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Review article

Assessment of renewable energy communities: A comprehensive review of key performance indicators

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ABSTRACT

Renewable Energy Communities (RECs) hold great promise as a key driver in the global shift toward sustainable energy systems. To realize their full potential, it is essential to evaluate their performance effectively and ensure their long-term sustainability. Key Performance Indicators (KPIs) play a pivotal role in this process, offering a structured way to measure the success of RECs across critical dimensions such as energy production, economic viability, social, and environmental impact. KPIs not only quantify REC achievements but also provide early insights into emerging trends and challenges. This enables stakeholders to make informed, data-driven decisions that optimize performance and contribute to long-term success. Recognizing the need for a more systematic approach to REC performance evaluation, this study conducts an extensive literature review, examining over 200 research papers to identify and categorize the most relevant KPIs to consider. The main contribution of this research work is a *KPI Reference List*, featuring 25 indicators that make a comprehensive toolkit for assessing REC performance across diverse operational areas. The KPIs were categorized across four key *Sector Domains*, energy, economic, social, and environmental, and assessed for their applicability across various *Usages* such as planning, operations, monitoring, and benchmarking. Additionally, KPIs were selected to address the specific needs of specific *Target* groups, including policymakers, REC managers, stakeholders, and community members. This research aims to deepen the understanding of REC evaluation but also highlights the ongoing need for thoughtful refinement of KPIs to better capture the complexities of these communities, and to avoid restricted and partial analyses.

1. Introduction

The Clean Energy for All Europeans (CEP) legislative package, especially through the Directive EU 2018/2001 (Renewable Energy Directive or RED II), introduced several new legal concepts that recognize specific market actors and activities that reflect the evolving role of consumers in the energy system, including Renewable Energy Communities (RECs) (A Roadmap to developing policy; Report: Barriers and action drivers for the development of energy communities and their activities). RECs are still a relatively new concept for many stakeholders in the EU energy market. Governments, regulators, distribution system operators, traditional market actors, and local and regional governments are required to support or cooperate for the spread of RECs, and yet many of these actors are still learning about the functioning and impact of Energy Communities on the EU energy system, economy, and society (European Commission,; López et al., 2024). Renewable Energy Communities (RECs) unite citizens, small and medium-sized enterprises (SMEs), and local authorities to collectively own and manage clean renewable energy sources and services. These communities promote democratic participation and governance in decision-making processes,

Abbreviations: CEP, Clean energy for all Europeans Package; DP, Data Perimeter; DSO, Distribution System Operators; ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development; EU, European Union; EP, Energy Poverty; FP, Fuel Poverty; IAD, Institutional Analysis and Development; KPIs, Key Performance Indicators; MCA, Multi-Criteria Analysis; NRAs, National Regulatory Authorities; RECs, Renewable Energy Communities; RED, Renewable Energy Directive; SME, Small and medium enterprises; TC, Target Coverage; UC, Usage Coverage; WoS, Web of Science.

