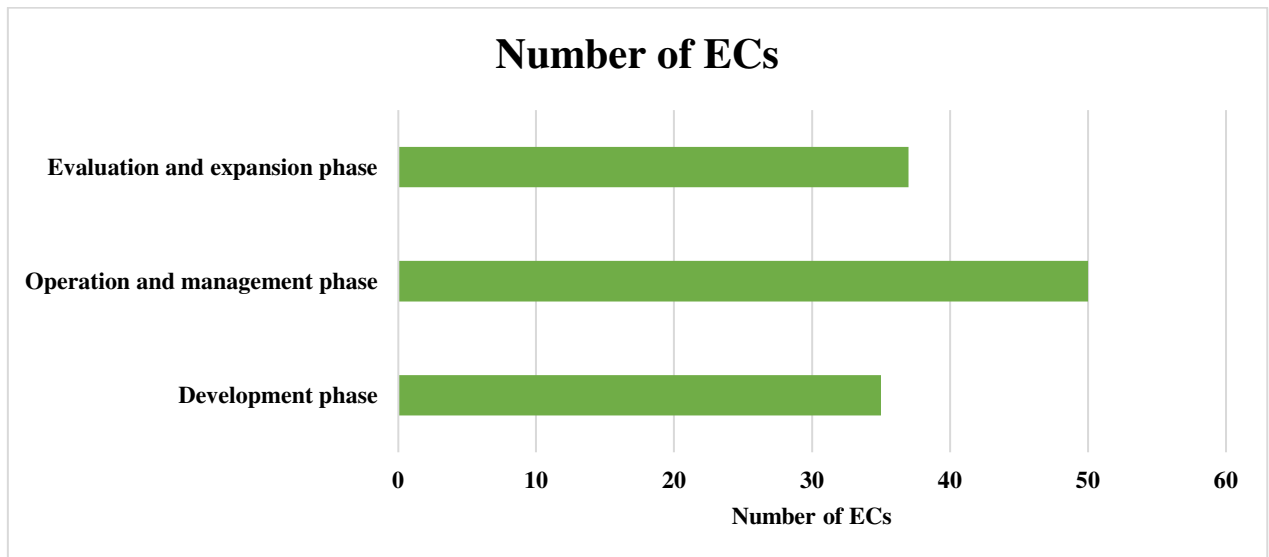


Figure 2: Maturity stages of ECs.

Figure 2 shows the maturity stages of ECs, emphasizing the recent growth of EC initiatives. This trend matches the timeline in Figure 1, 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.

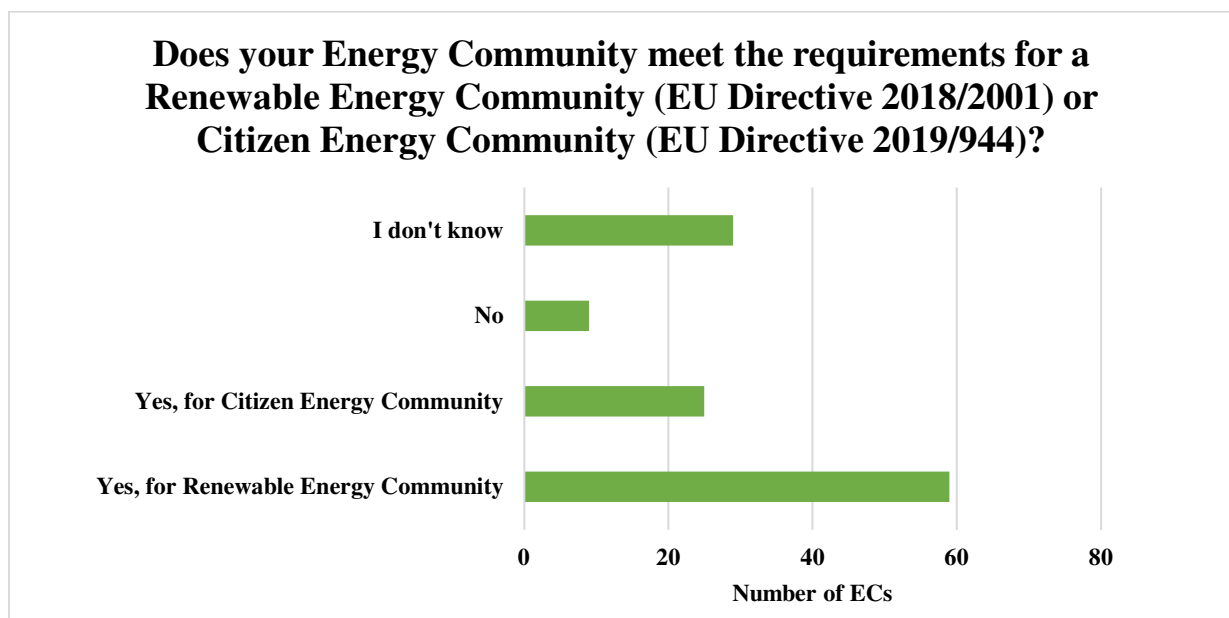


Figure 3: Compliance of ECs with EU REDII and IEMD

Figure 3 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.

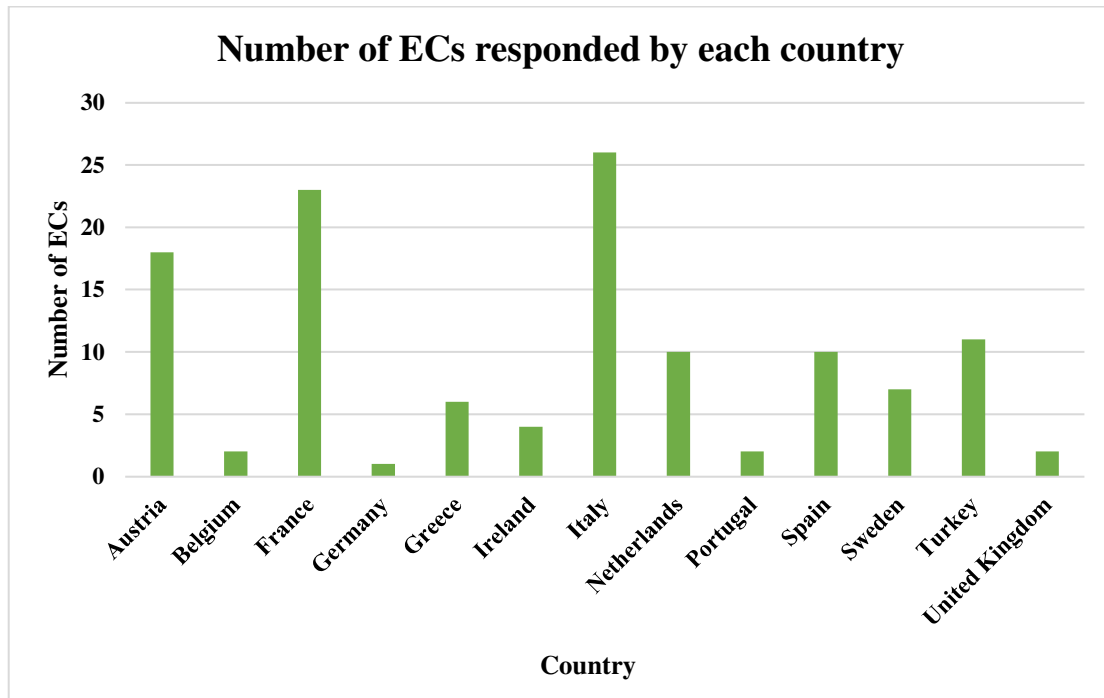


Figure 4: Geographical distribution of ECs.

The geographical distribution of ECs in the 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.

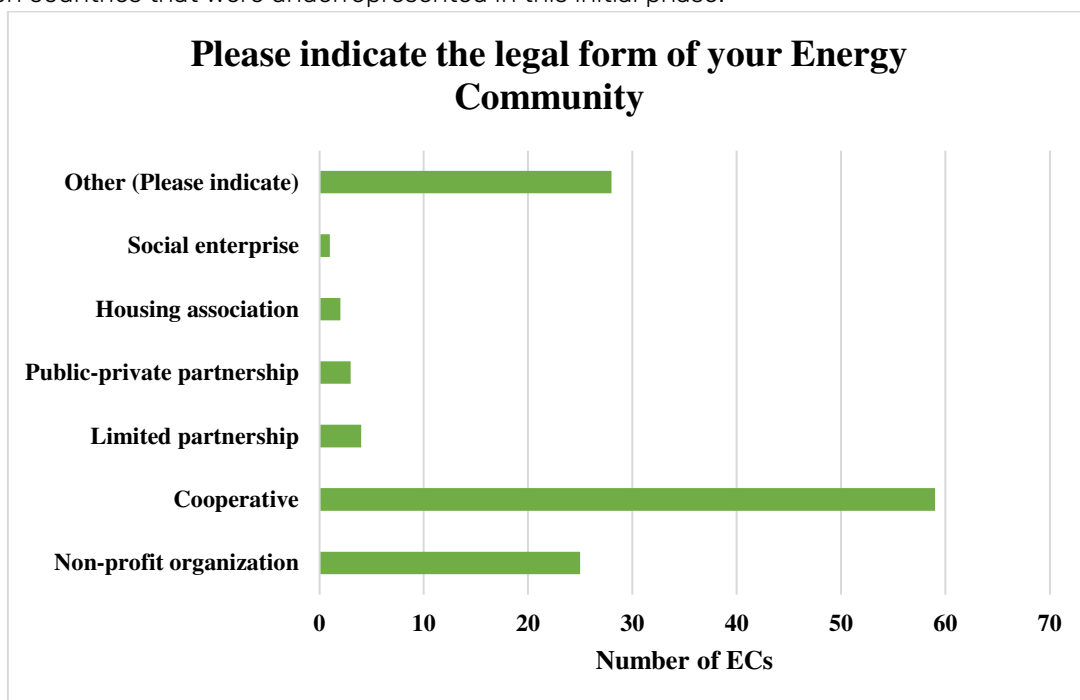


Figure 5: Legal forms of ECs.

Figure 5 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.

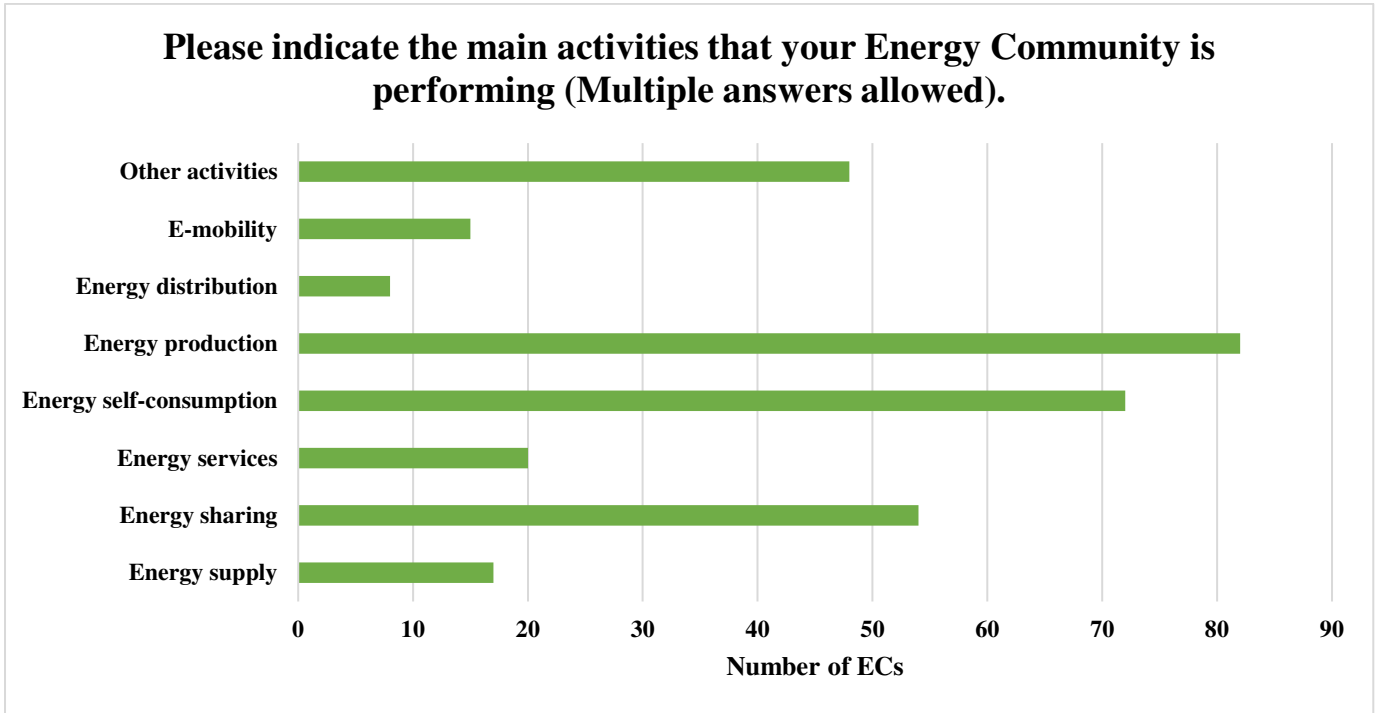


Figure 6: Main activities performed by ECs.

Figure 6 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.

