Power System Technology
ISSN:1000-3673

Received: 16-06-2025 *Revised: 05-07-2025* *Accepted: 20-08-2025*

Planning and Operation of Renewable Energy Community Using Multi-Energy Systems: A systematic review

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Abstract: Renewable Energy Communities (RECs), especially when integrated with Multi-Energy Systems (MES), hold significant potential to support the global energy transition. Yet, their planning and operation remain fragmented, with limited methodological standardization and scarce attention to social dimensions. This study aims to systematically review the scientific literature (2010–2024) on the integration of MES in RECs to identify prevailing practices, reported benefits, and research gaps. A Systematic Review (SR) was conducted using Scopus, Web of Science, IEEE Xplore, and selected grey literature sources, resulting in 78 relevant publications. The results show that MES-enabled RECs can deliver environmental (e.g., CO_2 emissions reduction), economic (e.g., cost savings), and social (e.g., improved energy equity) benefits. However, significant challenges remain, particularly in consistently quantifying the impacts of decarbonization and modeling governance and social arrangements. To address this, we propose a conceptual classification that organizes the literature into four analytical dimensions: Approaches, Environment, Decarbonization, and MES. Each dimension captures technical, operational, environmental, and social aspects, offering a structured perspective on the field. This classification helps synthesize fragmented knowledge and inform future investigations. In conclusion, while RECs integrated with MES present promising pathways for decarbonization and improved community well-being, the field would benefit from more critical, inclusive, and methodologically robust studies that better capture social complexity and long-term sustainability.

Keywords: *Systematic Review, Multi-Energy Systems, Renewable Energy Communities, Decarbonization.*

1. Introduction

Access to modern, reliable, and sustainable energy is essential for socioeconomic development and environmental protection, particularly in vulnerable and remote communities that continue to face challenges of energy exclusion [1,2]. According to the World Health Organization, approximately 733 million people still lack access to electricity, and without urgent action, an estimated 670 million will remain without access by 2030 [3]. In response to this global energy gap, international policies and initiatives have been mobilized to accelerate the transition to clean energy systems, aligning with the Sustainable Development Goals (SDG 7 – Affordable and Clean Energy; SDG 13 – Climate Action) and the European Union's guidelines on decarbonization and citizen empowerment through renewable energy [4–6].

Within this context, Renewable Energy Communities (RECs) have emerged as decentralized, participatory, and cooperative models for the production and consumption of clean energy. RECs are based on three core pillars: decentralization and localization of energy production; self-generation and collective consumption; and direct consumer involvement [7,8]. These

Power System Technology
ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

communities not only democratize access to energy but also support energy transition strategies, particularly when aligned with regulatory frameworks that enable energy sharing and peer-to-peer (P2P) trading [9–12]. On the other hand, Multi-Energy Systems (MES), which integrate multiple energy vectors such as electricity, heating, cooling, transport, and fuels, enhance the operational flexibility and efficiency of RECs, thereby expanding their decarbonization potential [13,14].

Despite the significant growth of literature on RECs and MES over the past decade, this field of study remains fragmented. Notable gaps include the absence of standardized assessment metrics, the scarcity of classification, and the limited integration of social and territorial dimensions. Considering this scenario, it is crucial to promote critical and systematic analyses that consolidate existing knowledge and guide the implementation of more inclusive, effective energy communities aligned with global decarbonization goals.

This paper develops a Systematic Review (SR) covering the period from 2010 to 2024, with the objective of identifying, classifying, and synthesizing scientific contributions related to the integration of MES into RECs, as well as the planning and operationalization of these communities. Based on a selection of 78 studies, the article proposes a conceptual classification comprising four key dimensions: Approaches, Environment, Decarbonization, and Multi-Energy Systems. This classification provides insights to support further academic investigations and practical applications in energy planning. Moreover, the study highlights significant gaps related to the quantification of decarbonization, the organization of social arrangements, and the enhancement of P2P energy trading. The remainder of this article is structured as follows: Section 2 presents the methods, that included the definition of research questions; Details the methodology applied in the mapping process; Describes the filtering and selection criteria; Section 3 shows the results and discusses the findings; Presents the conceptual classification; Section 7 outlines the main analyses, conclusions and future research directions.

2. Methods

2.1. Definition of Research Questions

In this section, we employ the SR methodology, as described by Ahmad et al. [15], Aliero et al. [16] and Werner de Vargas et al. [17], to conduct a comprehensive literature review. The objective is to investigate the approaches involving RECs alongside MES. The SR is a valuable tool for exploring a research area, enabling the identification of the quantity and frequency of publications over time, as well as trends, research types, and key findings.

The SR follows a sequence of steps: definition of research questions, execution of the research process, data filtering, and presentation of results and analyses. In this study, four general questions (GQ) and four specific questions (SQ) were defined. The general questions aim to explore fundamental information about the integration of MES in the context of RECs. In contrast, the specific questions seek to understand the quantitative details related to the application of MES for the planning and development of RECs. Table 1 presents the questions defined for the mapping, organized into four general questions and four specific questions.

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ISSN:1000-3673

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Type	Research Questions
	General Question
GQ.1	What are the approaches involving renewable energy communities?
GQ.2	What impacts do renewable energy communities generate for their members?
GQ.3	What are the methods for qualifying or quantifying the decarbonization of energy systems?
GQ.4	What are the approaches involving multi-energy systems in energy communities?
	Specific Question
SQ.1	What are the objectives of a renewable energy community?
SQ.2	What are the energy components within renewable energy communities?
SQ.3	How are the social arrangements of energy communities addressed?
SQ.4	How are the Peer-to-Peer energy transactions conducted within renewable energy communities?

Table 1 - Presentation of Research Questions

These questions were developed to provide a broad and detailed understanding of the role of RECs and MES in promoting sustainable energy systems and improving the quality of life in isolated communities. The analysis of these questions will enable the identification of best practices, gaps in the existing literature, and opportunities for developing replicable solutions in similar contexts.

2.2. Research Process

This study conducts a systematic literature review focused on RECs and MES. The research process was carried out until July 2024, utilizing the Scopus and Web of Science databases. These databases were selected due to their extensive coverage of academic articles and inclusion of major academic publishers, such as Elsevier, IEEE, and Springer [18,19]. Additionally, IEEE Xplore was consulted separately using the exact search string applied to the other databases, and it was verified that all relevant articles retrieved were already indexed in Scopus. A grey literature search was also conducted following recommended practices, including the analysis of reports, theses, institutional publications, and documents available on web pages from reputable organizations. This approach aimed to complement peer-reviewed sources and minimize potential selection bias.

2.2.1. Selection of Keywords and Search Strings

The research process began with defining initial keywords relevant to the study. The keywords included terms such as: *Sustainable Energy Communities, RECs, Mathematical Modelling, Multi-energy Systems Mathematical, Algorithm, Optimization, Renewable Energy Resources, Peer-to-Peer (P2P), Social Arrangements of Energy Communities, Distributed Energy Resources, Decarbonization, Decarbonization of the Energy System,* and *Decarbonization Index.* Initially, a general search string was created to perform searches in the databases. The

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ISSN:1000-3673
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initial search yielded a total of 8,340 studies, with 7,385 in Scopus and 955 in Web of Science. The general search string used is described in Table 2.

Search String	Scopus	Web of Science
ALL= (("sustainable energy communities*" OR "renewable energy communities*" OR ("sustainable*" AND "energy communities*") OR ("renewable*" AND "energy communities*")))	6678	942
ALL= (("sustainable energy communities*" OR "renewable energy communities*" OR ("sustainable*" AND "energy communities*") OR ("renewable*" AND "energy communities*")) AND ("multi-energy system*"))	707	13

Table 2 – Results obtained using the general string.

2.2.2. Refinement of the Search String

The refinement of the search string was carried out using a frequency-based approach inspired by Pareto's Law (80/20 rule). This heuristic assumes that a small subset of terms (approximately 20%) is responsible for the majority (around 80%) of the thematic relevance in a given set of studies. In this context, the frequency distribution of the keywords derived from the initial search results was analyzed, identifying the most frequently recurring terms as those most representative of the field. This method enabled the prioritization of core concepts and the elimination of redundant or marginal terms, thereby enhancing both the focus and efficiency of the search strategy. Next, these high-frequency terms were compared to the original list of keywords. Terms that matched or were conceptually similar were retained in the new refined search string. Table 3 presents the databases used, the search strings applied, the search periods, document types, and the number of studies retrieved using the refined strategy. This process resulted in a total of 676 studies: 19 from Web of Science and 657 from Scopus.