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prioritizing environmental and socio-economic benefits over profit maximization (Report: Barriers and action drivers for the development of energy communities and their activities; European Commission,; Gjorgievski et al., 2021). The clean energy production of RECs generally relies on technologies such as photovoltaic solar panels, wind turbines, and hydroelectric plants, and can include the production of electricity, the heating and cooling of buildings, and the charging of electric vehicles. RECs are designed to support the deployment of renewable energy sources, promote energy efficiency, the use of renewable sources, and the reduction of greenhouse gas emissions, as well as to foster the creation of more sustainable local entities. Additionally, they allow citizens to participate directly in the energy market as prosumers, thereby promoting self-consumption and allowing citizens to become the producers and owners of renewable-powered plants (Giannuzzo et al., 2024a). RECs also facilitate the transition from a centralized energy production model, in which large power plants supply energy to all consumers, to a more decentralized and local approach. These entities could also sell surplus energy when authorized by the electricity market, thus enabling revenue generation and active participation in the energy economy. Additionally, RECs have the potential to contribute to making the grid more stable and efficient. As energy is produced and consumed locally, there is a reduced need to transport electricity over long distances. This has the advantage of reducing losses and easing pressure on transmission infrastructure. These communities can also assist in balancing the grid by adjusting their energy use or storing excess power during periods of low demand and releasing it during periods of high demand. The investigation into the benefits of RECs is a rapidly expanding field, with ongoing research and data collection essential to fully evaluate their impact (A Roadmap to developing policy; Giannuzzo et al., 2024a). Over the last few years, the Energy Communities Repository has been systematically reviewing the regulatory frameworks established by EU Member States for energy communities. With additional insight from energy communities, local authorities, regulators, Distribution System Operators (DSOs), and other market actors across the energy system, the Repository has also published a report identifying the barriers and drivers that influence the development of energy communities (Report: Barriers and action drivers for the development of energy communities and their activities). This report examines factors that either facilitate or hinder the growth of various energy communities' activities. Two key observations emerge from the information gathered across the EU. First, RECs and other innovative initiatives that empower citizens and communities in the energy transition remain relatively new in EU energy policy (A Roadmap to developing policy; Report: Barriers and action drivers for the development of energy communities and their activities; European Commission). Prior to the adoption of the Clean energy for all Europeans Package (CEP), very few Member States had legislative frameworks specifically designed to support and enable energy communities. In many cases, they only began to emerge following the CEP's introduction, which encouraged action and the concurrent development of national policy frameworks. Second, creating new policy and legal frameworks for energy communities from the ground up is inherently complex. While EU definitions of RECs are principles-based, they may require further refinement and detail at the national level, including integration across various pre-existing sectors and policies, such as electricity, heating and cooling, gas, energy efficiency, and renovation. Integrating RECs into an established electricity grid may involve a trial period and iterative revision of the Member State legal framework to improve energy policy effectiveness in achieving EU goals (A Roadmap to developing policy). This process includes the recognition of REC rights and responsibilities, integrating RECs into existing renewable energy support schemes, developing an enabling framework, and removing barriers. It also involves promoting awareness, access to information and finance, capacity building for local authorities, and ensuring inclusiveness (A Roadmap to developing policy; Barabino et al., 2023; Minuto and Lanzini, 2022). Developing such a legal-economic-social framework requires national laws, grid regulation adaptations, integration into climate and energy plans, and definition of clear roles for National Regulatory Authorities (NRAs), executive agencies, and other authorities, at various governance levels. Building on this background, the scientific community is advancing the understanding of REC challenges, particularly through the lenses of technical design, policy integration, and economic models.

Barabino et al. reviewed the literature on RECs to determine the state of the art in RECs modeling (Barabino et al., 2023). They focused on the inclusion and detailed description of business models and objective functions. The results highlighted significant research opportunities at the intersection of technical design, policy, and economics, especially when considering multi-energy and sector-coupled systems, which they demonstrated have rarely been considered in the RECs field. They also noted that the number of REC studies has increased significantly over the past year, indicating a growing need for applied studies, especially multidisciplinary studies involving different research fields and expertise from different socio-economic and geographical contexts. They also noted that optimization models and business models are increasingly incorporating multiple scales, with environmental and social evaluation metrics taking precedence over economic ones. In their study, Reis et al. (2021). revealed the dominance of traditional place-based and self-consuming communities, while business models involving differentiated services such as demand flexibility, aggregation, energy efficiency, and electric mobility are not yet well developed. They emphasized that research on novel business models needs to be strengthened, as these models are expected to become crucial to maintaining RECs as key players in the energy transition and to support the evolution of the regulatory framework. Furthermore, they highlighted that more performance metrics on novel business models may be needed in the future. Fouladvand et al. (2022). organized the existing research on "community-based initiatives for heating and cooling" using the Institutional Analysis and Development (IAD) framework. Their analysis showed that while the number of publications in that area has grown rapidly recently, the focus has largely been on technological challenges, with few papers addressing the institutional perspective, policies, and price reforms. They found that informal rules and values are mainly studied from a consumer perspective and that evaluation criteria are often limited to economic aspects and greenhouse gas emissions, neglecting other important indicators such as soil pollution and spatial planning. The study by Bianco et al. (2021). also showed that there are limited studies on a stakeholder perspective and institutional design in the RECs literature, compared to the common studies on REC sizing and optimization. They concluded that institutions (both formal and informal rules) are frequently neglected in the literature.