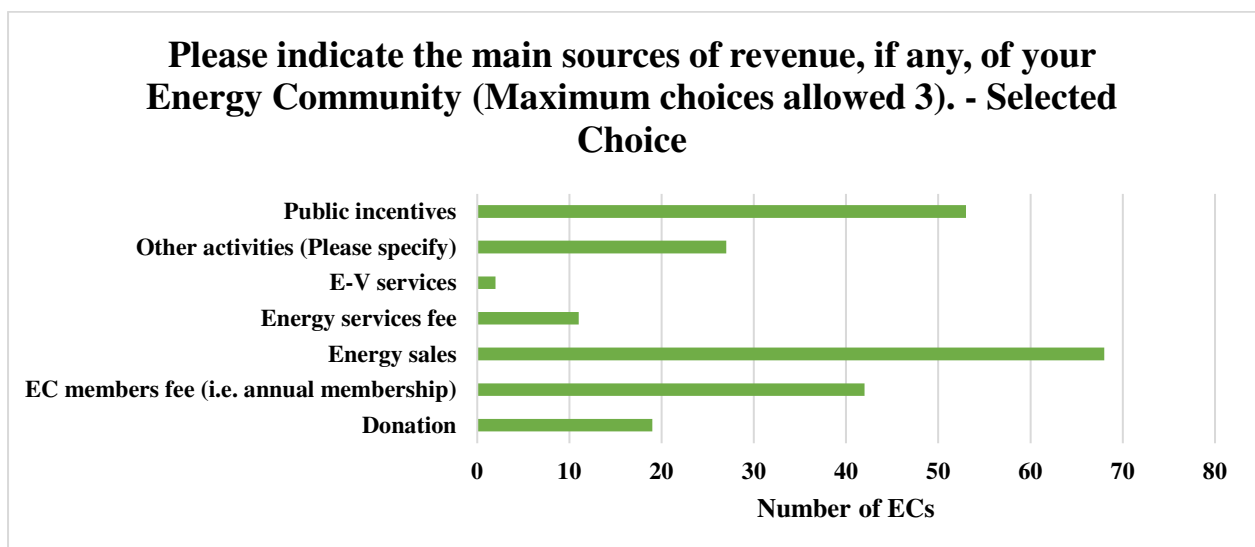


Figure 7: Main source of revenue of ECs.

Figure 7 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, results on the barriers' relevance are presented.

Economic barriers

The first Economic barriers considered refer to Financial barriers. Over 122 answers were 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".

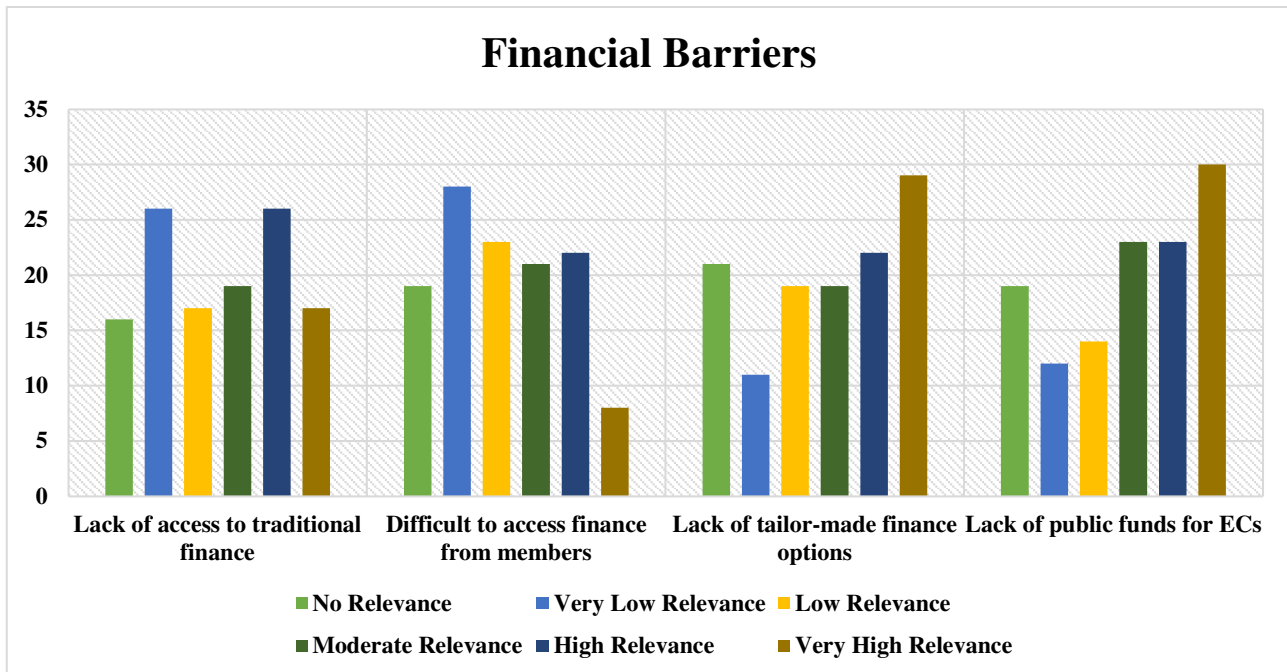


Figure 8: Financial barriers.

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 8 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.

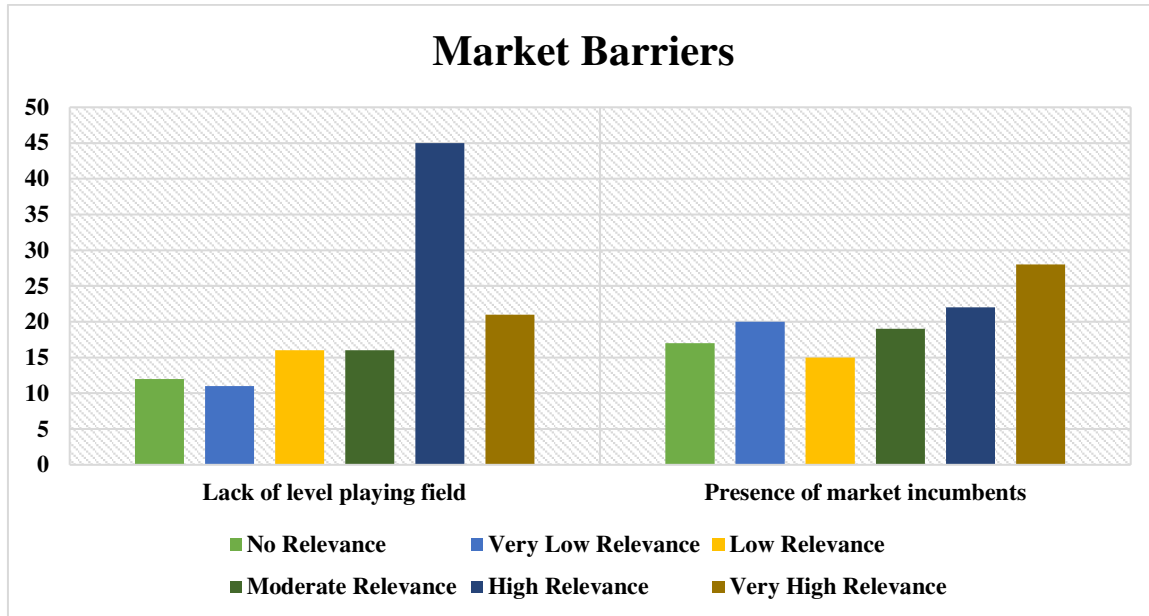


Figure 9: Market barriers.

Figure 9 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.



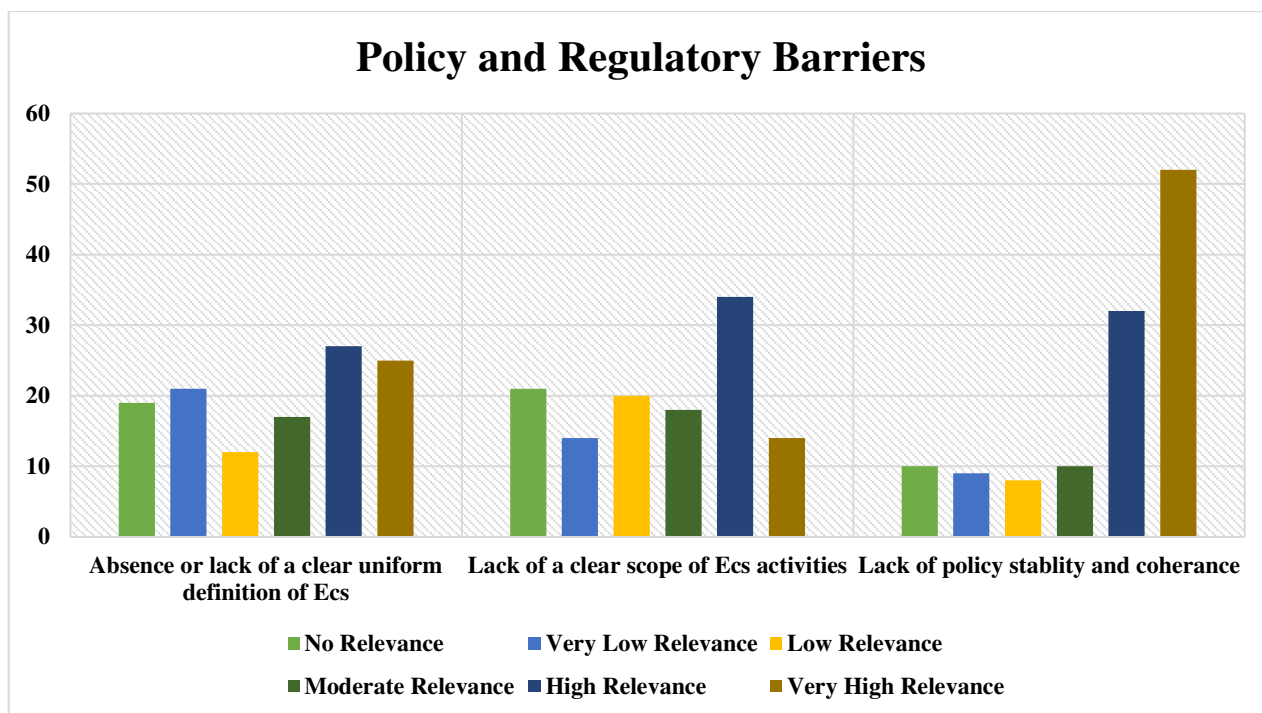


Figure 10: Policy and regulatory barriers.

Figure 10 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.

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.

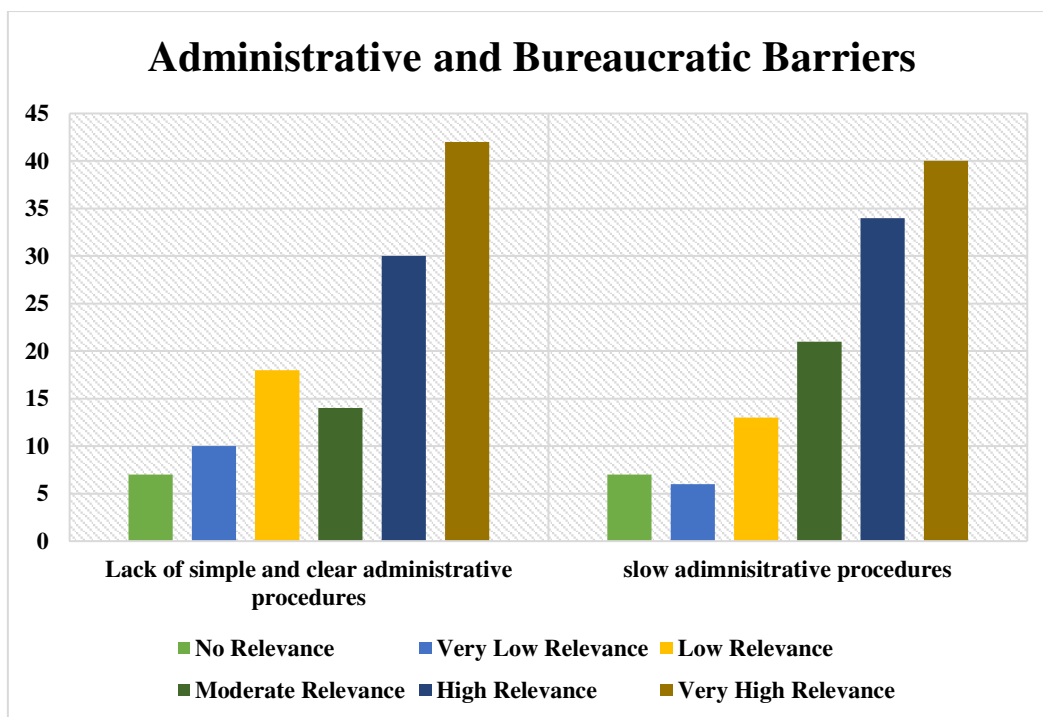


Figure 11: Administrative and bureaucratic barriers.

Figure 11 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 [11]. 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 Technical/Technological barrier considered 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".