Databases	Scopus	Web of Science	Studies Found	
Search String	ALL (((("multi-energy system*") AND ("sustainable energy communities*" OR "renewable energy communities*"))))	ALL (((("multi-energy system*") AND ("sustainable energy communities*" OR "renewable energy communities*"))))	168	5
	ALL (((("multi-energy system*") AND ("sustainable energy communities*" OR "renewable energy communities*") AND ("optimization*" OR "mathematical modelling*" OR "mathematical programming*" OR "mathematical optimization*"))))	ALL (((("multi-energy system*") AND ("sustainable energy communities*" OR "renewable energy communities*") AND ("optimization*" OR "mathematical modelling*" OR "mathematical programming*" OR "mathematical optimization*"))))	152	1

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	ALL (((("multi-energy system*") AND ("sustainable energy communities*" OR "renewable energy communities*") AND ("decarbonization *" OR “social arrangements*" OR "zero carbon*" OR " CO_2*"))))	ALL (((("multi-energy system*") AND ("sustainable energy communities*" OR "renewable energy communities*") AND ("decarbonization *" OR “social arrangements*" OR "zero carbon*" OR " CO_2*"))))	66	2
	ALL (((("sustainable energy communities*" OR "renewable energy communities*") AND ("decarbonization *" OR “social arrangements*" OR "zero carbon*" OR " CO_2*") AND ("optimization*" OR “mathematical modelling*” OR “mathematical programming*” OR “mathematical optimization*"))))	ALL (((("sustainable energy communities*" OR "renewable energy communities*") AND ("decarbonization *" OR “social arrangements*" OR "zero carbon*" OR " CO_2*") AND ("optimization*" OR “mathematical modelling*” OR “mathematical programming*” OR “mathematical optimization*"))))	271	11
Search Period	From January 2010 to July 2024	From January 2010 to July 2024		
Document type	Article, conference paper, and review	Article, proceedings paper, and review		

Table 3 – Investigation process and results using the second search string.

The search period was defined as January 2010 to July 2024 to capture the recent evolution of research and ensure the relevance of the studies included. This period is suitable for addressing emerging trends and technological advancements in the field of RECs and MES

2.2.3. Filtering Process

After the initial research, the process of filtering the articles began to ensure the relevance and quality of the selected studies. The filtering process followed the criteria below:

Inclusion Criteria (IC)

IC 1: The selected works must be published in journals and must be Articles, Reviews, Conference Papers, and Proceedings Papers.

IC 2: The works must be full articles and/or literature reviews, application of techniques in real systems, experiments, and/or simulations.

IC 3: The works must address the main terms of the research: Sustainable Energy Communities, RECs, Mathematical Modelling, Multi-energy Systems, Mathematical Algorithm, Optimization, Renewable Energy Resources, Peer-to-Peer, Social Arrangements of Energy Communities, Distributed Energy Resources, Decarbonization, Decarbonization of the Energy System, and Decarbonization Indices.

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IC 4: Consider additional works that are already known to the authors and were not found in the searches but are relevant to the study.

Exclusion Criteria (EC)

EC 1: Duplicated works.

EC 2: Works not published in English.

EC 3: Works in non-accepted formats, such as theses, dissertations, book chapters, presentations, slides, and posters.

EC 4: Works published before 2010, except for materials crucial to the study.

EC 5: Works that do not involve Multi-energy Systems and RECs.

EC 6: Works that do not answer any of the established research questions.

Filtering Steps

The reading and selection of studies were carried out in accordance with the established inclusion and exclusion criteria, and then a three-step approach, as outlined by Keshav (2007) [21], was applied. The following steps were performed:

Initial Reading: A quick review of the titles, abstracts, and introductions was conducted to provide an overview, excluding duplicate and irrelevant studies. After this step, 642 studies were selected. Detailed Reading: A more thorough reading was done to identify articles that met the inclusion and exclusion criteria. After this step, 225 articles remained. Re-implementation: In this step, an attempt was made to replicate the results of the articles, considering additional exclusion criteria. This stage required a more in-depth analysis, which led to the final selection of 78 relevant studies for the mapping. By applying these criteria and processes, 78 studies were selected to form the database for the systematic literature mapping. Appendix A presents a table with the questions addressed by the studies, the publication journal, the authors, and the type of study.

3. Results

3.1. General Questions

3.1.1. GQ.1 What are the approaches that involve renewable energy communities?

To answer this and the following questions, 225 articles were analyzed, of which 78 addressed one or more related questions. Based on the literature review conducted in this mapping, it was observed that various approaches interact with RECs and/or MES, and can be classified as either operational or planning-oriented. Figure 1 presents a conceptual map that summarizes the 75 studies identified in Research Question GQ.1, organizing them according to the approaches adopted. On the left side of the Venn diagram are the studies with an operational

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focus, addressing topics such as energy resource management strategies, generation forecasting, system sizing, and real-time operation. On the right side are the studies with a planning focus, emphasizing the potential creation of RECs, impact analysis (such as cost minimization, CO_2 emission reductions, and effects on the electrical grid), configuration comparisons, and guidelines for future implementation. The intersection between the two circles represents studies that address both operational and planning perspectives, such as those by Weckesser et al. (2021) and Corsini et al. (2023), which combine short-term strategies with long-term structural projections. Thus, the figure provides a clear visualization of how the literature has applied these approaches to RECs and MES, allowing the identification of trends, gaps, and complementarities in the field.

Figure 1 – Conceptual map containing the summary of solutions for the approaches involving RECs.

The results presented in Figure 1 indicate that most studies adopt the operational approach, with 36 articles. The approaches identified focus on strategies aimed at enhancing economic advantages, load allocation to reduce peak-hour consumption, and increasing self-sufficiency, as observed in the works of Cielo et al. [20], Moncecchi et al. [21], Weckesser et al. [22], and Ceglia et al. [23].

Another common characteristic among these studies is the use of linear programming models Cosic et al. [24], Weckesser et al. [22], Ceglia et al. [23], Velkovski et al. [25], Manso-Burgos et al. [26], and Cielo et al. [20]. In this context, Comodi et al. [27] explore the concept of local energy communities to reduce carbon footprints through district-level energy planning strategies. Their approach seeks solutions to challenges related to the efficient management of energy in urban districts. To this end, the authors develop an optimization model based on MILP, which proves effective in evaluating different proposed scenarios. These scenarios are constructed based on local energy consumption reduction targets, aiming to decrease carbon emissions. The results demonstrate that thermal storage technologies and district cooling

Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

networks perform better in warm climates. Additionally, PV generation and trigeneration plants significantly contribute to achieving energy consumption reduction targets of 10% and 20%.

Similarly, Cosic et al. [24] propose an integrated optimization approach to investment planning and technology operation within energy communities. The strategy is based on an MILP model that considers the allocation of distributed resources and the definition of decision variables. As in the study by Manso-Burgos et al. [26], different tariff scenarios are analyzed, considering an annual time horizon. The main innovation of Cosic et al. [24] lies in the introduction of renewable energy transfer nodes, combined with time-of-use tariffs, which enable energy exchange among community members.

In turn, Weckesser et al. [22] apply a method that evaluates different configurations for energy communities. The sizing and capacity of PV systems and BESS are analyzed through various operational strategies, such as maximizing economic advantages, reducing energy transfers with the grid, and maximizing energy self-sufficiency, considering scenarios both with and without battery taxation. Furthermore, the community impact is assessed according to the type of application area, considering urban, suburban, and rural networks. Likewise, Ceglia et al. [23] developed potential scenarios for a REC in an Italian city, utilizing programmable renewable energy resources (biomass, hydropower) and non-programmable resources to meet electricity and heating demands.

This approach is exemplified by the study by Tostado-Véliz et al. [25], who developed advanced energy management strategies for 100% renewable, isolated communities, coordinating individual (controllable devices and small generators) and collective (wind turbines and batteries) assets, as well as peer-to-peer (P2P) transactions between prosumers. The optimization problem was organized into three stages: the first managed individual household energy, the second dealt with energy exchanges between prosumers, and the third addressed the scheduling of collective assets. Velkovski et al. [25] proposed an MILP optimization model for a REC consisting of local generators, BESS, EV, heat pumps, and thermal energy storage, forming an integrated local multi-energy system. The objective was to examine the impact of different tariff structures on the operational parameters of the distribution network.

Moncecchi et al. [21] describe a user management strategy for energy communities that allows the joint participation of users and generators. Delivery points are considered for both passive participants connected to the grid and for generators, which may be linked to their own delivery point or a delivery point associated with these users. The adopted approach contemplates three modes of operation for users: (i) self-consumption, where energy production and consumption occur at the same delivery point; (ii) shared, where energy generated by a community generator is consumed by participants connected to different delivery points; and (iii) purchase, which occurs when the production from community generators is insufficient to meet participants' demand, requiring the purchase of energy from the grid.