To achieve significant results and evaluate the impact of REC projects, stakeholders, aggregators, and REC promoters typically adopt systematic approaches, such as the creation of evaluation models that often require the definition of Key Performance Indicators (KPIs) (Bianco et al., 2021). KPIs are quantitative measures that express the performance of a complex phenomenon or activity in a concise numerical form and allow for monitoring over time. The selection of KPIs and the variables associated with their calculation depends on the specific aspects of the phenomenon or activity being emphasized, the objectives pursued, and the availability of data. In the literature, the impact of REC projects both for simulations and real-world applications is measured through social, economic, environmental, and energy-based KPIs, providing a neutral and objective assessment (Trevisan et al., 2023; Ghiani et al., 2022; Mansó Borràs et al., 2023; International Energy Agency, 2019, 2023; Intergovernmental Panel on Climate Change, "Climate Change, 2023, 2022; Intergovernmental Panel on Climate Change, 2018). KPIs are also used to compare and evaluate different user aggregates, such as smart grids (Definition of an assessment,; Personal et al., 2014; Al Dakheel et al., 2020) or smart districts (Angelakoglou et al., 2020; Agbali et al., 2018; Quijano et al., 2022).

Energy and economic-based performance metrics have usually been employed to evaluate REC projects from a community and stakeholder perspective, including activities such as sizing and optimization, and assessing the energy and economic value of communities in the territory (Barbaro and Napoli, 2023; Canizes et al., 2023; Esfandiary Abdolmaleki et al., 2023; Haji Bashi et al., 2023a). For instance, De Lotto et al. (2022). highlighted the technical and regulatory opportunities to achieve energy independence by exchanging energy between communities when there is surplus production, using various performance metrics, and underlined the strengths and barriers to the development of RECs. Other studies, such as (Cutore et al., 2023a), extended their analysis to include environmental KPIs in the analysis of RECs, while others (Bosone et al., 2023; Kaiser et al., 2022; Piselli et al., 2022; Biresselioglu et al., 2024; McMaster et al., 2024) have examined the social impact of communities, focusing on factors such as participant engagement, social awareness, and energy poverty. Furthermore, energy-based KPIs have also been used to evaluate the interaction between aggregates, such as RECs and the electrical grid, often including the evaluation of flexibility and demand response programs (Pelekis et al., 2023; Couraud et al., 2023). As an example, the study of Di Silvestre et al. (2021). investigated various aspects concerning the interaction of RECs with the power system, highlighting that certain issues must still be addressed for the complete integration of communities into the power system. Some other researchers made use of energy-based KPIs differently, for instance, Mustika et al. (2022). used them to analyze the expansion of existing energy communities, particularly focusing on selection criteria for new members from a pool of candidates.

As shown, the literature on KPIs for analyzing RECs is extensive and varied. However, there is a notable absence of a systematic review that rigorously collects, categorizes, and describes the metrics across the literature. Specifically, there is no comprehensive review detailing the applicability of KPI to different stakeholders involved in REC projects, such as policymakers, REC members, service providers, and national agencies. Moreover, the literature lacks a synthesis of KPIs based on the REC project phases, such as planning, management, monitoring, and implementation (Minuto et al., 2022), as well as by scope of use. Additionally, there does not seem to be a fully developed reference nomenclature and mathematical definition of KPIs within the context of REC literature. These gaps highlight the need for a robust framework to guide future studies in systematically analyzing REC projects. Providing a reference list containing KPIs that are well categorized based on their characteristics, scope of use, and target audience can serve as an effective tool for evaluating RECs more easily. This can be especially useful in real-world contexts and applications where the impact of RECs needs to be assessed in a systematic way, particularly when it is necessary to compare RECs over time, or to make comparisons between different communities. To address these gaps, this paper proposes to:

- Introduce a systematic methodology for identifying KPIs used in RECs from the literature;
- Categorize and organize KPIs according to sector domain, scope of use, and their target;
- Define the data requirements for calculating KPIs within specific physical perimeters;
- Uniform the mathematical definition of KPIs for each sector domain;
- Extrapolate a list of the most frequent and effective KPIs for each scope of use, based on the analyzed literature, and redesign the selected KPIs to improve KPI effectiveness.

The paper organization is as follows: Section 2 outlines the systematic methodology for identifying and collecting KPIs from literature related to REC projects and their performance evaluation. Section 3 presents the results obtained from applying the proposed methodology. Section 4 provides a critical discussion and analysis of these results, assessing the extent to which the objectives were met. Finally, Section 5 summarizes key insights and offers an outlook for future research.

2. Literature review methodology

This section describes the systematic review, and the process used to collect KPIs employed in the context of RECs. The review was conducted by all co-authors with multidisciplinary expertise in energy systems, renewable energy, RECs, and machine learning techniques for renewable energy applications. The main question driving the literature review was "What is the current state of the art in applying performance metrics to analyze RECs projects?". The methodology includes a bibliographic search of research documents on REC analysis, the categorization of metrics based on their use, and the identification of key metrics. The process is divided into four phases:

1) *Literature search* - Comprehensive search of relevant studies and research related to KPI and RECs using Scopus and Web Of Science databases;
2) *Database Creation* – Extraction of KPIs from papers identified in the previous step that have been used to analyze RECs;
3) *KPIs Categorization and Unification* – Grouping, categorization, and schematization of KPIs according to different criteria;
4) *KPIs Reference List* – Obtain a list containing the most important KPIs in the context of RECs.

2.1. Literature research

This phase is divided into three sub-phases:

1) *Papers Exploration* – Comprehensive search of papers in the field of RECs using Scopus and Web Of Science databases;
2) *Papers Screening* – Initial screening of collected literature based on research domain and accessibility;
3) *Papers Eligibility* – Further filtering papers by extracting those that explicitly define KPIs through mathematical formulations in the context of the RECs.

In the *Papers Exploration* step, the authors conducted a systematic review of the state-of-the-art of literature on performance metrics in the context of the renewable energy community. The search was conducted in March 2024 using the search engines Scopus and Web Of Science. The specific query is reported in Table 1.

The output of this phase is a large database of the most recent and

Table 1
Search engines and queries used for the literature research.

Search Engines	Method	Query
Scopus	Article title, Abstract, Keywords	"key performance indicator" OR kpi OR "performance evaluation" OR indicator OR metric OR "performance metrics" OR "performance measures"AND"energy community" OR "community energy" OR "community institution* " OR "citizen* energy" OR "energy citizen* " OR "power to people" OR "citizen power plants" OR "cooperative energy" OR "energy cooperative" OR "power cooperative" OR "community-owned"ANDlocal OR projects OR systems OR renewable OR sustainable OR integrated OR clean OR wind OR solar OR self-organized OR self-consumption
Web of Science	All field	

relevant studies, cataloged by the following information: authors, article title, abstract, author keywords, index keywords, and year of publication. At this stage, only journal articles and research works published after 2010 were considered. In the *Papers Screening* phase, the articles are further filtered by the authors screening manually all papers based on keywords, titles, and abstracts, removing articles not relevant to the context of the RECs. In addition, articles for which it was not possible to access the full text are excluded. In the *Papers Eligibility* phase, the articles are entirely read to identify those articles that directly address the use of performance metrics. The eligibility criterion used by the reviewers' team refers to the explicit definition of KPIs through mathematical formulas combined with their direct usage to evaluate RECs' performances. The main objective of this phase is therefore to identify those articles that explicitly define and use KPIs, so that they can later be collected and labeled, based on their definition and usage.