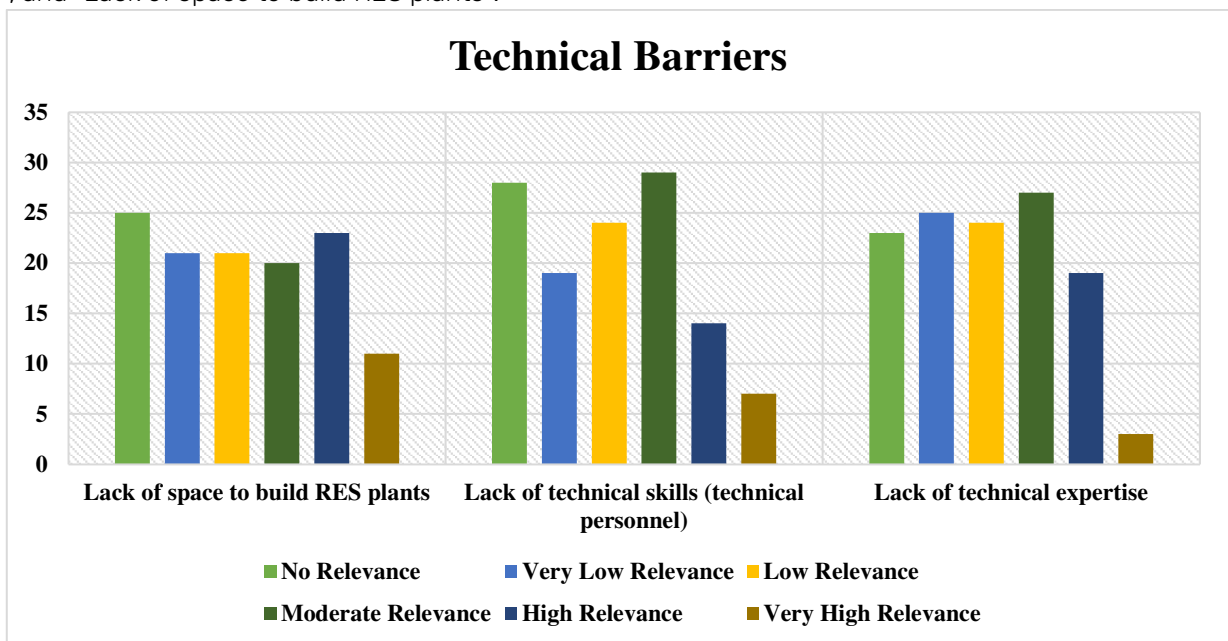


Figure 12: Technical barriers.

The "Lack of technical expertise" is rated as "Moderate Relevance" by the majority of respondents (27 respondents). While it is not widely seen as a major obstacle for all ECs, 72 EC respondents participated in the survey. 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 moderate to 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”.

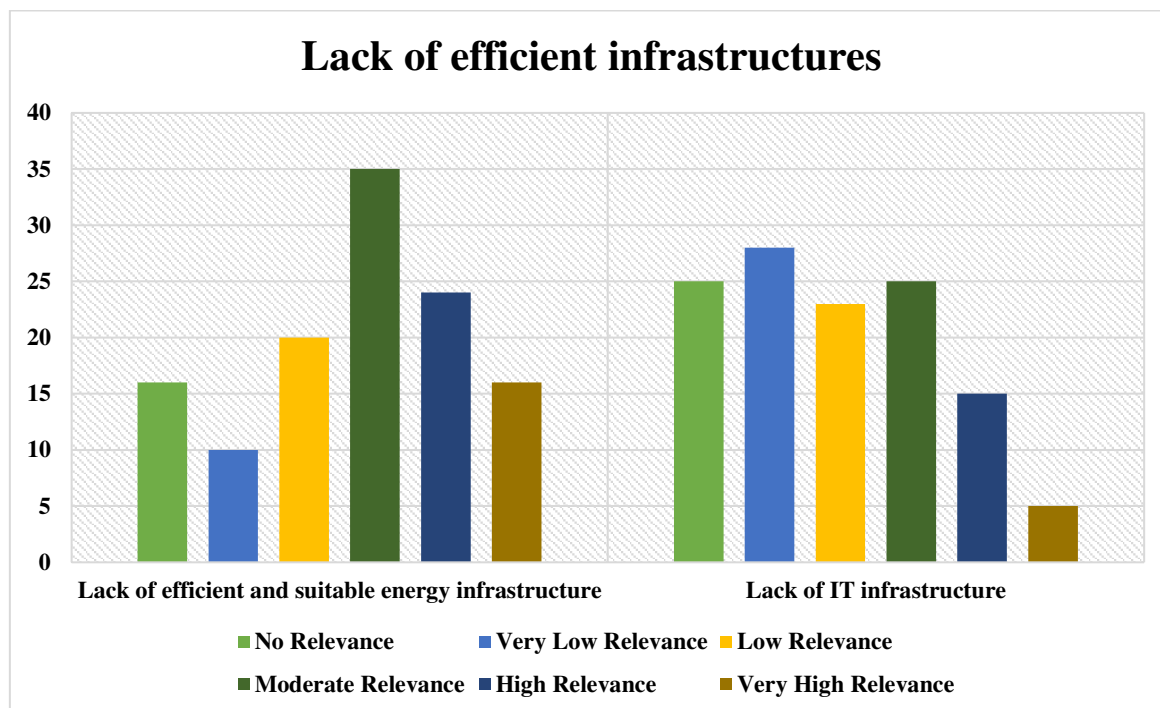


Figure 13: Lack of efficient infrastructures.

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.

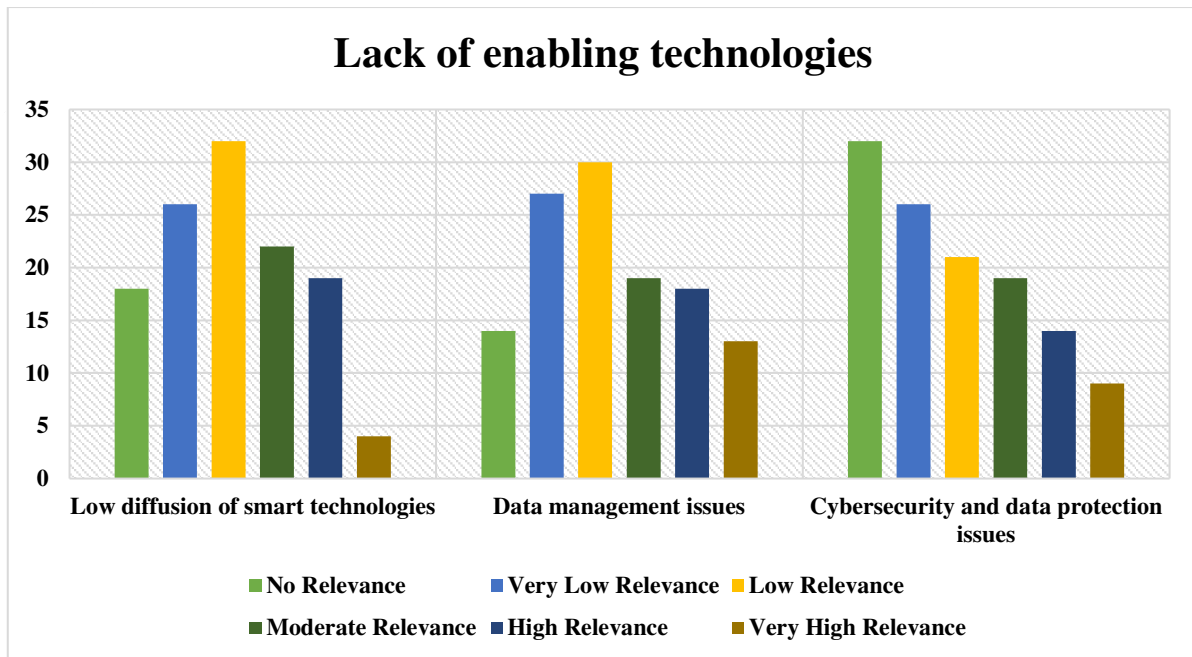


Figure 14: Lack of enabling technologies.

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”.



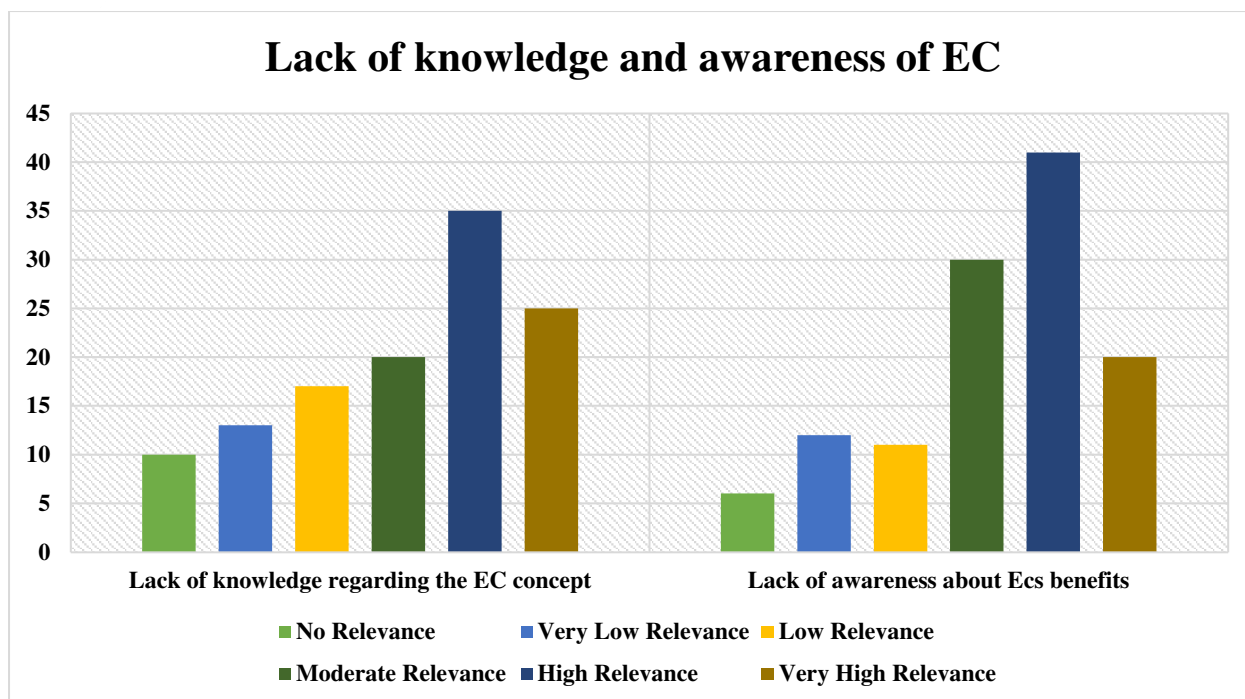


Figure 15: Lack of knowledge and awareness of EC.

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.

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”.

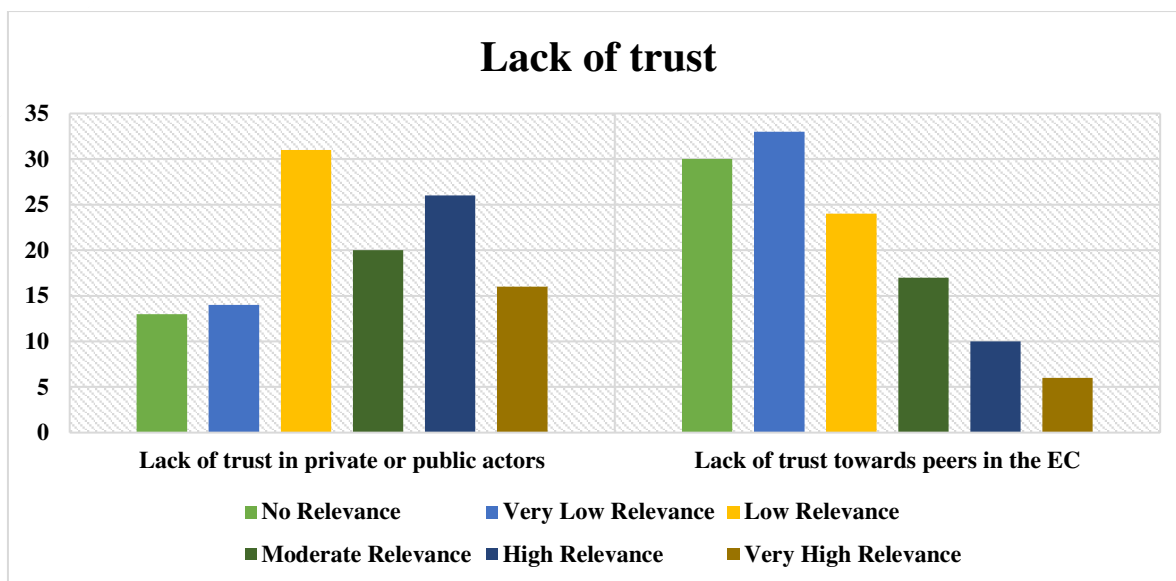


Figure 16: Lack of trust.

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”.