Manso-Burgos et al. [26] develop a mathematical model based on MILP to explore concepts of local energy communities and to evaluate different tariff scenarios. The adopted case study

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ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

defines the location and size of the community, allowing the characterization of consumption points. Based on this definition, various operating scenarios are simulated, and energy-sharing strategies are applied, taking into account the effects of tariff regulations. The study aims to analyze the implementation of the new Spanish regulatory system, highlighting the importance of such studies for evaluating the economic performance of local energy communities.

Gjorgievski et al. [28] examine the social arrangements, technical designs, and societal implications of Community Energy Regimes (CERs). They review the technical aspects of various local energy systems, considering the goals of CER members and external stakeholders. Furthermore, they compare the methods and constraints used in the planning process, quantifying the economic, environmental, technical, and social impacts of energy communities. Baigorrotegui et al. [29] focus on community repair practices in Puerto Edén, Chile, an off-grid region, where residents themselves carry out the maintenance and restoration of local energy systems. This type of REC is structured around collaborative practices, empirical knowledge, and the use of available materials, prioritizing the continuity of energy access in the absence of technical and institutional support.

Cielo et al. [20] argue that energy communities should rely on properly sized PV generation and energy storage systems to enhance self-consumption and self-sufficiency, as well as to reduce greenhouse gas emissions. To achieve this, they developed a methodology based on MILP combined with multi-criteria optimization, applied to the evaluation of different system sizes and configurations, considering efficient performance and the Pareto front. Gjorgievski et al. [28] present a comprehensive literature review aimed at understanding energy communities in the contexts of social arrangements, technical designs, and associated impacts. Among the main findings, the authors discuss the different types of participants, their interactions, and their roles within the community.

The analysis of the results presented in Figure 1reveals a predominance of operational approaches, highlighting the priority of addressing immediate technical challenges in the management of RECs. In contrast, planning and hybrid approaches emphasize the importance of long-term strategies, which are crucial for ensuring the sustainability of these communities. This dichotomy highlights the need for closer integration between strategic planning and daily operations, with the goal of aligning immediate solutions with long-term objectives. Moreover, an interdisciplinary approach, encompassing technical, economic, social, and environmental aspects, could aid in maximizing RECs as a response to global energy and sustainability challenges.

3.1.2. GQ.2 What Impacts Do Renewable Energy Communities Generate for Their Members?

The analysis of the 66 identified studies reveals that RECs generate a wide range of economic, environmental, and social benefits for their members. Figure 2 presents a conceptual map that organizes these impacts into three main goals: economic (such as reducing electricity costs, increasing energy self-sufficiency, and enabling the sale of surplus energy), environmental (mainly through the reduction of CO_2 and other greenhouse gas emissions), and social (with

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ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

emphasis on alleviating energy poverty). The overlapping areas in the Venn diagram indicate synergies between these dimensions, highlighting that many studies report multidimensional benefits. For instance, works such as Ahmed et al. (2024) appear at the intersection of all three domains, suggesting integrated approaches. However, the figure also reveals a thematic imbalance, as social impacts, particularly those related to equity and poverty reduction, are less frequently explored in the literature compared to economic and environmental benefits. This conceptual representation illustrates the plurality and interconnection of REC benefits, rather than linking them to specific projects, reinforcing their potential as tools for a just and sustainable energy transition.

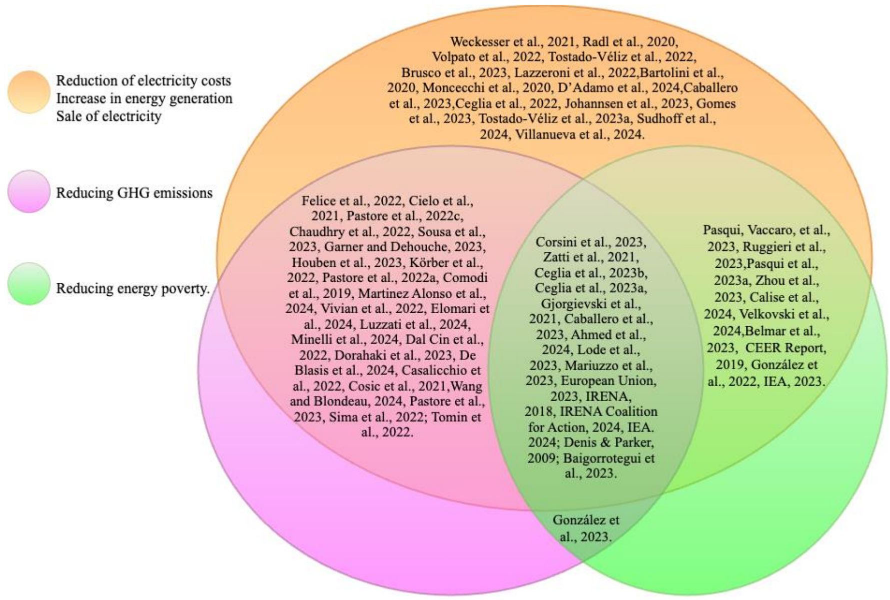

Figure 2 – Conceptual Map Summarizing the Impacts of RECs for Consumers.

Studies focusing on the social benefits of RECs indicate that they help reduce energy poverty by providing access to high-quality energy for individuals with unreliable or no access to electricity. For instance, Ruggieri et al. [30] analyzed a public REC with a PV system installed in an educational institution, demonstrating that, beyond economic benefits such as reduced electricity costs, the community generated significant social benefits, directly addressing energy poverty and providing local social services. Regarding economic benefits, several studies highlight that RECs lower total electricity costs for both prosumers and conventional consumers. Even individuals without PV systems can access energy generated by the community. Another significant benefit is the ability to share generated energy, which enhances the self-sufficiency of members, as observed in Lazzeroni et al. [31]. In this setup, surplus energy can be sold to the grid, further reducing energy purchase costs from utility companies. Environmental benefits are also widely reported. Since RECs typically generate energy from renewable sources such as solar PV, wind, and biomass, there is a significant reduction in CO_2 and other greenhouse gas emissions.

Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

Environmental benefits are documented in most studies, particularly due to the adoption of renewable energy sources, resulting in a significant reduction of CO_2 and other greenhouse gas emissions. The literature shows that substantial CO_2 reductions occur when RECs are implemented in communities, as renewable energy replaces grid electricity or fossil-based sources. However, although REC benefits are well documented, the literature often focuses on aggregated outcomes without sufficiently analyzing how these benefits are distributed among participants. For example, “prosumers” tend to benefit more than passive consumers, who may lack the financial means to install generation systems or participate in governance processes. This raises concerns about equity and inclusion, which are often underexplored.

Additionally, reported impacts are sometimes presented without a critical assessment of potential trade-offs. For example, maximizing economic returns through energy sales may conflict with goals of community-level self-sufficiency or equitable access. To address these gaps, future research should adopt equity-oriented evaluation frameworks that capture both qualitative and quantitative impacts across different user profiles. Furthermore, stronger integration of environmental and social metrics into REC performance assessments will be essential to ensure that these communities promote not only decarbonization but also justice and resilience in the energy transition.

3.1.3. GQ.3 What Are the Methods to Qualify or Quantify the Decarbonization of Energy Systems?

Among the 78 studies reviewed, only 19 explicitly address methods for quantifying or qualifying decarbonization in RECs, making this the least developed topic in this mapping. Figure 3 presents a conceptual map that summarizes the main methods used to account for carbon emissions in RECs, categorizing the studies by the emission sources considered. These categories include emissions associated with grid electricity consumption, natural gas use, primary energy consumption, PV system manufacturing and use, and battery production and application. The overlapping areas indicate multi-source approaches, where studies combine operational emissions with those embedded in energy technologies. For example, studies such as Tomin et al. (2022) and Brauer et al. (2022) consider multiple emission sources simultaneously, reflecting efforts toward a more holistic assessment of RECs’ climate impacts. However, the figure also reveals significant methodological diversity, with most studies relying on direct CO_2 estimates related to grid electricity or primary energy use. Thus, the diagram highlights not only the most assessed emission sources but also gaps and opportunities for developing more comprehensive and standardized methods for evaluating decarbonization in RECs.