2.2. Database Creation

In the *Database Creation* phase, KPIs identified in the previous analysis are systematically collected and organized. Each KPI is accompanied by its definition and the mathematical formula as originally presented in the literature. Additionally, KPIs used in research articles that include real case studies are specifically marked. The KPIs are categorized based on two additional parameters: *Sector Domain* and *Usage*. The *Sector Domain* refers to the specific areas in which a REC operates, and in this research, four domains are considered - energy, economic, environmental, and social - reflecting typical operational areas identified in the literature, as shown in (Agbali et al., 2018; Haji Bashi et al., 2023a; De Lotto et al., 2022; Di Silvestre et al., 2021). In the context of RECs, *Sector Domains* can be defined as follows:

- **Energy** – Activities involving energy consumption, production, and the exchange of energy among members of RECs or among community members and third-party users, such as the injection or withdrawal of energy from the grid and physical or virtual self-consumption;
- **Economic** – Activities involving the exchange of monetary flows between REC users or between community members and third-party users, such as installation costs of renewable energy systems, maintenance costs, savings in energy bills, or revenues from selling energy to the grid;
- **Environmental** – Activities aimed at evaluating or reducing the environmental impact of REC projects' activities, such as the benefits obtained from the generation of electricity from renewable energy facilities or the adoption and use of electric vehicles within the community;
- **Social** – Activities that are designed to promote social initiatives that are intended to assist and engage members of the REC, such as the organization of events to raise awareness of consumption and the approach of social topics such as energy poverty.

On the other hand, the *Usages* categorizes the purpose for which a KPI was used in the literature as follows:

- **Planning** – Referring to all those activities that concern the process of sizing and creating a REC through simulations and the use of optimization algorithms based on synthetic or real data that are not based on real-time monitoring. An example of activities related to planning is the sizing of power generation plants and the identification of the type and number of users to be involved in the project;
- **Operation** – This refers to the active management and execution of processes within established Renewable Energy Communities (RECs). It encompasses the planning, coordination, and optimization of activities aimed at achieving the project's objectives and enhancing overall performance. Operations involve implementing strategies, allocating resources, and ensuring that all components of the REC function effectively to deliver desired outcomes;
- **Benchmarking** – Concerning the comparison of RECs performance in their various operational fields, both for simulated and real case studies;
- **Monitoring** – This process entails the systematic and ongoing evaluation of procedures and performance within the REC. Monitoring encompasses the collection of data, the analysis of trends, and the evaluation of operational effectiveness over time. The primary objectives of monitoring are threefold: firstly, to identify areas requiring improvement; secondly, to ensure compliance with established standards; and thirdly, to provide feedback for the purpose of decision-making. The overarching goal of monitoring is to support the continuous enhancement of the REC's performance.

2.3. KPIs Categorization and Unification

The *KPIs Categorization and Unification* phase focuses on grouping and uniforming similar KPIs to avoid repetitions, assigning them a new mathematical definition when necessary. In synthesis, the KPIs identified during the *Database creation* process are refined and grouped according to the following unification criteria:

- **Equality** – KPIs that share the same mathematical definition, and depend on the same variables. Two or more KPIs are deemed equal if they are mathematically equivalent, meaning their formulations satisfy the principle of identity. For example, KPIs that are generally used in the same mathematical way in this field, such as self-consumption and self-sufficiency rates, are considered under this unification criteria;
- **Similarity** – KPIs that express the same concept and depend on the same variables but have slightly different formulations. These KPIs can be classified as similar if their mathematical expressions are equivalent under a transformation, such as applying the principle of reciprocity. Conceptually, KPIs that convey the same information but are modified for specific contexts without altering their fundamental meaning also fall under this category. The application of the aforementioned unification criteria is exemplified by the Annual Energy Cashflow parameter. In certain instances, not all income and expenditure are taken into consideration in all the examined papers. In such cases, a new mathematical definition that has the aim of being as general as possible is usually proposed. However, in some cases, existing definitions are used if they have already been defined in a satisfactory general way;
- **Relatedness –** KPIs that are derived from other KPIs and convey equivalent information. These KPIs are functions of other KPIs, involving basic arithmetic operations such as ratios, multiplication, addition, or subtraction, with the exception of transformations already accounted for under Similarity. This unifying criterion can be illustrated by an example involving Capital Expenditure (CAPEX) and Net Present Value (NPV). Whenever NPV needs to be evaluated, CAPEX will also need to be assessed, even though in some cases CAPEX is considered to be a separate KPI. In such cases, the general KPI (in this case NPV) is considered to be the most representative KPI, i.e. the more general one;
- **Uniqueness –** KPIs that do not conform to the previous criteria are categorized as unique. These indicators are distinctive in their formulation and purpose and are thus labeled with the term "Uniqueness".