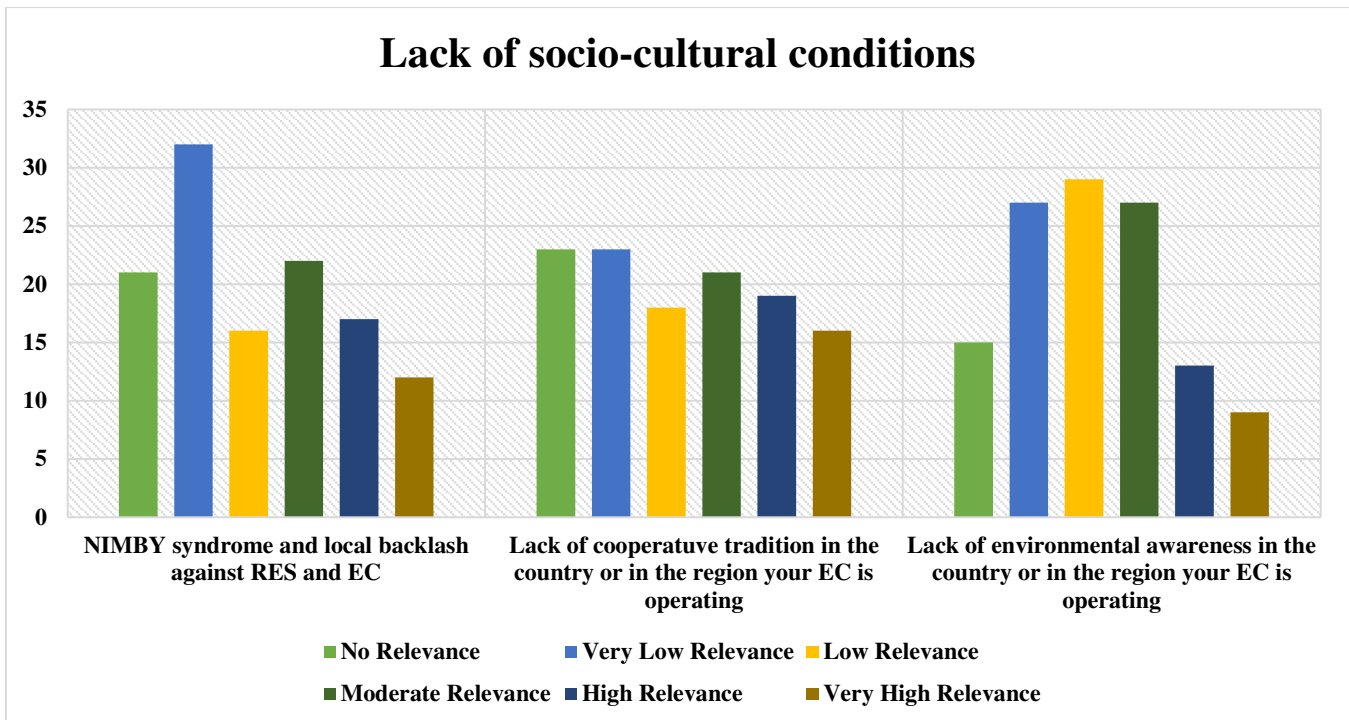


Figure 17: Lack of socio-cultural conditions.

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 the survey

Looking at all barriers, a list of the most relevant barriers across technical, regulatory, financial, and socio-cultural categories of barriers according to our sample of respondents can be identified. 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

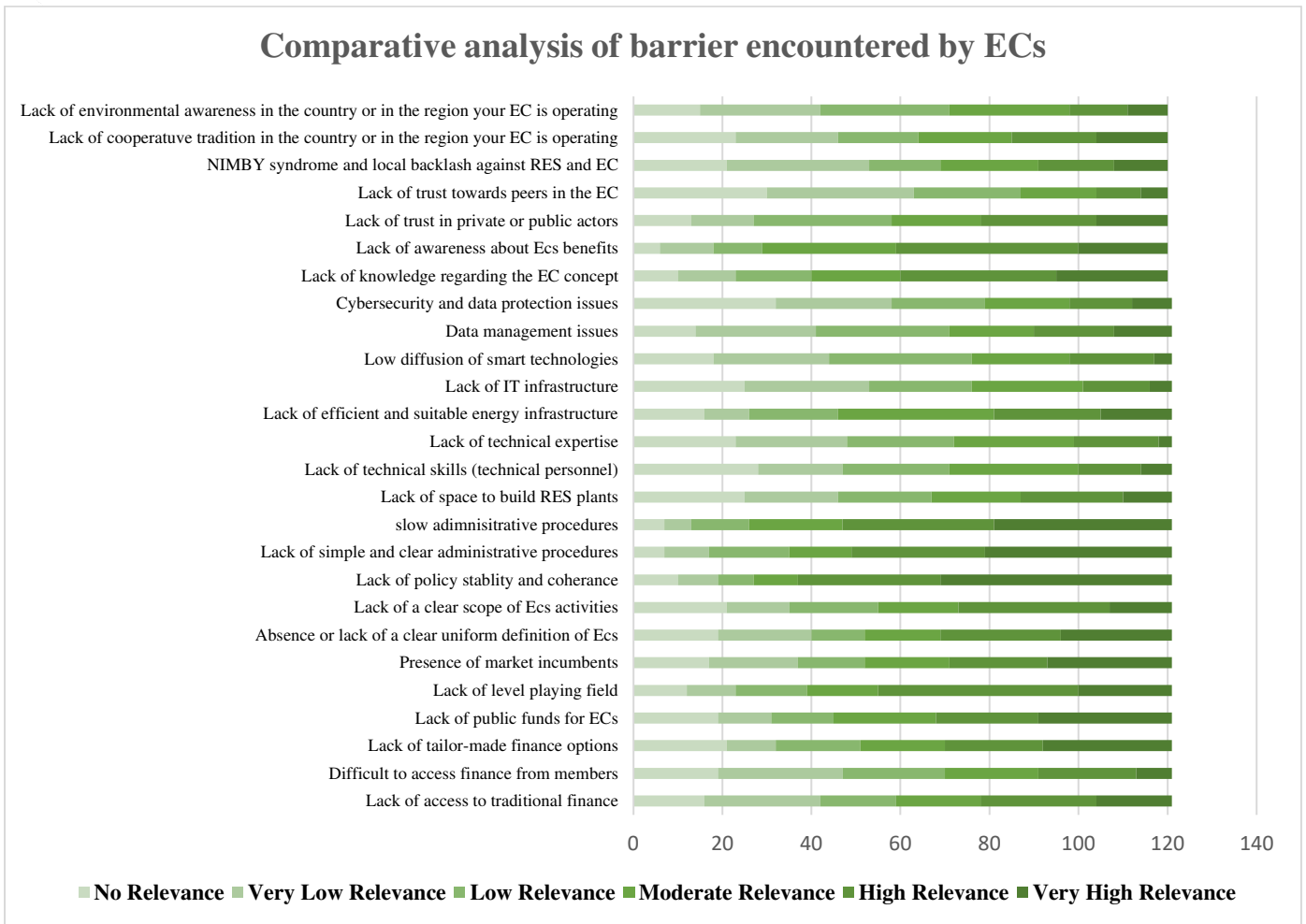


Figure 18: Comparative analysis of barriers.

3. 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.

To identify the key enablers of ECs in the literature, a traditional literature review process was conducted by searching Google Scholar with two keywords, namely "energy communities" and "enabler". Based on the analysis of current literature, it was 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 [12]. 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) CO2 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, [28], and (c) Social learning [13]. 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 [14], (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 [9] that can be integrated with ECs [16], (f) Virtual Power Plants have developed into advanced facilitators of various energy assets which can be considered as enabler [17]), (g) microgrid facilitating peer-to-peer [12], and (h) EVCSs where EV can play as energy storage and EVCS can sellback energy during RES generation [18]. Figure 19 illustrates the enablers of ECs.

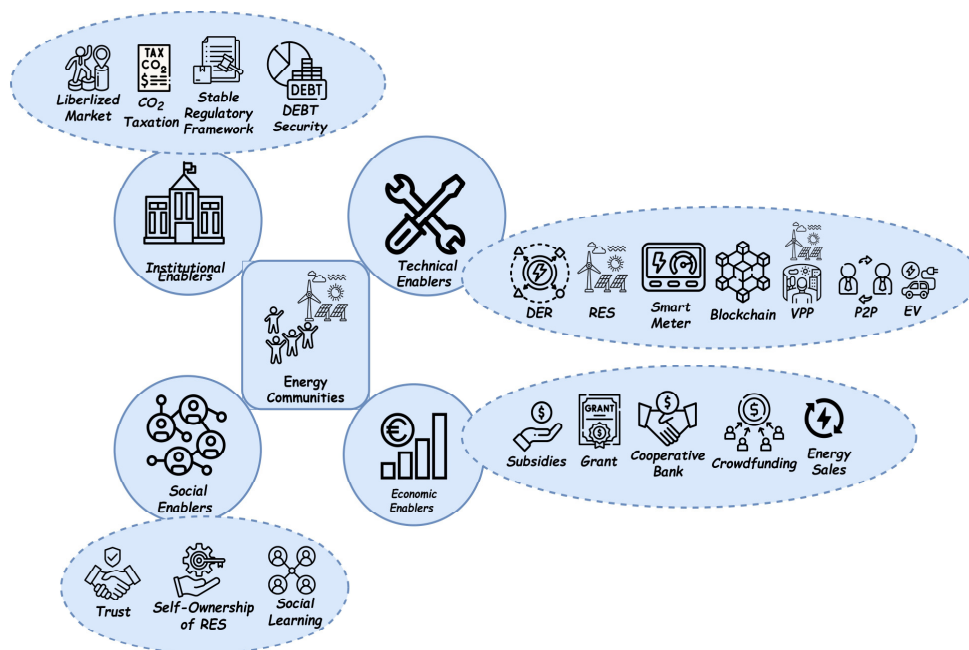
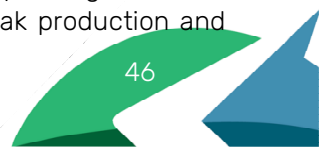


Figure 19: Enablers of ECs.

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

25% of the EU's total CO₂ emissions were produced from the transportation sector, 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 [19]. The market must be able to accept new EV customers, since EV's are essential in mitigating GHG emissions. Furthermore, EV consumers are facing several barriers to buying EVs, including a lack of knowledge [20], high purchase cost [21], and limited autonomy, but mostly about the lack of EVCS availability [22]. The lack of availability of EV charging infrastructure slows down interest in buying EVs in many countries [23], [24]. 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, vehicle to the grid (V2G) and vehicle to home (V2H). 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. Summarized literature matrix of the selected paper in Table 1.

Table 1

Summarized literature matrix of the selected paper.

Ref	Location	Year	Simulation tool/Method	Application	Charger Method	MG configuration	Charger number	Economic Parameters
[25]	Portugal	2022	HOMER Grid	Not Found (NF)	Leverl-2 (L-2), Leverl-3 (L-3)	PV-ESS-Grid	2	COE, NPC, CAPEX, OPEX
[26]	Romania	2019	HOMER Pro	Residential	L-2	PV-Grid-WT-BESS	2	COE
[27]	Portugal	2021	GAMS, MILP	University	L-2	PV-Grid	110	COE
[28]	Bangladesh	2023	FLC, RNN, LSTM, HOMER Pro	Airport	L-3	PV-WT-Grid	25	COE, NPC, CAPEX, OPEX
[29]	Qatar	2022	HOMER Pro	NF	L-3	PV-WT-Biomass-ESS	50	COE, NPC
[30]	Turkey	2019	ETAP	NF	L-2	PV-Grid	100	Not Found (NF)
[31]	NF	2020	MILP, GAMS	NF	Leverl-1 (L-1), L-2, L-3	BESS-WT-Grid	14	CAPEX
[32]	Australia	2020	MATLAB 2018b	NF	NF	WT-PV-CSP-Grid	NF	COE, CAPEX
This work	Portugal	-	Python, HOMER	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 [25]. The energy system was designed for two levels of EV chargers (L-2 is semi-fast charging, and L-3 is fast charging) [25]. 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 [27]. 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) 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 [30].

Furthermore, Hasan et al. proposed an EVCS for an International airport in Bangladesh [28]. 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 [28]. 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 [29]. In this research work, the combination of the best configurations was PV-WT-Biomass-ESS. They used HOMER Pro software to optimize the COE, and their proposed design could charge 50 EVs 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 [25], [26], [27], [28], [29], [30], [31], [32], 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 the study was to perform an energy-economic-environmental optimization by conducting the





feasibility of RES-powered EVCS at the NOVA University Lisbon, Caparica, Portugal (this location is considered as a pilot case¹).

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/m²/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 [33]. 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 20 and 21 show the monthly profiles of solar radiation (including clearness index) and wind speed, highlighting the renewable energy potential of the chosen area.