Power System Technology
ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

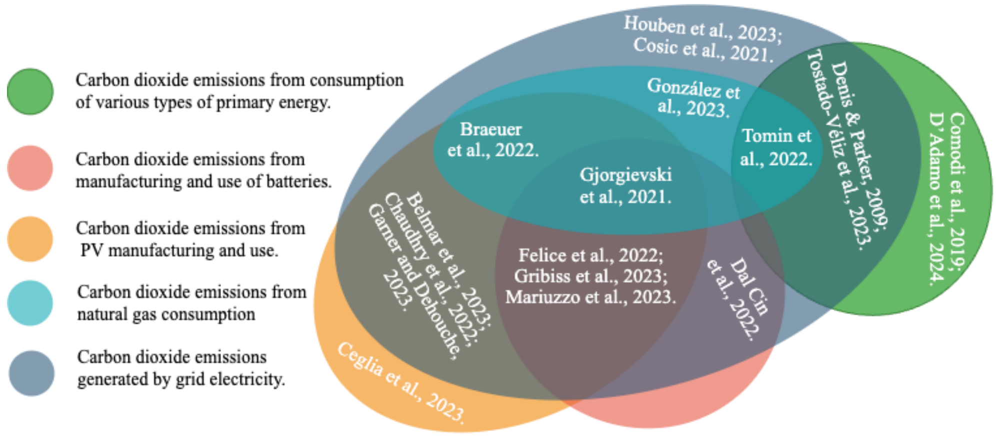

Figure 3 – Conceptual map containing the summary of ways to quantify and/or qualify the decarbonization of energy systems.

For instance, Felice et al. [9] illustrate this approach by estimating the annual CO_2 emissions per kWh consumed, calculated as the sum of emissions from grid electricity imports and annualized emissions associated with the manufacturing of PV and BESS systems, based on their installed capacity. Houben et al. [32] focus exclusively on the costs of CO_2 emissions generated by grid electricity in each analyzed period. Mariuzzo et al. [33] apply Life Cycle Assessment (LCA) to assess emissions based on the total installed capacity of each energy generator and storage system, multiplied by the respective LCA emission factors for renewable generators and electrochemical batteries. Net grid emissions are calculated as the difference between the total energy demand of all users and the amount of energy shared within the community.

Comodi et al. [27] quantify and qualify decarbonization through a model that applies primary energy consumption constraints, using this metric as the primary focus. These consumption constraints allow for the evaluation of the trade-off between economic solutions and alternatives that consider carbon emissions. Additionally, the study employs scenario simulations to examine decarbonization efforts and includes targets for consumption reduction. One of the advantages identified is the use of real demand data, which supports the model's application in various contexts. Cielo et al. [20] adopt key performance indicators (KPIs) to quantify and qualify the decarbonization of energy systems. These indicators assess the self-consumption and self-sufficiency indices, which are relevant for measuring the efficiency and environmental impact of communities. The authors apply KPIs in an hourly energy balance, reducing the energy flow to the grid through the application of MILP.

Gjorgievski et al. [28] observe that research involving renewable communities aims to quantify and qualify the decarbonization process in terms of environmental impacts. This impact is treated as an indicator, considering life cycle emissions, particulate matter emissions, and gas releases from cooling systems. Cosic et al. [24] incorporate a metric into the mathematical model formulation to quantify CO_2 emissions, calculating them on an annual basis.

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ISSN:1000-3673
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Few studies go beyond these approaches, neglecting temporal and spatial variability, which are essential for a more precise analysis. The carbon intensity of the electricity grid varies significantly between regions and over time due to factors such as seasonality, energy mix, and demand patterns. This lack of consideration limits the accuracy of the results and the ability to compare RECs in a robust manner. Furthermore, the analyses do not incorporate uncertainties or sensitivity, a gap that undermines the usefulness of the findings. The absence of detailed spatial analysis also hinders adequate differentiation of emissions between regions with different climatic conditions and infrastructures. Climatic variability, including extreme events and seasonal patterns, is not considered, which weakens the models' ability to reflect local realities accurately. Sensitivity and uncertainty studies are crucial for enhancing the reliability of the results.

To address these gaps, it is crucial to adopt more dynamic and spatially explicit LCA methodologies that incorporate both direct and embodied emissions. Additionally, it is necessary to consider temporal variability and regional differences in the carbon intensity of the electricity grid. The use of regional data and the consideration of extreme climate events are essential steps for a more accurate and contextualized analysis. Including sensitivity studies and uncertainty modeling will enhance the robustness of the analyses, facilitating a better understanding of the factors that impact decarbonization. Finally, methodological standardization and transparency are critical to ensuring comparability between studies and the applicability of the results in diverse contexts. These approaches should align with international sustainability goals, such as SDGs 7 and 13, and ensure that the benefits of RECs are distributed equitably, particularly to communities with limited resources.

3.1.4. GQ.4 What Are the Approaches Involving Multi-Energy Systems in Energy Communities?

Figure 4 presents a conceptual map based on 45 studies exploring the integration of MES within RECs. These systems combine different energy vectors, such as solar, wind, biomass, natural gas, hydrogen, and thermal energy, with storage technologies like BESS and EVs. The map highlights the frequent co-occurrence of photovoltaic energy, the electric grid, thermal systems, and storage, indicating a dominant trend toward hybrid electric-thermal configurations. Less common, but still relevant, are systems incorporating hydrogen, biomass, and natural gas, often used in isolated or backup scenarios. The overlaps illustrate both the synergistic potential of integrating diverse resources and the operational complexity involved. Overall, MES integration is emerging as a key strategy to enhance energy flexibility, self-sufficiency, and resilience at the community level.

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ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

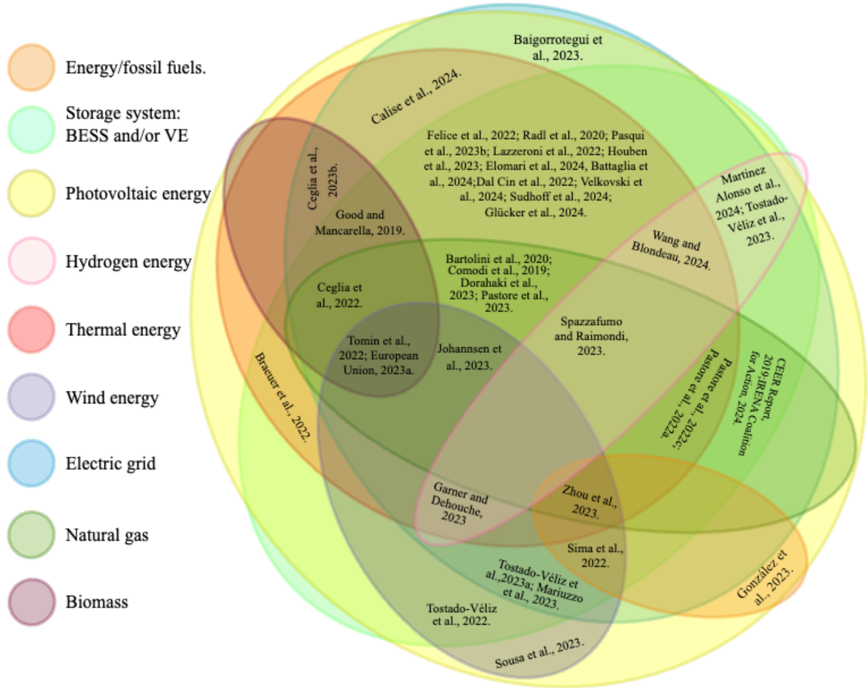

Figure 4 – Conceptual Map of Approaches Involving Multi-Energy Systems in Energy Communities.

Comodi et al. [27] propose an approach based on the use of different energy vectors, such as electricity, heating, and cooling, structured through the concept of energy hubs. Their study highlights that the simultaneous generation of multiple energy systems significantly contributes to reducing carbon emissions. Complementarily, Good and Mancarella [34] advocate for the strategic use of multi-energy systems, combining operational and technical aspects to increase flexibility, enhancing the economic efficiency of services in competitive markets, and strengthening local energy management. In this context, Gjorgievski et al. [28] note that the studies analyzed not only seek to integrate multiple energy sources within communities but also develop strategies to optimize the interaction among the various elements involved, such as generation sources, storage systems, and associated technologies. These initiatives aim to efficiently meet local energy demand, in alignment with the principles of sustainable development.

Other studies emphasize the benefits of MES for balancing supply and demand in decentralized settings. Felice et al. [9] examine the effects of electricity tariffs and implementation costs on RECs, focusing on renewable generation and storage systems, including BESS, EVs, and controllable heat pumps. Their study assesses the economic feasibility and CO_2 emissions of RECs, showing that the flexibility and integration of diverse energy sources enhance operational efficiency and community sustainability. [38] Tostado-Véliz et al. [35] expand the discussion by incorporating wind and PV generation into a multi-energy system for an isolated REC with a 100% renewable matrix. Their study employs advanced energy management

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ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

strategies to coordinate REC agents, using a community BESS to improve system reliability. Zhou et al. [36] analyze a combination of multiple energy sources in an energy community utilizing both renewable sources and fossil fuels. Their study highlights the role of various technologies, including wind turbines, solar panels, gas turbines, gas boilers, heat pumps, and electrical and thermal storage systems, in configuring a complex multi-energy system. Martinez Alonso et al. [37] investigate the potential of hybrid multi-energy system models, including hydrogen, to optimize energy dispatch in off-grid environments. Their study minimizes both operational costs and greenhouse gas emissions, promoting efficient energy flows between renewable sources, storage devices, and electrical loads.