For clarity, given the number and variety of KPIs in the literature, multiple unification criteria may be used for the creation of one single unified KPI. After obtaining a set of unified KPIs, the indicators are further classified according to the following additional parameters:

- **Type** – Specifies whether the KPI is numeric or categorical (e.g., boolean indicators that reflect the presence or absence of specific characteristics within the REC);
- **Targets** – Identifies the specific stakeholders for whom the KPIs are intended, providing insight into which groups or entities would benefit from visualizing these KPIs. Common target groups in the context of RECs (Haji Bashi et al., 2023; Vernay et al., 2023) include:

o *Policymakers*: Government officials and regulatory authorities responsible for creating and implementing policies, laws, and regulations that affect RECs. Their role includes establishing legal frameworks that support the creation and operation of RECs; providing incentives, subsidies, or grants to promote renewable energy projects; ensuring compliance with environmental standards and goals; and facilitating cooperation among the various stakeholders involved in renewable energy (Campagna et al., 2024; D'Alpaos and Andreolli, 2020);
o *Stakeholders*: Individuals or groups (including residents, businesses, environmental organizations, energy providers, and financial institutions) that finance the REC project (Standal et al., 2023; Tatti et al., 2023);
o *REC members*: Individuals, households, businesses, or organizations that are part of a REC. Their role includes consuming, producing, or storing renewable energy generated within the community, having the opportunity to participate in decision-making processes related to the REC, sharing the benefits, such as reduced energy costs, and contributing to and supporting the community's sustainability goals (Ahmed et al., 2024);
o *REC or REC Manager*: Entity or individual responsible for managing the day-to-day operations of the renewable energy community. Their responsibilities include overseeing the production, distribution, and consumption of renewable energy within the community, ensuring the efficient and effective operation of renewable energy systems, handling administrative tasks such as billing, maintenance, and customer support, facilitating communication and collaboration among REC members and other stakeholders.

- **Data Perimeter** (DP) – Defines the physical boundaries within which data must be known to calculate the respective KPIs, providing a quick and immediate indication of the perimeter of the analysis when evaluating performance metrics. The DP can be selected from the following:

o REC members DP: the physical portion of space within the perimeter of the REC containing only the members of the REC (Fig. 1a) (exchange flows excluded);
o REC DP: the physical portion of space that coincides with the entire perimeter of the REC (Fig. 1b) (exchange flows included);
o REC-to-Grid DP: the physical portion of space within the perimeter of the REC containing only the exchange flows between the community and the electrical grid (Fig. 1c) (exchange flows included).

2.4. KPIs Reference List

In the final phase, the *KPI Reference List*, the essential KPIs for assessing the performance of one or more RECs are selected from those identified during the *KPIs Categorization and Unification* phase. The selection is guided by a Multi-Criteria Analysis (MCA) combined with the authors' expertise. MCA techniques are employed to identify the most preferred KPIs, rank them, shortlist key options for detailed appraisal, or distinguish acceptable from unacceptable possibilities (Multi-criteria analysis,). A crucial feature of MCA is its reliance on the judgment of the decision-making team in establishing objectives and criteria, assigning relative importance weights, and evaluating each option's contribution to the performance criteria. Another important aspect of MCA is the *performance matrix*, or consequence table, where each row represents an option, and each column details the performance of the options against specific criteria. For each *Sector Domain*, the KPIs are evaluated based on the following criteria:

- **Frequency** – The number of times the unified KPIs appear with mathematical formulations in the analyzed articles;
- **Usages Coverage** – The number of different *Usages* for which the unified KPIs were applied;
- **Targets Coverage** – The number of different *Targets* to which the unified KPIs are addressed.