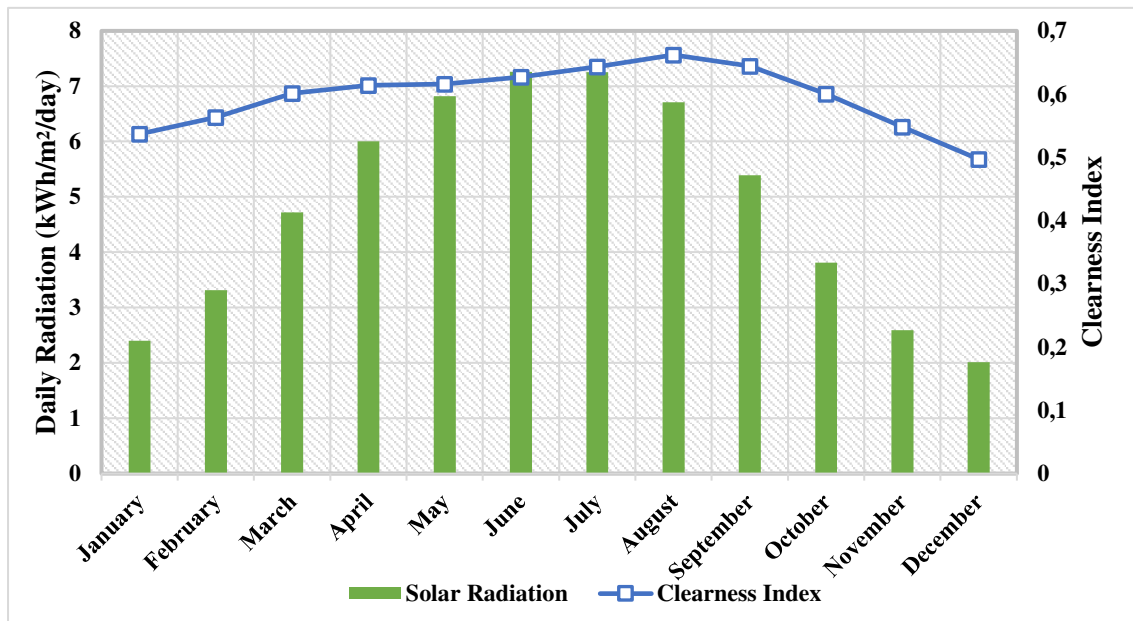
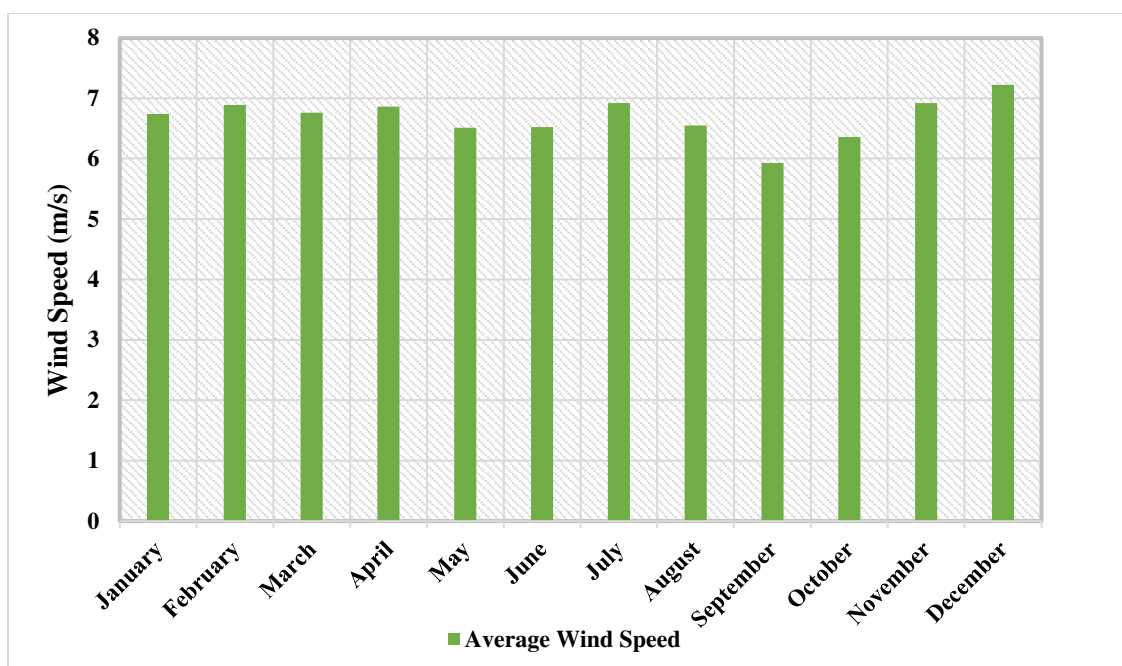


Figure 20: Monthly solar radiation to understand the potential of the selected location with clearness index.



¹Many 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.





Figure 21: Wind speed to understand the potential of the selected location.

At first, data (TOA and TOD of parked cars in the university) was 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, we faced a challenge: 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 arrives at or leaves the university. However, the data on the TOD and TOA of the cars were available. A Python script was written with a developed algorithm by utilizing the first in first out (FIFO²) method [34]. As we found in the literature, many researchers employed the FIFO method for EVCS parking lot scheduling [35], [36], [37], [38].

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 is calculated by employing equation (1) [1].

$$N_{T_{EV}} = N_{T_{C,E}} * A_{P_{EV}} \quad (1)$$

$N_{T_{EV}}$ 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 was 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) [1].

$$L_{Est} = N_{T_{EV}} * A_{PP} * t * P_{SOC} \quad (2)$$

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 was fed with collected energy-economic-environmental parameters into the HOMER optimization tool for the EVCS integrating a decentralized microgrid [7].

After developing the equation, the scenario development was 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 [7].

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. Performing techno-economic analysis by entering 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 (NPC³), CAPEX⁴, Operational Expenditure (OPEX⁵), COE⁶, and CO2 reduction. Table 2 displays the summarized economic analysis of Case Study I [7].

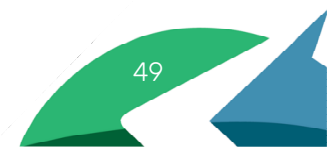
² FIFO means "First In, First Out" and is an asset-management and valuation method in which assets produced or acquired first are sold, used, or disposed first [39].

³ The NPC is the difference between the total cost of the project and the revenue generated by the system during the project period [40].

⁴ CAPEX refers to an organization's funds to acquire, upgrade, or maintain physical assets such as property, buildings, technology, or equipment [41].

⁵ 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 [42].

⁶ The COE is defined as the annual cost ratio to the supplied electrical load [40].



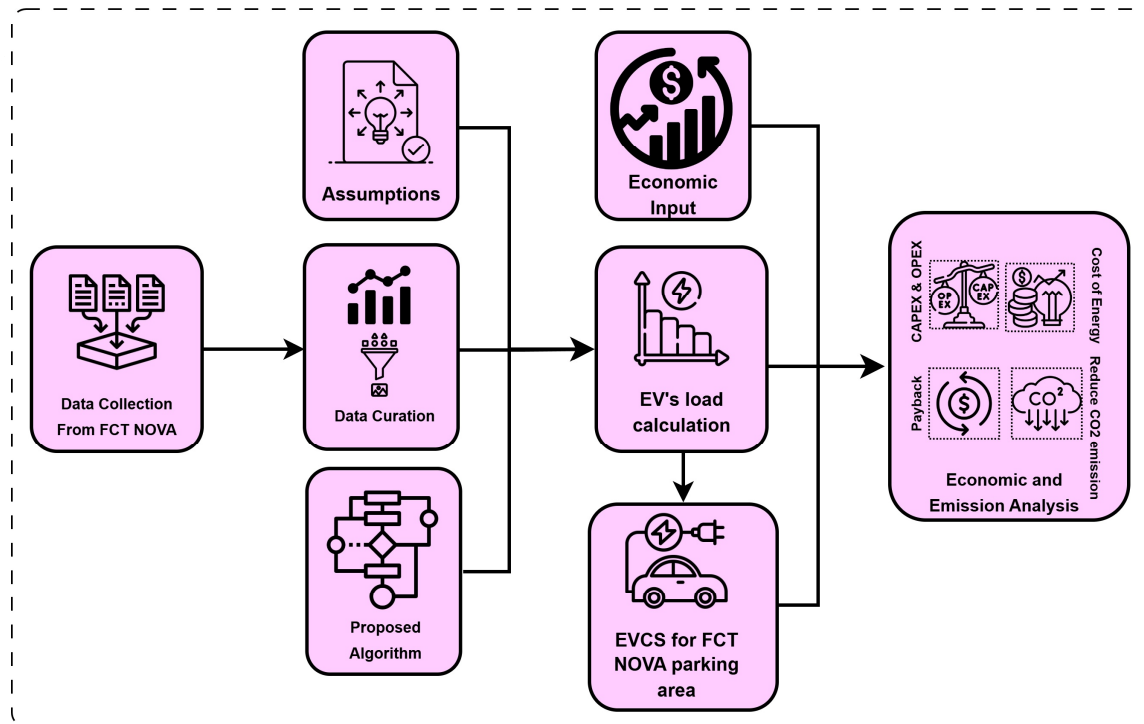


Figure 22: Methodology of the work [1].

Table 2

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 S2'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 has the best CAPEX at 5.89 million \$. Nevertheless, with the highest CAPEX, S4 is 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 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 who can cooperate for investments and offer a sustainable service will be investigated. 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.

5. 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. While the optimisation analysis for Case Study I was conducted in a single step, 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. 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, 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 [10]. 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. 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. 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. 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) 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.

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. Similarly, Alabi et al. did not consider key economic aspects such as COE and CAPEX, while González-Romera et al. did not perform a detailed economic analysis. 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 was 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-load. This study seeks to provide insight into both the economic and environmental benefits of using RES or VPP-supported EVCS infrastructure.

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. By combining these two datasets a load profile⁷ was developed. This load profile, technical and economic data was entered into the HOMER) software to perform a first layer technical and economic optimization. After performing the first layer optimization, the CAPEX, OPEX, COE, NPC, and CO₂ 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. 23, displays the two-layer optimization methodology for EVCS.

⁷ A load profile is a graph depicting power consumption over time, whereas load profile diagram illustrates accumulated power consumption in relation to operating period.



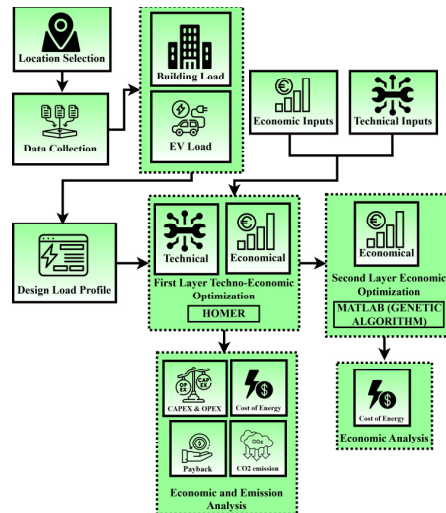


Figure 23: Methodology of two-layer optimizations for EVCS [10]

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. 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 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. The first two scenarios were 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 [10]. In this subsection economic analysis results of case study II are summarized.

Table 3 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 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.

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, CO₂ emissions are lower than in the FS, amounting to 458.847tons/yr.





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.

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

Contribution to the WP objectives

ESR-14's research aligns closely with the objectives of WP5, contributing to both T5.3 and T5.4. The work focused on developing innovative energy-related services and business models, with a particular emphasis on ECs and EVCS. During the project period, ESR-14 conducted literature analyses of barriers and policy assessments, establishing a solid foundation for the design of sustainable services within distributed EES. Planned activities, including the collection of EC data and the development of techno-economic methodologies, further support the advancement of WP5's objectives. A key contribution of ESR-14 lies in the development of techno-economic models to optimize the COE and GHG emissions. Case studies in university campuses and residential communities demonstrate that integrating EVCS, RES, and storage systems, modelled using optimization techniques which can significantly improve energy efficiency, reduce costs, and decrease emissions. These findings validate EVCS as an innovative and scalable service in ECs and promoting self-consumption. In collaboration with ESR-15, ESR-14 also contributed to identifying the barriers and enablers affecting the development of ECs. A structured typology of barriers (regulatory, technical, financial, and social) has been developed based on SLR (PRISMA methodology) and empirical data from a survey of 122 ECs. Overall, the work of ESR-14 supports WP5 by bridging the gap between theoretical analysis and practical validation, contributing to the development of innovative, sustainable, and replicable BMs for distributed EES.

Scientific achievements

Publications

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
1.	(Ahmed, S.M.M., Croci, E., Bagaini, A. (2023). A Critical Review of District Heating and District Cooling Socioeconomic and Environmental Benefits. In: Camarinha-Matos, L.M., Ferrada, F. (eds) Technological Innovation for Connected Cyber Physical Spaces. DoCEIS 2023. IFIP Advances in Information and	Book Chapter	Published	https://doi.org/10.1007/978-3-031-36007-7_1





	Communication Technology, vol 678. Springer, Cham.			
2.	Ahmed, S. M., Alvi, A. A., Pantazis, K., Bagaini, A., Croci, E., Romero-Cadaval, E., & Martins, J. (2025, June). Techno-Economic Optimization of Electric Vehicle Charging Station with Virtual Power Plant—a University Campus Use Case. In IEEE EUROCON 2025-21st International Conference on Smart Technologies (pp. 1-6). IEEE.	Conference	Published	10.1109/EUROCON64445.2025.11073409
3.	Ahmed, S.M., Bagaini, A., Molteni, T., & Croci, E (2025). Energy Communities Enablers: Techno-Economic Optimization Analysis of Renewable Energy System for Electric Vehicle charging Station	Book Chapter	Published	https://www.smartgysum.eu/Home/Outcomes
4.	Ahmed, S. M., Bagaini, A., & Croci, E. (2025). District Heating Benefits and Economic Assessment Methods: A Systematic Review and the Role of Emerging Technologies. <i>Energies</i> , 18(24), 6464.	Journal	Published	https://doi.org/10.3390/en18246464
5.	Ahmed, S. M., Bagaini, A., Martins, J., Croci, E., & Romero-Cadaval, E. (2026). Energy-Economic-Environmental (3E) Optimisation of Grid-Connected Electric Vehicle Charging Station for a University Campus in Caparica, Portugal. <i>Energies</i> , 19(6), 1466.	Journal	Published	https://doi.org/10.3390/en19061466





Task 5.4 – IRP15 “Identifying enablers and barriers to foster the replicability of business models for Green Energy Systems”

Introduction

ESR-15 was recruited to the project in January 2023 (01/01/2023) by Università commerciale Luigi Bocconi (UB) at GREEN (Centre for Research on Geography, Resources, Environment, Energy & Networks) in Milan, Italy and concluded its contract on December 2025 (31/12/2025), thus completing a 36-month period at UB. Furthermore, ESR-15 registered as a Ph.D. student at the University of Extremadura in December 2023. He has completed a 2-year Ph.D. period and is now in the third year of his program.