Despite the consistent emphasis on the technical and environmental benefits of MES, the studies reviewed present contrasting perspectives on key aspects of their implementation. One major point of divergence concerns the role of fossil fuels: while Zhou et al. [36] include them as complementary sources within transitional strategies, others, such as Tostado-Véliz et al. [35], propose fully renewable configurations. This highlights a lack of consensus regarding the trade-offs between short-term reliability and long-term decarbonization goals. There are also variations in methodological depth: some studies adopt complex multi-criteria optimization models, while others rely on more simplified techno-economic analyses, with limited attention to governance structures or user behavior. Another important aspect that warrants attention is the sociotechnical and regulatory dimension, which appears to be less explored in part of the reviewed literature. Although most publications assess the technical and economic feasibility of MES in RECs, aspects such as public policy mechanisms, institutional arrangements, and stakeholder engagement are not addressed with the same frequency or depth. Moreover, while flexibility is a recurring theme, few studies have quantitatively examined the interoperability challenges or operational value of flexibility within community energy systems.

From a forward-looking perspective, future research should prioritize comparative frameworks that systematically evaluate different MES configurations using consistent criteria (e.g., cost, emissions, reliability, and social acceptance). Evidence-based guidelines that identify which technological combinations are most effective in different contexts, urban or rural, grid-connected or off-grid, or under varying levels of policy support, would be valuable in informing public policies and investment strategies.

3.2. Specific Questions

3.2.1. SQ.1 What Are the Objectives of a Renewable Energy Community?

The review identified 63 studies that investigate the objectives of RECs. These objectives are primarily focused on key points: to promote the generation, storage, consumption, management, and sale of RECs; to mitigate the negative impacts of RECs penetration into the electrical grid; to drive the energy transition from non-renewable to renewable sources; to transform consumers into prosumers (producers and consumers of energy); and to generate economic, environmental, and social benefits for community members. These aspects are visually synthesized in the conceptual map presented in Figure 5, which organizes the scientific literature around the main objectives attributed to RECs. Through a multicolored Venn

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ISSN:1000-3673
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diagram, the figure highlights how different studies address these objectives either in isolation or in combination, revealing thematic convergences and specializations. Studies such as Caballero et al., (2023) and Velkovski et al., (2024) cover multiple dimensions simultaneously, from the promotion of energy generation to social and environmental impacts, while others, such as Lode et al. (2023), focus on specific objectives, such as economic benefits and encouraging the use of renewable resources. Thus, Figure 5 provides an integrated overview of the scientific production on RECs, enabling the identification of both the most explored areas and potential gaps for future research.

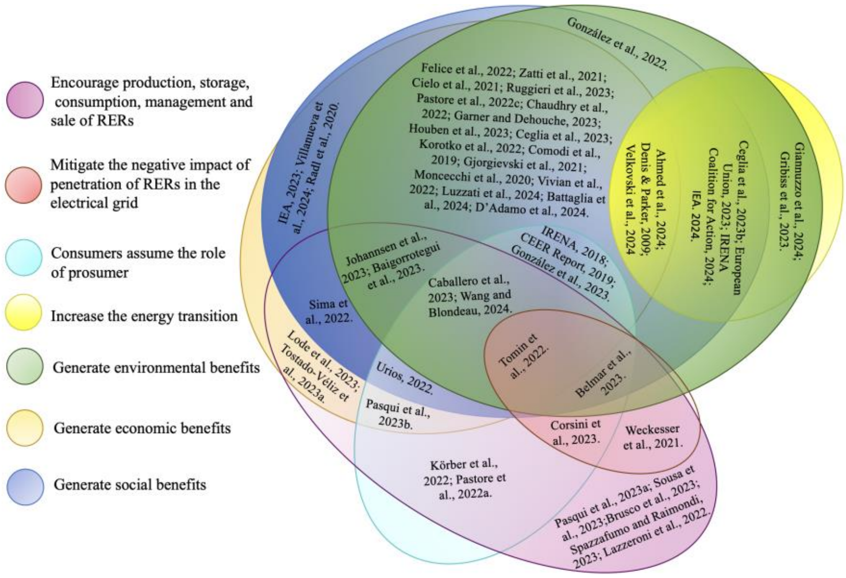

Figure 5 – Conceptual map of REC objectives.

The literature converges in pointing out that energy communities pursue multiple objectives, encompassing environmental, economic, social, and operational dimensions. In the ecological aspect, Comodi et al. [27] emphasize the reduction of the carbon footprint through the adoption of multi-energy systems, highlighting the need to balance economic and environmental goals to ensure sustainable and low-carbon communities. Complementarily, Cosic et al. [24] highlight the importance of self-consumption and renewable energy sharing in contributing to decarbonization. In the economic field, Good and Mancarella [34] identify economic optimization as one of the primary objectives, aligning with the analysis of Manso-Burgos et al. [26], who emphasize load shifting to periods of lower demand as a strategy to reduce costs. Socially, Moncecchi et al. [21], Cielo et al. [20], and Gjorgievski et al. [28] argue that communities should promote active user participation, not only to strengthen energy exchange practices but also as a mechanism to combat energy poverty. Finally, from an operational perspective, Good and Mancarella [34] highlight the importance of flexibility, the integration of multiple energy vectors, and operational robustness as key elements for the viability and resilience of energy communities.

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ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

Several authors, such as Chaudhry et al. [38], follow the concept established by RED II (2018), which defines the primary goal of RECs as generating economic, environmental, and social benefits for the community, its members, and the area of operation, without focusing on financial profit. Pasqui et al. [39] emphasize promoting renewable energy, while Radl et al. [40] highlight the reduction of electricity costs and GHG emissions, as well as increased awareness of clean energy. Felice et al. [9] and Ruggieri et al. [30] underscore the energy sector's democratization, decentralization, and decarbonization. Sousa et al. [41] point out that RECs serve as a solution for the energy transition and global warming mitigation. Pastore et al. [42] stress the collective use of renewable energy resources, enabling self-management of energy production, storage, and sales. Ahmed et al. [43] note that RECs have evolved into a more flexible and decentralized model, increasing citizen participation. Finally, Corsini et al. [7] emphasize the local integration of energy generation and consumption, ensuring greater penetration of renewable sources into the power grid without relying on external incentives.

Taken together, these studies suggest that while RECs are often framed as technical solutions, they also have broader implications for sociopolitical transformation, energy autonomy, and participatory governance. Rather than simply listing these objectives, it is essential to recognize that different stakeholders (policymakers, citizens, utilities, investors) may prioritize different goals, and that tensions may arise between environmental, economic, and social targets. For example, maximizing self-consumption for individual savings can conflict with collective optimization or grid stability. A forward-looking perspective suggests that RECs must navigate these tensions through inclusive governance models, transparent benefit-sharing mechanisms, and tailored technical solutions that balance efficiency with justice. This synthesis underscores the need to move beyond a generic understanding of REC objectives toward a more integrated vision that addresses the complex sociotechnical and political realities of energy transitions.

3.2.2. SQ.2 What Are the Energy Components of Renewable Energy Communities?

An analysis of 61 selected studies shows that RECs incorporate a wide variety of energy components, shaped by local conditions and community objectives. The most common elements include residential buildings, energy storage systems, generation systems (such as photovoltaic), EVs, the power grid, and the tariffs applied to the community. Figure 6 illustrates the distribution and interaction of energy components discussed in the literature, structured as a conceptual Venn diagram. The Figure 6 shows that RECs are rarely designed around isolated technologies; instead, they tend to integrate combinations of components that support local generation, storage, and optimized consumption. The most frequent overlaps involve electricity generation systems, grid energy and tariffs, and residential buildings, indicating a tendency toward decentralized, grid-connected architectures. Less frequent intersections with EVs and gas generation system suggest that these technologies, while promising, are still in the early stages of integration. This representation highlights both dominant patterns and technological gaps, supporting a forward-looking agenda for more holistic system designs.