The MCA numerical analysis typically consists of two stages, scoring and weighting:

1) *Scoring*: Each KPI is assigned a numerical score for each criterion

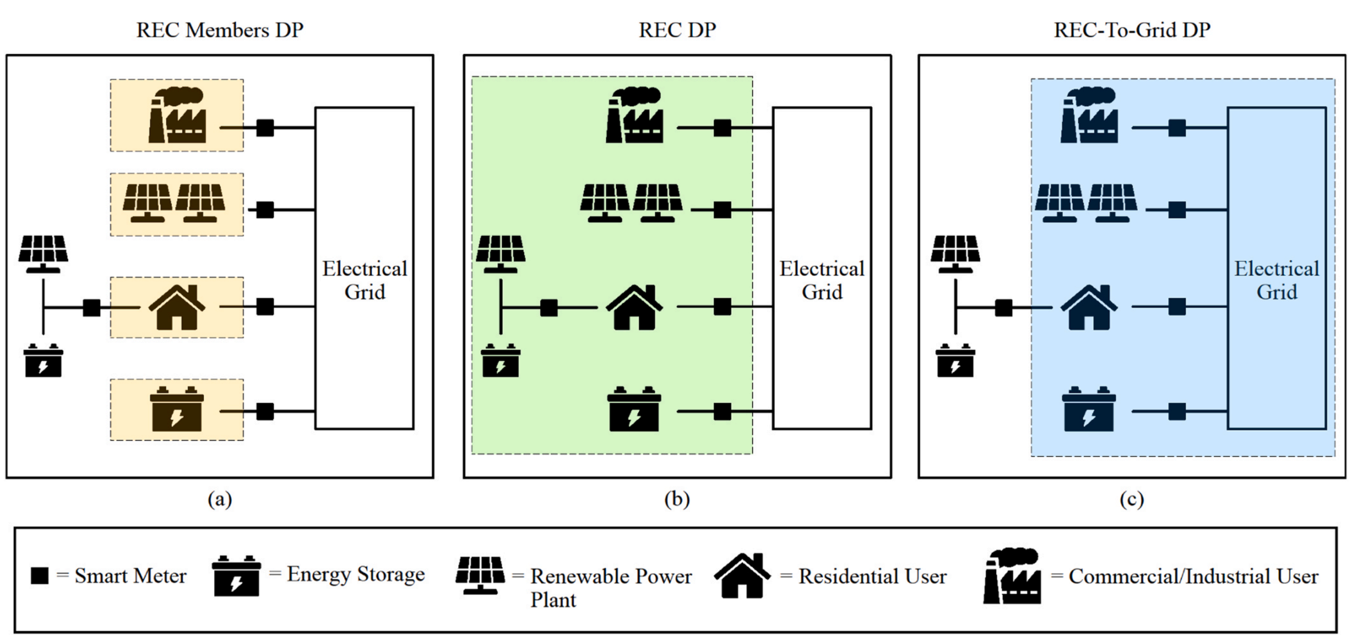

Fig. 1. Data Perimeters chosen to categorize the collected KPIs.

Table 2
Scoring applied to the performance matrix during MCA.

Score	Frequency	Usages Coverage	Targets Coverage
0.25	from 1 to 8	1 out of 4	1 out of 4
0.50	from 9 to 14	2 out of 4	2 out of 4
0.75	from 15 to 21	3 out of 4	3 out of 4
1.00	greater than 21	4 out of 4	4 out of 4

based on a preference scale, where higher scores reflect more preferred options. The evaluation in this paper follows the scale in Table 2.