ESR-15 was involved in IRP-15 which aims to “Identify enablers and barriers to foster the replicability of business models for Green Energy Systems”. ESR-15 research connects to IRP-15 since it plans to identify and assess the relevant factors that favour and hinder the diffusion of innovative business models related to sustainable energy systems and energy transition in the EU. Considering the current research direction, ESR-15, in order to achieve the objectives of IRP-15, decided to narrow down his research focus to the analysis of Energy Communities (ECs) in the EU context. Energy communities are collaborative schemes about power energy systems with a particular focus on Renewable Energy Systems, that can be characterized by different business models. ECs can perform various activities such as energy generation and storage, but also provide services to the grid such as demand-response. In addition, they aim to deliver also socio-environmental benefits, addressing current challenges such as the climate crisis, energy poverty, etc. ECs incorporate different types of actors, with citizens being at the centre but also involving other actors with different purposes, motives, and interests.

The analysis of Energy Communities by ESR-15 has been carried out from a business model perspective. Based on the foregoing, ESR-15 research objectives were to:

- taxonomize different types of Energy Community Business models
- analyse barriers that specific EC business models face
- provide policy solutions to overcome these barriers
- provide recommendations for a successful replication of innovative Energy Community business models.

The final beneficiaries of the research are ECs members and key stakeholders, as well as policy makers at various levels. The main innovation of this work is to explore business models of ECs considering the role of different actors and their capacity to generate different types of values. The research has grounded on literature, but also real data obtained from various ECs, providing to the final beneficiaries a set of recommendations on the implementation and replication of innovative EC business models.

Scientific outcomes

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 [44]. 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 [45]. 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 [45].

Although citizen participation in the energy systems has a long history that goes back to the late 19th and early 20th centuries [46], 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 [47].

However, the topic of ECs remains complex due to the various terms and definitions found in academic literature [48], [49]. 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” [49]. 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 [50]. Some scholars aim to clarify the fluid meaning of “community” and propose definitions [51], [52], while others develop typologies of ECs based on energy citizenship [53]. Furthermore, other studies have examined the potential of ECs to democratize the energy system and promote justice [54], [55], [56].





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. [49] 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. [57] 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 [58] 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 [59]. ESR15 engaged 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.

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.

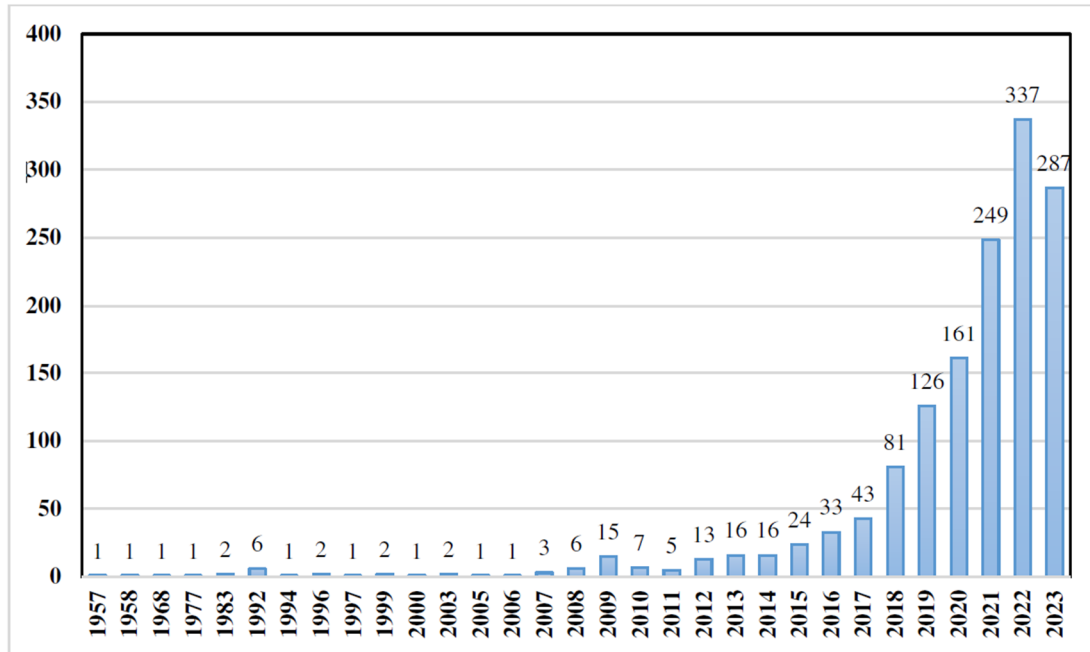


Figure 1: Annual publication related to the topic of Energy Communities

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 1

Most productive countries, in terms of number of papers published and cited

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

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. The most influential authors, each with over 200 citations, are listed in Table 2.

Table 2

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

Science mapping: Keywords co-occurrence analysis.

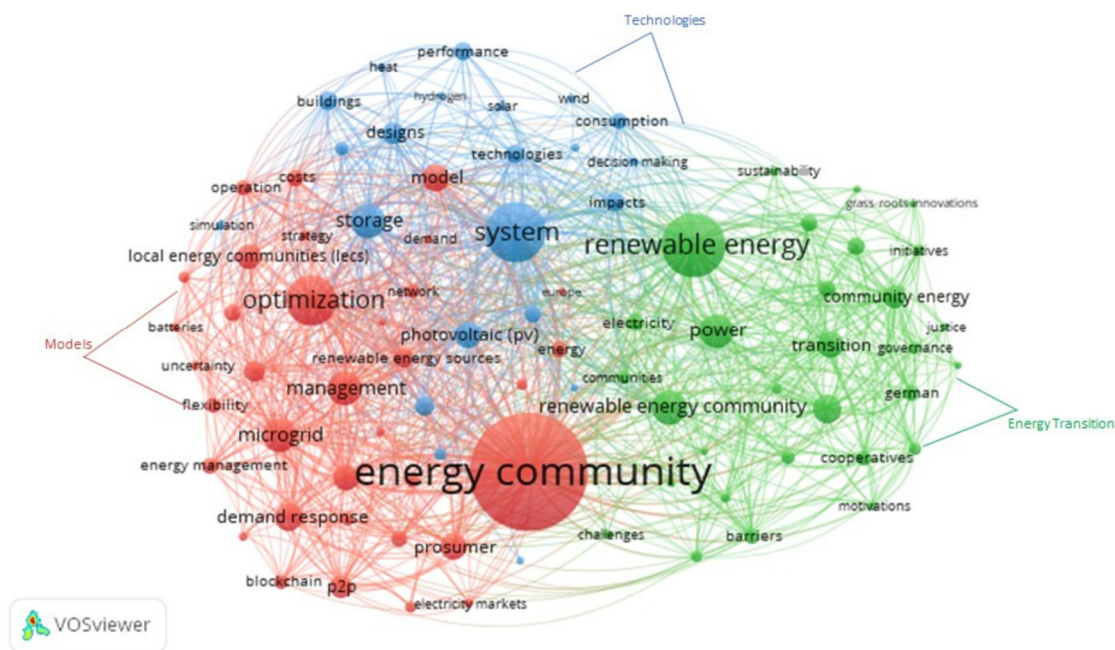


Figure 2: Keyword co-occurrence analysis related to the topic of ECs.

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 [52] 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 [60] 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) [61], [62].

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. [63] 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. [64] 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. [65] 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. [66] 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. [67] 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."

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 [45]. 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. [68], 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. [69] 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" [69]. 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 [70], [71], [72]. 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) [71], [73] and lean canvas framework (LCF) [74]. Additionally, some studies have sought to analyze and categorize EC BMs based on unique characteristics of ECs, such as membership and governance [75].





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.

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 [49], 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.

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. 3).

Table 3

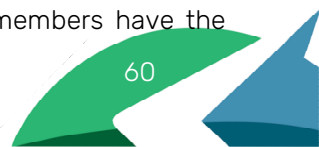
The five dimensions of the tailored BM framework of ECs.

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

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 [45], goals [14], or benefits [77], and it describes the EC's main objective. Based on Osterwalder et al. [68], 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 [72], value-sharing mechanisms [78], and energy value capture [75]. These terms illustrate how ECs allocate profits among their members [79]. 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 [79], 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 [57], [80], [81], as these technologies are vital for achieving the objectives of ECs [75]. 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 [82], and appears 9 times in our literature review. However, not all studies use the same terminology. For instance, Caramizaru & Uihlein [45] 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 [45]. 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 [45], members of the EC [75], or actors [81]. Reference [53] 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 [83], while others highlight their positions in the energy market, differentiating between categories like "prosumers," "pure consumers," and "storage operators" [44]. 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.

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.

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.

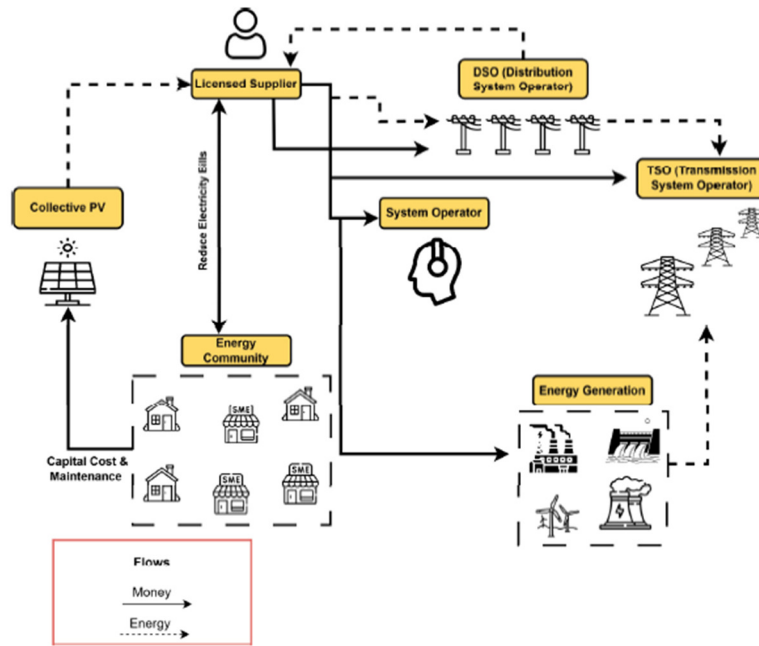


Figure 3: Self-consumption business model archetype

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.



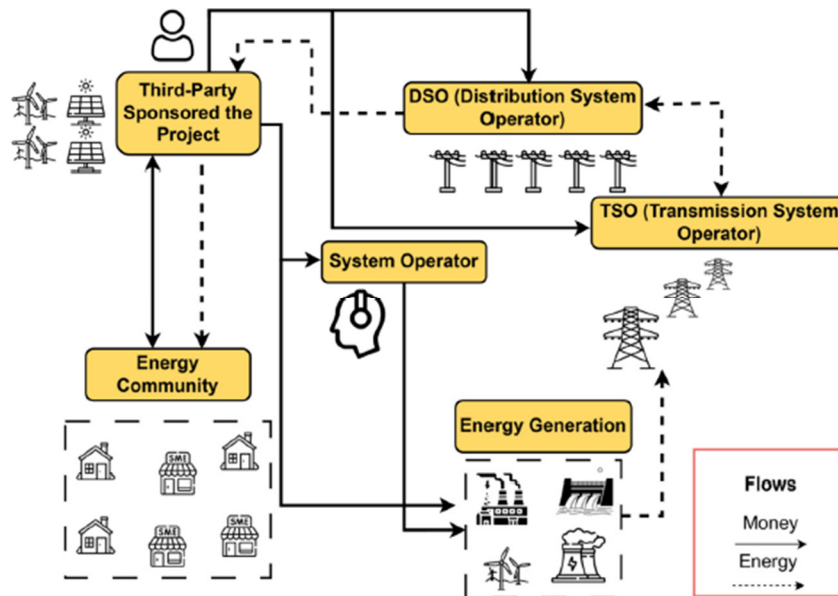


Figure 4: Third-party business model archetype

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.

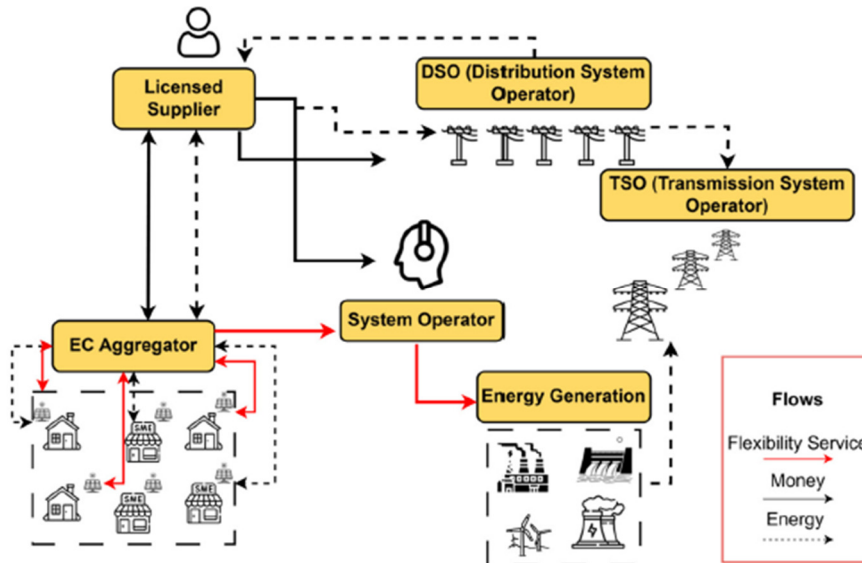


Figure 5: Aggregator business model archetype

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.