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Received: 16-06-2025 *Revised: 05-07-2025* *Accepted: 20-08-2025*

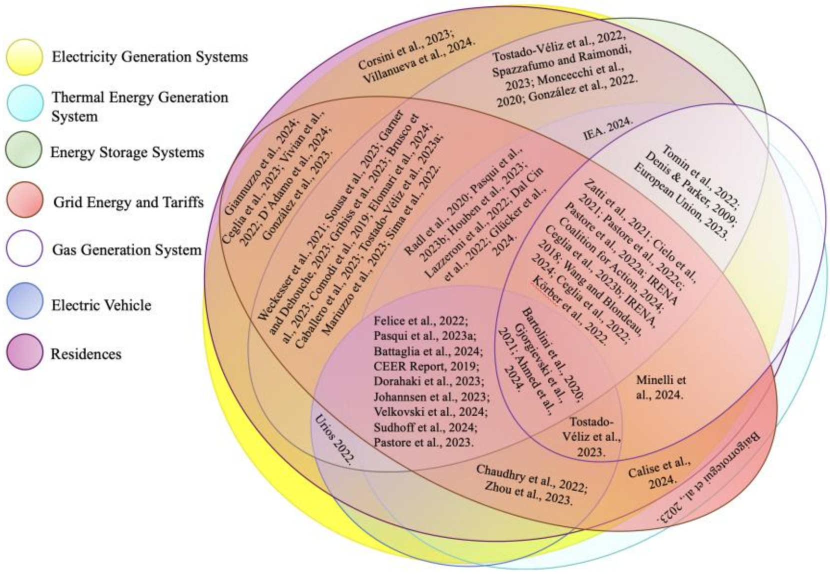

Figure 6 – Conceptual map of the components of RECs.

Several studies support these findings. For instance, Felice et al. [9] studied a REC with 11 residential buildings, integrating DERs like PV, BESS, EV chargers, and heat pumps for efficient energy management. Studies addressing the components of renewable energy communities, such as those by Comodi et al. [27] and Good and Mancarella [34], identify a variety of energy devices commonly employed in these initiatives. Among the main integrated generation elements are cogeneration systems, electric heat pumps, boilers (both gas and electric), and, in some configurations, additional renewable sources such as PV panels and wind turbines. The combination of these devices aims to provide greater operational flexibility, energy efficiency, and the effective use of local resources. Similarly, Moncecchi et al. [21] identify users and generators as the main components, detailing that the generators may include renewable sources such as PV and wind turbines connected to specific points of the grid. Moreover, authors such as Cielo et al. [20], Gjorgievski et al. [28], Manso-Burgos et al. [26], and Cosic et al. [24] discuss the use of BESS, which plays a fundamental role in balancing community operations and optimizing the use of energy generated by photovoltaic systems.

Pastore et al. [42] analyzed a REC with 10 buildings and 200 apartments, using EnergyPLAN to assess the impact of Power-to-Heat (PtH), Power-to-Gas (PtG), and self-consumption tariffs. Sousa et al. [41] explored a REC with three members connected to the medium-voltage grid, allowing surplus energy sales. Tostado-Véliz et al. [35] described a self-sufficient REC relying on locally generated PV, wind, and storage.

Glücker et al. [44] proposed a modular REC model incorporating BESS, PV, heat pumps, and thermal networks for scalable and flexible energy management. Houben et al.[32] a REC with nine participants using PV, BESS, and PtH systems, operating under five different tariff scenarios. However, the model treats the community as a single aggregate node, optimizing dispatch without distinguishing between individual user profiles. While this provides insights

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ISSN:1000-3673
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into system-level flexibility and cost-effectiveness, it limits the evaluation of how energy and economic benefits are distributed among members and consideration for equity and inclusiveness in community energy systems.

Despite the wide range of technologies considered in RECs, the literature offers limited assessments of the trade-offs between technical performance, equitable access, and user participation. Technologies such as EVs and PtH are frequently modeled in simulations but still face significant real-world adoption barriers, including high upfront costs and insufficient infrastructure. Few studies explicitly analyze how different component configurations influence governance, accessibility, or community engagement. To address these limitations, future research should move beyond purely techno-economic optimization and adopt multidimensional approaches that incorporate aspects of social equity, usability, and long-term sustainability. Policies and design choices must prioritize inclusivity, especially in resource-constrained contexts where technological adoption may be more challenging. Only by balancing performance with social justice can RECs fully realize their transformative potential in the energy transition.

Additionally, while some studies assume the availability of advanced infrastructure, such as thermal networks, others propose incremental or retrofit-friendly solutions, revealing disparities in the applicability of certain configurations across different regional contexts. This heterogeneity underscores the need for context-sensitive planning frameworks, particularly for policymakers aiming to scale RECs beyond pilot initiatives. Despite the methodological and technological diversity observed, a key gap remains: few studies conduct holistic cost-benefit analyses that integrate social, environmental, and governance dimensions. For investors and industry stakeholders, this lack of comprehensive evaluation presents uncertainty regarding the scalability and replicability of specific REC models. Establishing a systematic comparative base of performance indicators could help bridge this gap and support more informed decision-making in both public policy and investment strategies.

3.2.3. SQ.3 How Are the Social Arrangements of Renewable Energy Communities Addressed?

Based on the analysis of 43 studies, RECs exhibit a wide variety of social arrangements, reflecting the flexibility and adaptability of energy systems at the community level. The main groups of participants include residential consumers (who only consume electricity), residential prosumers (who both generate and consume energy), and public or educational institutions (such as schools and universities). In addition, RECs often integrate commercial prosumers (such as restaurants, shops, and hotels), as well as agricultural and industrial prosumers, and investors, as illustrated in Figure 7.

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ISSN:1000-3673
Received: 16-06-2025 *Revised: 05-07-2025* *Accepted: 20-08-2025*

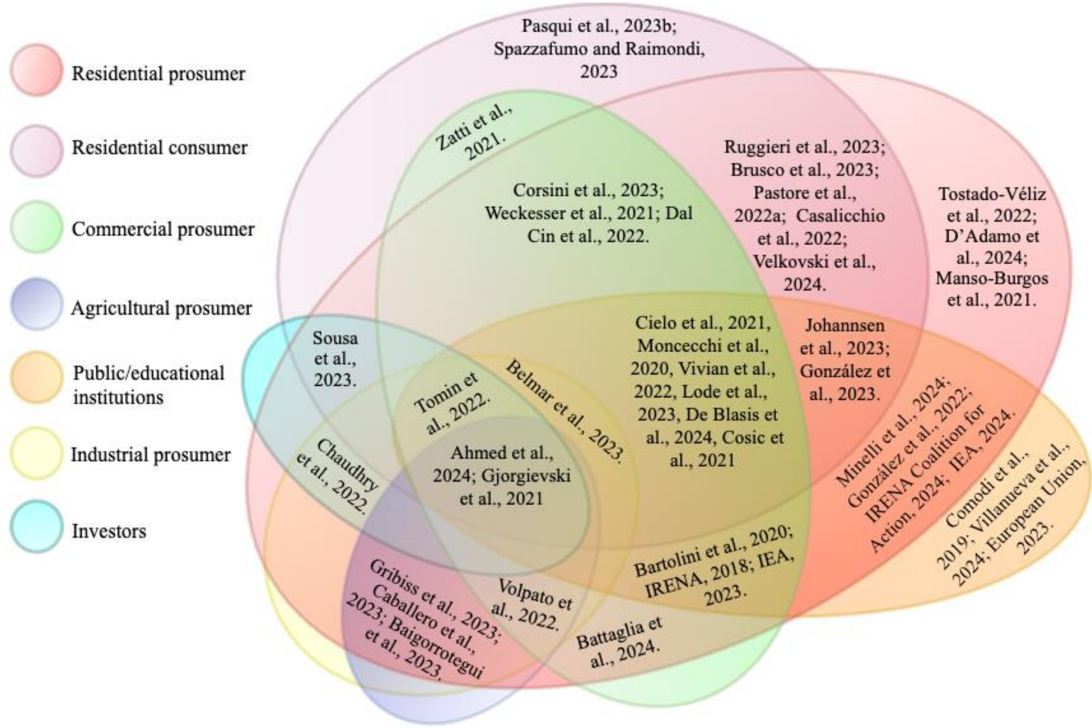

Figure 7 – Conceptual map of the social arrangements in RECs.

Figure 7 presents a conceptual map of these arrangements, demonstrating how different actors interact within REC configurations and highlighting the diversity of roles and their potential overlaps. The diagram includes residential consumers, residential prosumers, public and educational institutions, commercial, agricultural, and industrial prosumers, as well as investors. The overlapping areas represent scenarios in which multiple actors share infrastructure, participate in local energy markets, or collaborate in resource management. These intersections highlight the complexity of the social and institutional networks that surround energy generation, consumption, and governance.