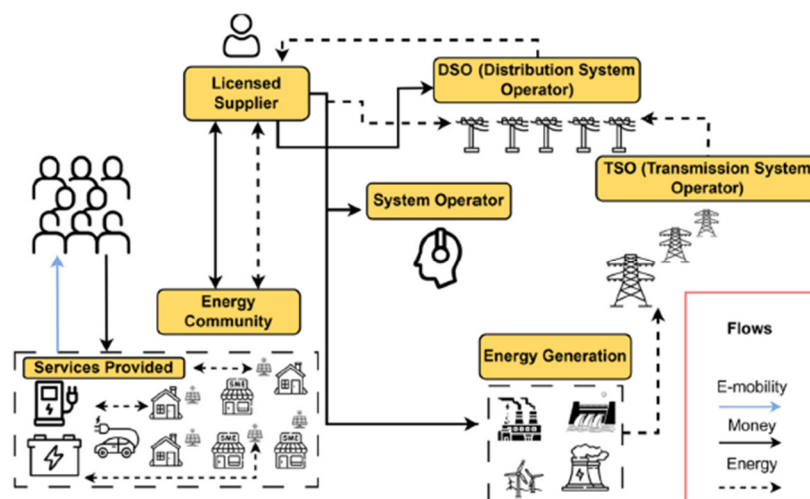


Figure 6: Integrated energy services and e-mobility business model archetype.

Energy Community Ownership Model and Funding Mechanisms

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) [50], [85]. One substantial barrier that almost all ECs need to overcome is finding the capital to finance their activities [86]. As Braunholtz-Speight T. et al. [87] 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". [87]. 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" [88].

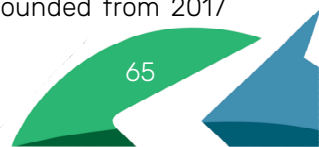
ECs funding mechanisms can take various forms, which can be categorized into four main types: (i) equity finance, consisting of shares that a community offers in exchange for ownership rights to the community or a project [49]; (ii) debt finance, which refers to the money that an EC borrows from another 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 [89]; (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 [52]. 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 [86]. 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. 7). 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 [47]. Consequently, other activities that could introduce inconsistencies and hinder comparability between the different ECs were deliberately excluded from the analysis.

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. 4).

Table 4
Eight Categories of ECs Based on Membership and Initiator Dimensions

Categories	Initiators	Membership	Number of EC in the sample
1	Citizens	Citizens	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. 4) and the funding mechanisms employed, it is noted that ECs initiated by citizens, which include public and/or private actors as members (Tab. 4, 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. 4, 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. 5, barriers 4-6). In contrast, barriers concerning crowdfunding and citizen participation are reported less often (Tab. 5, barriers 7 and 8).

Table 5
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	11





	plants; thus, it isn't easy to raise capital from equity shares	
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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. 5, 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.

Energy Community 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 [91], [92], [93], [94]. 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

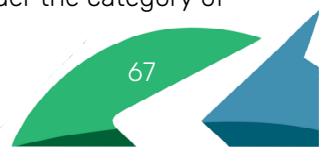
As already mentioned, the first stage of this research concentrates on the identification and categorization of the different types of barriers. To that end, ESR14 and ESR15 conducted a semi-structured literature review and desk research to identify papers and policy reports addressing EC barriers. The 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" [49]. 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. 6).

Table 6

Types of documents and references are utilized to identify and develop a categorization of ECs barriers.

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 higherorder 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. 8).

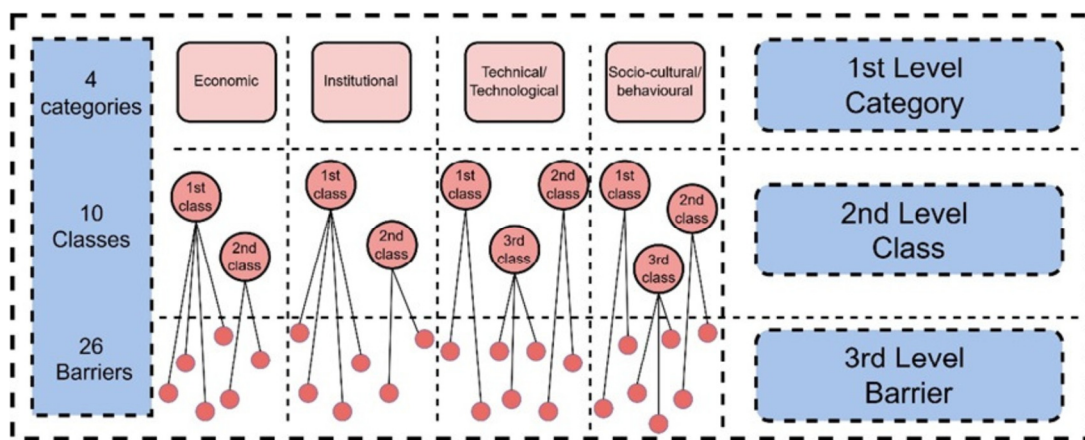


Figure 8: The three level categorization of barriers in current research

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.

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 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 management of ECs, such as smart meters, smart control systems, digital twins, etc.

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 sociocultural conditions, which refers to barriers resulting from the lack of socio-cultural conditions necessary for the development of ECs.

Table 7

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/Tech nological	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 ⁸ 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

EC barrier Validation

At this stage, ESR15 seeks to validate the previously presented barriers through a SLR utilizing the PRISMA 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. 8).

Table 8

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 8). 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 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

⁸ Not In My Back Yard (NIMBY)



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. 9).

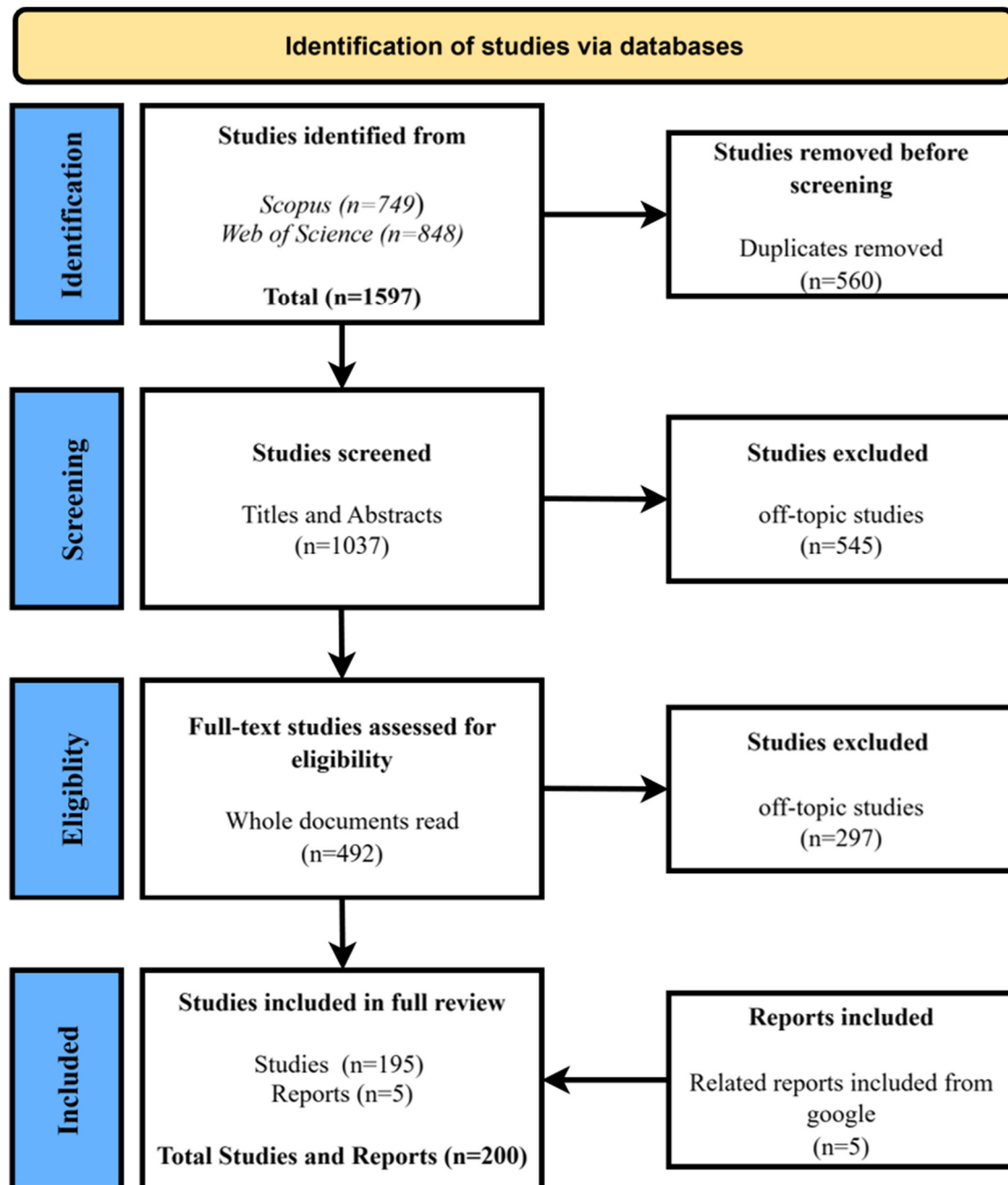


Figure 9: PRISMA diagram of paper selection on SLR

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. 10).

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.

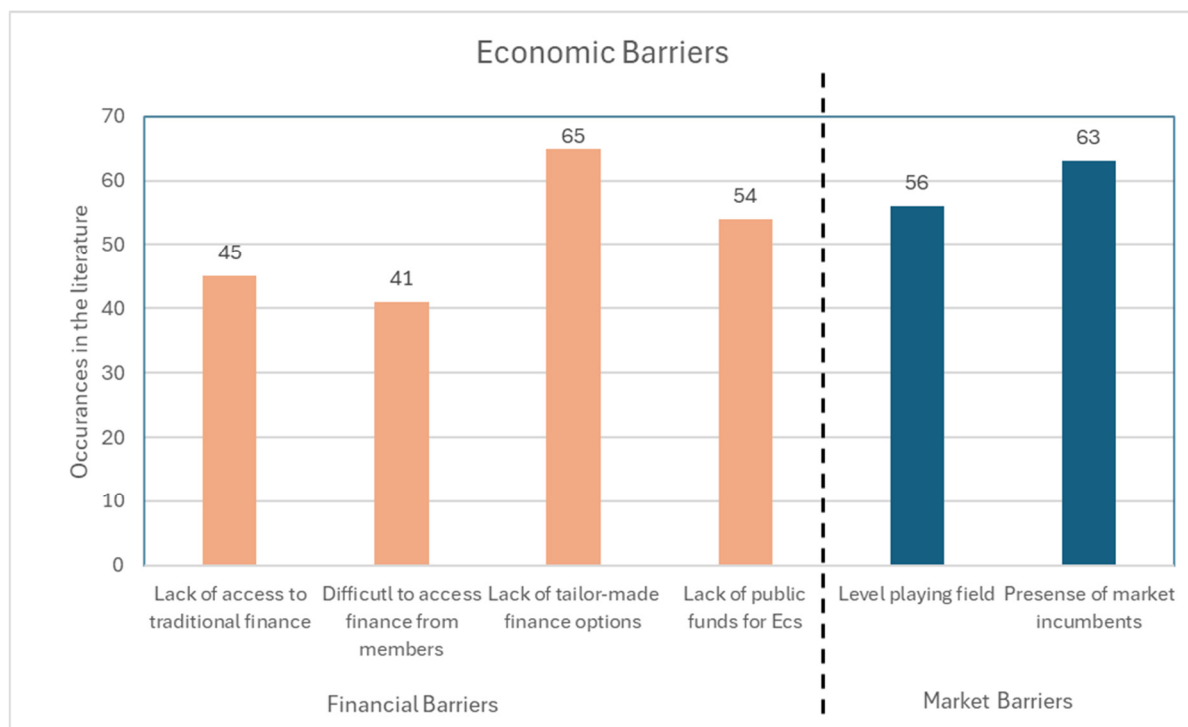


Figure 10: The frequency of occurrence of economic barriers identified in the literature.

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 11 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.