Some case studies offer different perspectives on such arrangements. Corsini et al. [7] categorized REC actors into residential prosumers, consumers, restaurants, and hotels, sizing PV plants based on available rooftop and parking space. Volpato et al. [45] analyzed a REC where prosumers (residential, industrial, agricultural, and tertiary) shared a low-voltage network for energy exchanges. Ruggieri et al. [30] grouped 100 households into clusters based on occupancy patterns and building envelope quality, which in turn influenced heating and cooling demands. Chaudhry et al. [38] classified REC actors into prosumers, energy system managers, and financial investors. Tostado-Véliz et al. [35] described a REC where prosumers provide generation capacity via PV panels and demand flexibility through controllable loads, managed by a communication system for energy optimization. De Blasis et al. [46] simulated load profiles for hypothetical RECs in Los Angeles, analyzing energy demand across residential, commercial, and institutional buildings using real meteorological data. Moncecchi et al. [21], Gjorgievski et al. [28], and Manso-Burgos et al. [26] discuss the social arrangements

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ISSN:1000-3673
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of renewable energy communities, highlighting that active user participation in energy exchange can contribute to a sense of community engagement and local resilience. Cielo et al. [20] further discuss the social structures of energy communities through the lens of the RED II Directive, emphasizing that these communities should promote open and voluntary participation while ensuring active control by their members, in line with the established objectives.

The analysis of these studies reveals two key points. First, social arrangements in RECs are highly diverse, encompassing multiple types of participants with different capacities, roles, and motivations. Second, the integration of heterogeneous actors enables the development of energy systems that are more locally adapted and responsive, enhancing operational performance and fostering cooperation among members. However, despite this diversity, the literature still lacks sufficient attention to contradictions and asymmetries among participants. While some RECs emphasize collaborative self-management, others centralize control in actors with greater resources, such as industrial prosumers or investors. These imbalances can lead to unequal distribution of benefits, limited democratic participation, and tensions in decision-making processes. Residential consumers who do not generate energy often have less influence over governance, raising concerns about inclusion and energy justice. These gaps underscore the critical need to deepen our understanding of how social arrangements influence equity, governance, and the long-term sustainability of RECs.

Future research should investigate how REC governance models can foster equitable participation and mitigate entry barriers for underrepresented groups. The development of standardized actor typologies, combined with participatory design frameworks, can enhance model replicability, support inclusive public policies, and strengthen the legitimacy of RECs across diverse socioeconomic contexts.

3.2.4. SQ.4 How are Peer-to-Peer Energy Negotiations Conducted in Renewable Energy Communities?

Figure 8 presents a conceptual map based on 35 studies addressing P2P energy trading mechanisms in RECs. Three main types of transactions were identified: self-consumption, trading with the electric grid, and energy sharing among community members. The overlap between these categories shows that many models combine more than one strategy, reflecting the pursuit of greater flexibility and efficiency. Trading with the grid remains the most explored mechanism, highlighting the importance of connection to the conventional electrical infrastructure. On the other hand, direct energy sharing between users, although promising, remains less frequent, suggesting an opportunity for future advancements in more autonomous and collaborative Peer-to-Peer (P2P) models.

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ISSN:1000-3673
Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

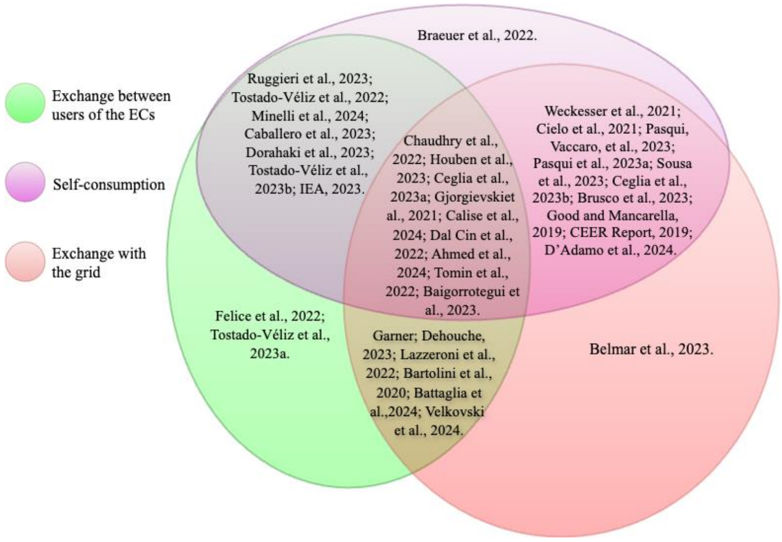

Figure 8 – Conceptual map of P2P negotiations in RECs.

Several studies propose innovative negotiation and compensation mechanisms. Felice et al. [9] analyzed P2P pricing in RECs, modeling it as the difference between the purchase and sale values of community-generated energy, and highlighted the impact of tariffs on negotiations. Sousa et al. [41] examined a model where P2P transactions are influenced by self-consumption and time-of-use tariffs, with excess energy sold at 90% of the previous month's average market price. Houben et al. [32] explored capital sharing among REC members for acquiring generation and storage assets, enabling distributed PV and wind installations, and facilitating P2P trading. Dorahaki et al. [47] discussed a regulated P2P market with restrictions on energy trading, preventing reselling, and ensuring that simultaneous transactions are avoided. Gjorgievski et al. [28] discuss how, in renewable energy communities, P2P energy negotiations occur both among prosumers and with the electric grid. These transactions are enabled by facilitating technologies such as blockchain, which ensure the security and transparency of the processes, along with the use of systems for monitoring energy consumption and generation.

It is observed that among the detailed studies, there is a predominance of theoretical approaches, simulations, and case studies, with few works providing longitudinal data or comparative performance metrics. This gap makes it challenging to evaluate the effectiveness and scalability of P2P negotiations under various regulatory, technical, and social conditions. While the technical and economic aspects are widely explored, the social dimension of P2P negotiations remains underdeveloped. Few studies address how power asymmetries between prosumers and consumers impact participation, or how factors such as trust, transparency, and collaborative decision-making processes influence negotiation outcomes. This gap can compromise the social legitimacy and scalability of communities in the long term, especially in contexts where community involvement is central to the success of RECs.

Given this, the need for advances in both conceptual and methodological terms becomes evident. The incorporation of more integrated approaches, which combine technical, economic,

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ISSN:1000-3673
Received: 16-06-2025 *Revised: 05-07-2025* *Accepted: 20-08-2025*

and social factors, will be crucial to ensuring the sustainability and fairness of RECs. This perspective is particularly relevant for policymakers focused on promoting energy equity and inclusion, for investors interested in predictions and social legitimacy of models, and for companies in the sector that involve technological innovation with community engagement.

3.3. Conceptual Classification

The responses to the general and specific questions contributed to the development of a conceptual classification with the main aspects found in the literature on the topic addressed. Figure 9 presents a conceptual classification developed with SR.

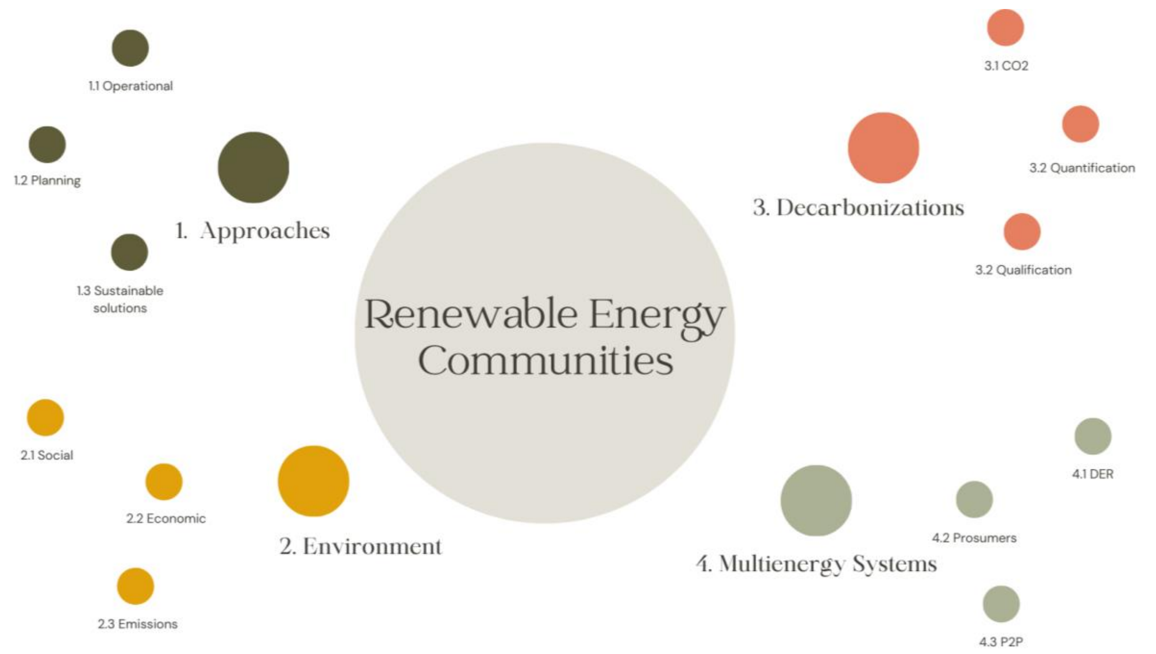

Figure 9 – Conceptual classification of the main aspects found in the studied literature.

The classification presented aims to serve as a classification structure, organizing the main dimensions and subcategories identified in the studies analyzed on Energy Communities (ECs). Its purpose is to provide a comprehensive conceptual mapping of the literature by organizing key aspects related to ECs into four central dimensions: (1) Approaches, (2) Environment, (3) Decarbonization, and (4) Multi-Energy Systems, thereby highlighting the thematic diversity addressed by the reviewed publications. These dimensions were derived from a detailed analysis of the literature, which enabled the identification and categorization of the most relevant contributions by the authors. Each dimension is composed of subcategories that delve into specific themes, such as operational, social, economic, and environmental aspects, forming a comprehensive and structured overview of the subject.

The first dimension, approaches, covers strategies and solutions applied to RECs. In the subcategory 1.1 Operational, authors such as Sousa et al. [41] highlight the integration of DERs with dynamic pricing, while Felice et al. [9] discuss the optimization of collective self-

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Received: 16-06-2025 Revised: 05-07-2025 Accepted: 20-08-2025

consumption. In Section 1.2 Planning, studies such as those by Pastore et al. [39] and Houben et al. [30] explore modeling tools, including EnergyPLAN, and the application of PtH technologies. In 1.3 Sustainable Solutions, Ruggieri et al. [30] and S. Ahmed et al. [43] emphasize the importance of energy democratization and flexibility for the sustainability of RECs.

In the Environment dimension, the subcategories examine the social, economic, and environmental impacts of RECs. In 2.1 Social, studies by Corsini et al. [7] and De Blasis et al. [46] emphasize the integration of diverse communities and the social impact of forming residential clusters. In 2.2 Economic, Felice et al. [9] and Chaudhry et al. [38] discuss the financial feasibility of RECs, with a focus on the P2P transaction model. In 2.3 Emissions, authors such as Radl et al. [40] and Sousa et al. [41] highlight the role of RECs in reducing greenhouse gas emissions.

The third dimension, Decarbonization, focuses on mitigating environmental impact. In 3.1 CO_2 and 3.2 Quantification, evaluation methods, such as those proposed by Glücker et al. [44] demonstrate the effectiveness of RECs in reducing carbon emissions. In 3.3 Qualification, Tostado-Véliz et al. [35] discuss energy autonomy as a key indicator for assessing the ability of RECs to mitigate the impacts of non-renewable sources.

The MES dimension addresses the integration and technological innovation in RECs. In 4.1 DER, studies by Felice et al. [9] and Pastore et al. [42] detail the incorporation of technologies such as PV and PtG systems. In 4.2 Prosumers, authors such as S. Ahmed et al. [43] and Chaudhry et al. [38] analyze the transformation of consumers into prosumers, thereby fostering greater citizen participation in the energy transition. In 4.3 P2P, negotiations are explored as a strategy to optimize energy management, with significant contributions from Sousa et al. [41] and Felice et al. [9].

The cross-analysis of data between the dimensions and authors reveals important similarities. For example, the intersections between Planning (1.2) and Sustainable Solutions (1.3) indicate how modeling tools can drive sustainability, as discussed by Houben et al. [32] and Ruggieri et al. [30]. Similarly, the connection between Social aspects (2.1) and Prosumers (4.2) highlights the importance of social engagement and the active role of individuals, as noted by Corsini et al. [7] and Chaudhry et al. [38]. Additionally, the links between Emissions (2.3) and CO_2 (3.1) reinforce the relevance of RECs in mitigating greenhouse gases, as emphasized by Radl et al. [40] and Glücker et al. [44].

4. Discussion

The results presented indicate that the insertion of the REC concept and the use of MES, through the planning and optimization of operational systems, can bring various benefits to humans. Among the main benefits, the maximization of decarbonization stands out, generating positive environmental, economic, and social impacts. RECs can, for example, contribute to reducing energy poverty, lowering electricity costs, and improving the living conditions of users.

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ISSN:1000-3673
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The analysis of research indicators reveals that the similarity between RECs and MES has garnered increasing attention from the scientific community, primarily due to the energy transition and the UN's Sustainable Development Goals (SDGs). This systematic review offers a comprehensive overview of RECs, establishing a consistent foundation for future methodological development. The aspects analyzed in this review explore fundamental concepts of RECs related to MES, reinforcing the relevance of the topic for future scientific contributions.

It was found that the studies are broadly divided between planning and operational scenarios, with a predominant focus on operations. Of the 75 studies reviewed, 39 addressed the operational scenario. These studies involve conceptual elements of RECs, comparisons between different configurations, and the measurement of positive impacts generated by adopting this technology.

In terms of impacts for REC members, the most frequent are economic and environmental. A significant portion of the research indicates that RECs reduce greenhouse gas emissions, including CO_2. However, only 19 studies describe or detail how to calculate this reduction, whether through the manufacturing of PV, the use of batteries, the consumption of different types of primary energy, or the use of the electrical grid. From the conceptual map in Figure 3, it is concluded that most studies (16) quantified the CO_2 emissions generated by electricity consumed from the grid, combined with other forms of generation. Additionally, 45 studies address the integration of multi-energy systems in RECs, all of which use PV energy generation due to its lower cost and ease of management.

The study also showed that the implementation and use of RECs have clear objectives, such as: encouraging the production, storage, consumption, and management of RECs; mitigating the negative impacts of RECs penetration on the grid; accelerating the transition from non-renewable to renewable energy; and promoting the transformation of consumers into prosumers. Of the reviewed studies, 40 highlight that the main objectives of RECs are economic and environmental benefits.

RECs generally consist of key components such as residences, storage systems, energy generation, EVs, the electrical grid, and community tariffs. Among these, the most used are residences and electricity generation through RECs, as identified in 60 studies.

The social arrangements of RECs involve a variety of actors: residential consumers, residential prosumers, public and educational institutions, commercial, agricultural, investor, and industrial prosumers. Most studies (37 out of 43) focus on residential prosumers. Regarding energy negotiations, the mapping revealed that P2P negotiations generally involve decisions on the destination of the generated energy, whether for exchange with the electrical grid, self-consumption, or sharing among community members. Of the 35 studies that addressed this issue, 27 indicate that P2P negotiations are predominantly related to self-consumption by REC members.

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Received: 16-06-2025 *Revised: 05-07-2025* *Accepted: 20-08-2025*

Although this review has yielded significant findings, some issues were less thoroughly explored, such as social arrangements, peer-to-peer (P2P) negotiations, multi-energy systems integration, and, in particular, the quantification of decarbonization. Many studies mention the mitigation of CO_2 and GHG emissions, but few present clear methods for quantifying these impacts, revealing a significant gap. Additionally, there is a lack of studies focused on REC planning.

In the Global South, community-based renewable energy initiatives have emerged as crucial pathways to promote a fair and decentralized energy transition, aligning with the goals of SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Although many are not yet formally recognized as RECs in the European model, they share similar objectives, including collective management, social inclusion, and the use of renewable energy sources. Experiences in Sub-Saharan Africa and Latin America, including initiatives in Brazil and Chile, illustrate context-specific approaches that prioritize vulnerable populations and emphasize citizen participation. Despite persistent regulatory and institutional challenges, these initiatives have become important drivers of the energy transition in the region, underscoring the need for inclusive governance and enabling regulatory frameworks.

Given these gaps, there is an opportunity for new studies that consider the detailed planning of REC creation and implementation, taking into account economic, environmental, and social aspects, as well as the use of multi-energy systems. Furthermore, there is a need to develop methods to quantify decarbonization, address social arrangements, and improve P2P negotiations.

In countries like Brazil, with vast, remote, and hard-to-access areas, many regions still lack access to basic services, such as electricity. Some communities rely exclusively on diesel generators, which have a significant environmental impact and contribute to the exacerbation of the greenhouse effect. Universal access to energy is a considerable challenge, particularly in these remote areas. In this context, applying the concept of RECs, combined with MES, can be a solution to bring energy to these locations, reducing dependence on fossil fuels and promoting positive social and environmental impacts.

Based on the results of this review, the authors plan to conduct a new study, focused on planning an MES to transform a community into a REC to be implemented on an island in the Amazon. This community faces significant challenges in electricity supply, and the study will address economic, environmental, and social issues by utilizing multi-energy systems to support decarbonization and enhance access to affordable and sustainable electricity. This proposal aligns with SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

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