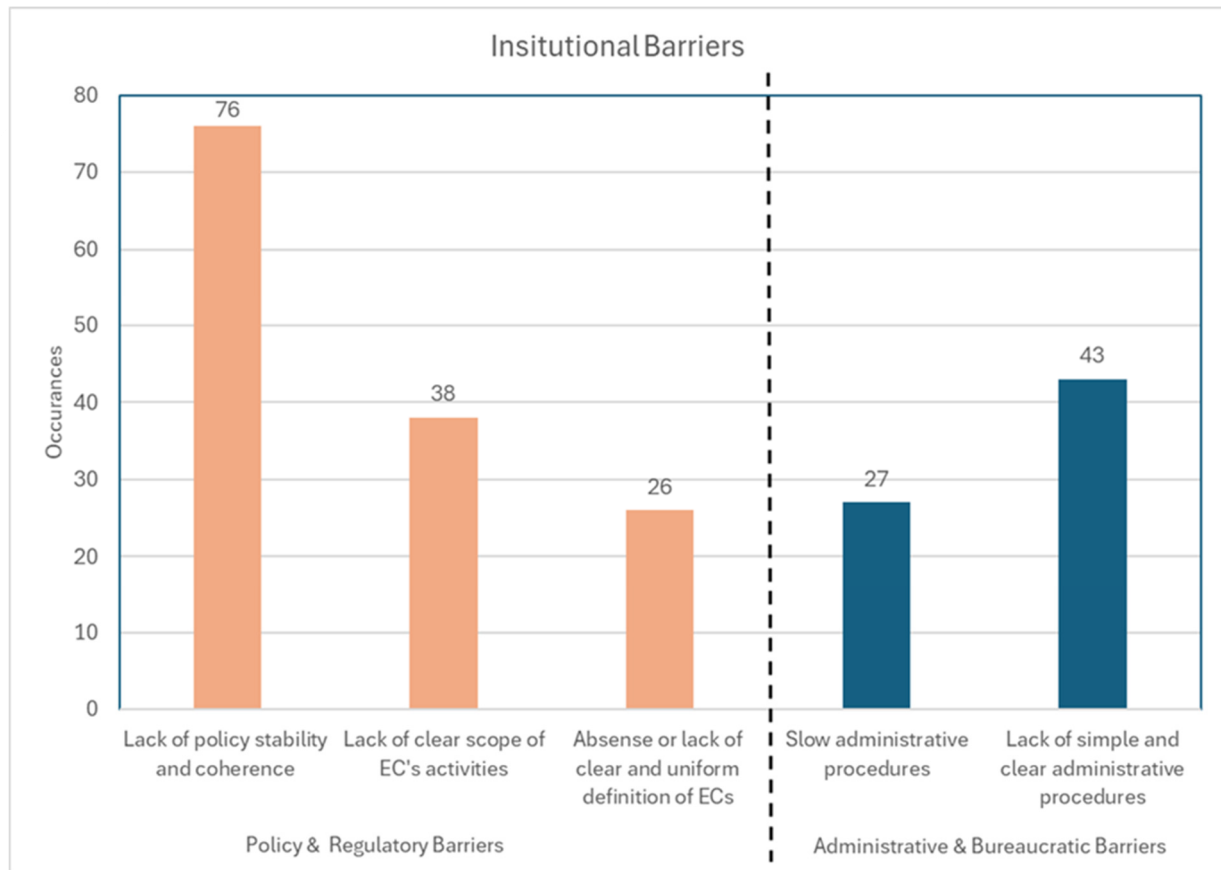


Figure 11: The frequency of occurrence of institutional barriers identified in the literature.

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. 12).

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.



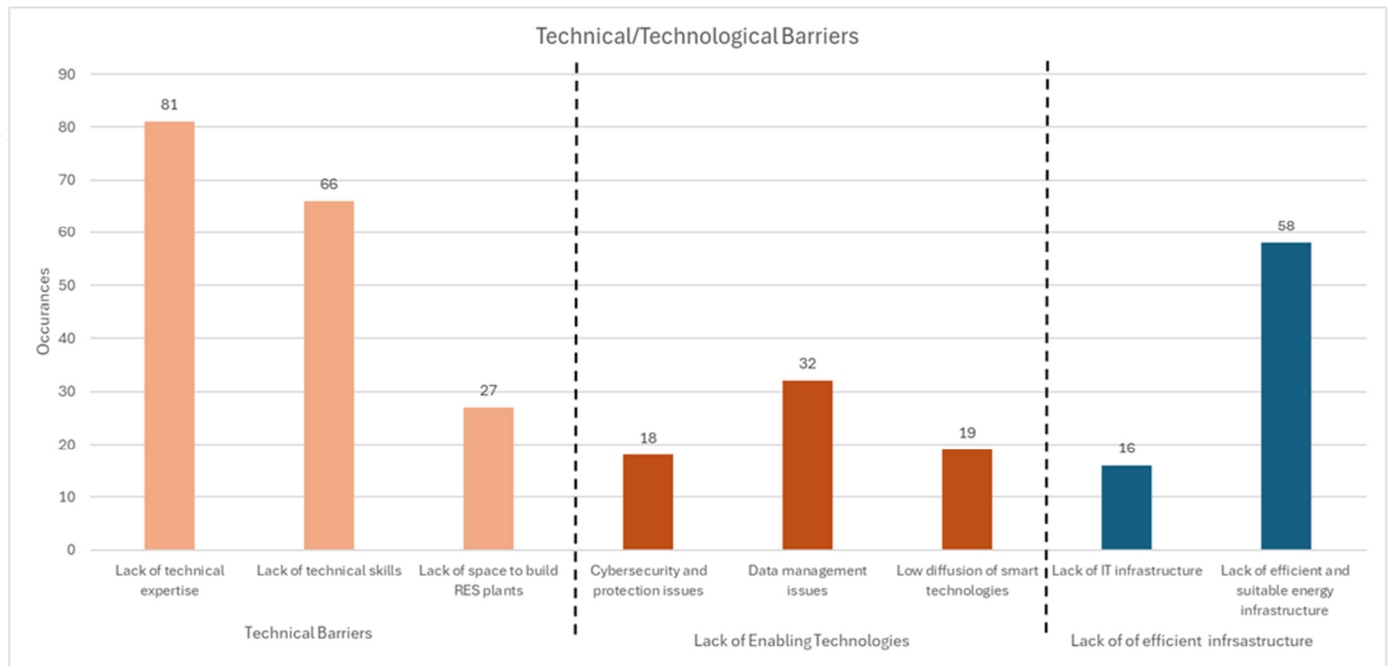


Figure 12: The frequency of occurrence of technical/technological barriers identified in the literature.

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.



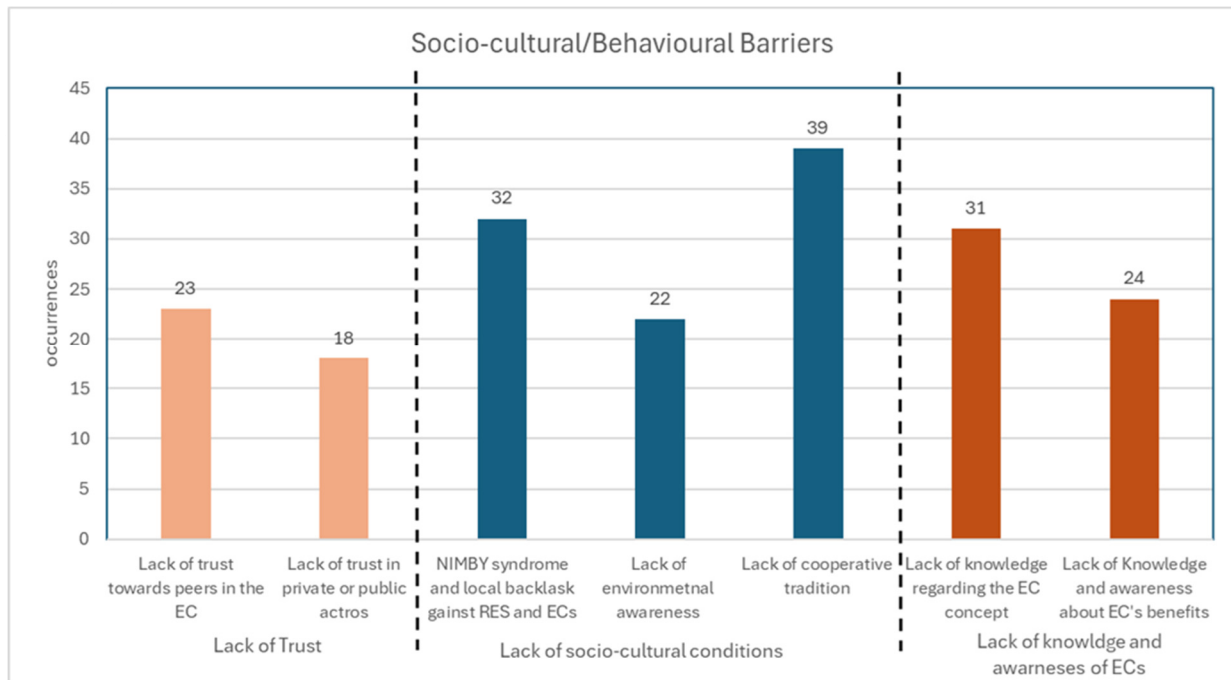


Figure 13: The frequency of occurrence of socio-cultural/behavioural barriers identified in the literature.

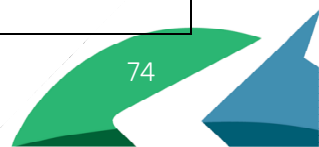
In summary, all the barriers are present in the literature, although they appear with varying frequencies. The barriers that appear more often in the literature are the lack of technical expertise, which appears in 81 documents, followed by the lack of policy stability and coherence, which has been cited 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. 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. 9).

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.

Table 9

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

Contribution to the WP objectives

ESR15's contribution focused 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.

Moreover ESR15's work focused on the investigation on 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.

Scientific achievements

Publication

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
1	Pantazis K., Croci, E., Molteni, T. (2023, October) Energy Communities in the EU: analysis of different ownership models and financing mechanisms, In 16th International Conference on Energy and Climate Change – Prometheus	Conference	Published	https://promitheasconference.wordpress.com/wp-content/uploads/2024/12/proceedings_2023_f.pdf
2	Pantazis K., Palaioyiannis F., Margosi M. (2025) Energy communities – lessons learnt, challenges and policy recommendations	Journal	Published	https://doi.org/10.1093/oenergy/oiaf002
3	Pantazis, K., Bagaini, A., Ahmed, S.M.M., Croci, E.) (2025) Energy Community Business Models Archetypes	Conference	Published	https://ieeexplore.ieee.org/document/11027308
4	Pantazis, K., Bagaini, A., Molteni, T., & Croci, E. (2025). Energy Communities in the EU: An analysis of Ownership, Funding Mechanisms, and Business Models	Book chapter	Published	https://www.smartgysum.eu/Home/Outcomes
5	Pantazis, K., Calderón, E. P., Montero P. M., Croci E., Molteni T., Analyzing research on energy communities: insights from a bibliometric literature review	Journal	Submitted	



Conclusions

In this final report on WP5 progress, ESRs' scientific outcomes and contribution to WP5 are summarized. Four ESRs were involved in WP5, working on different topics concerning green energy systems and business models.

ESR-12 worked on the development of sustainable strategies for Net Zero Energy Buildings (NZEBS) and energy communities, focusing on energy flexibility, smart appliances, user-centric energy awareness, and cooperative energy management. ESR-13 focused on the development of digital twins of prosumers, integrating technical, socio-economic, and behavioural factors to optimise energy consumption, enhance self-consumption, and support new business models. ESR-14 research topic focused on improving flexibility services for Energy Communities through innovative solutions such as EV charging infrastructure, techno-economic optimisation, and analysis of energy value chains and market mechanisms. ESR-15 worked on identifying enablers and barriers affecting the replicability of business models for green energy systems, with a particular focus on Energy Communities, including their ownership structures, financing mechanisms, and policy frameworks.

ESR-12 submitted 2 journal papers, 1 conference paper, and 1 book chapter. He also performed 2 secondments. ESR-12 contributed to WP5 by developing advanced optimisation models and flexibility assessment frameworks for NZEBs and energy communities, integrating economic, environmental, and user-comfort constraints. His work provided quantitative tools for energy management systems and supported the role of buildings as active and flexible participants in energy systems.

ESR-13 published 1 conference paper and performed 2 secondments. ESR-13 contributed to WP5 by designing and validating a multifactor digital twin framework capable of modelling complex prosumer systems under real-world constraints, including data scarcity. His work enabled scenario-based optimisation, integration of socio-economic factors, and the development of viable business models for digital energy solutions.

ESR-14 published 2 journal papers, 2 conference papers, and 1 book chapter, and performed 2 secondments. ESR-14 contributed to WP5 by bridging technical and economic aspects of distributed energy systems through the development of innovative services (e.g., EV charging stations), techno-economic feasibility analyses, and the identification of barriers and enablers for Energy Communities. His work supports scalable and sustainable business models and provides practical solutions for enhancing flexibility and reducing emissions.

ESR-15 published 1 journal paper, 2 conference papers, and 1 book chapter, and performed 2 secondments. ESR-15 contributed to WP5 by analysing Energy Community business models from a systemic and policy-oriented perspective, identifying key barriers (regulatory, financial, technical, and social) and proposing enablers and recommendations to support replication and scalability. His work strengthens the business and governance dimension of WP5 and supports the transition from technical solutions to real-world implementation.

Overall, the combined work of the four ESRs has significantly advanced WP5 objectives by integrating technical innovation, economic analysis, and policy insights. Their contributions provide a comprehensive framework for the development, optimisation, and replication of sustainable and collaborative energy systems, supporting the transition toward a more flexible, decentralised, and user-centric energy landscape.





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