2) *Weighting*: numerical weights (*w1*, *w2*, *w3*) are assigned to each criterion to reflect their relative importance. In this analysis, all criteria are considered equally important to better highlight the most general KPIs, so each weight is set to one.

After scoring, a linear additive model is applied to combine the scores for each criterion, resulting in an overall rating for each unified KPI (Multi-criteria analysis,). The combined score is calculated using the following Eq. 1:

$$MCA_{score} = w_1 * F + w_2 * UC + w_3 * TC \quad (1)$$

where:

- *F*, *UC,* and *TC* represent the scores for frequency, usage coverage, and target coverage, respectively, as determined from Table 2.

In addition to the MCA, the authors' experience and knowledge in the field of RECs is leveraged to finalize the KPI Reference list. This combined approach ensures the selection of metrics that comprehensively analyze the most important aspects across the four domains in which RECs operate—from individual community members to broader interactions with external entities like other RECs or the electrical grid. To ensure the KPI Reference List is practical and user-friendly, a concise set of metrics is proposed, with a maximum of eight KPIs per operational domain. This approach offers a streamlined, comprehensive, and easy-to-use selection of metrics for practical application in real REC projects.

3. Results

3.1. Literature Review

This section provides an objective description of the results obtained by the methodology described in Section 2, offering a critical overview and highlighting the most crucial aspects. The research on papers related to RECs and the use of KPIs to analyze their performance developed through the Literature Search phase, composed of *Papers Exploration*, *Papers Screening*, and *Papers Eligibility* sub-phases, led to the results shown in Fig. 2.

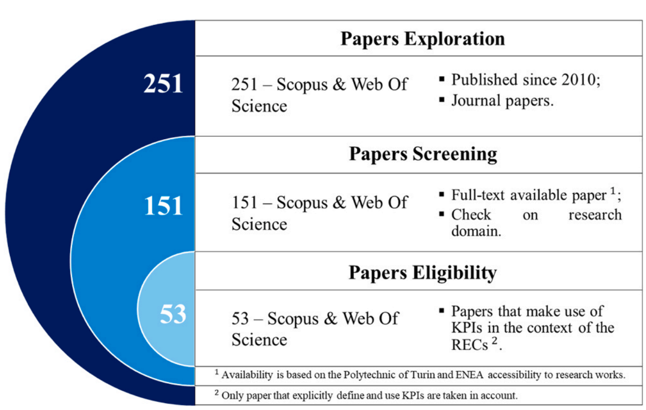

Fig. 2. Surveyed scientific journal papers from the first three phases of the systematic review.

The full results of the Literature Search phase are available in (Giannuzzo et al., 2024b), namely the dataset containing all the papers involved in the analysis. During the *Papers Exploration* step, 251 papers were obtained using the search engines Scopus and Web of Science (WoS) queries as described in the previous sections, respectively 207 from the combined research with Scopus and WoS, and 44 additional papers from WoS only. This high number of papers highlights the growing interest in RECs, as stated in many articles, such as in (Barabino et al., 2023; Bianco et al., 2021). The full-text accessibility of the obtained research articles and a further check of the research area reduced the total number of articles from 251 to 151, respectively 122 in Scopus and WoS and 29 in WoS only. The availability criterion is based on the Polytechnic of Turin and ENEA accessibility of the full text of the analyzed research works, meaning that papers that were not accessible to the authors were excluded from the analysis. The final stage of filtering, namely the *Papers Eligibility* phase, greatly reduced the total number of articles to 53, excluding those articles that do not use or explicitly define KPIs to analyze RECs. The exclusion of a large number of articles in the last stage of filtering is probably due to the fact that many research papers make extensive use of KPIs that are well-established in the literature, without necessarily having to redefine them explicitly, which indeed excludes them from the search for the criteria described in Section 2.

3.2. Database Creation

From the 53 identified papers, 316 KPIs were extracted during the *Database Creation* phase, which were explicitly defined through mathematical formulations and used in the RECs analysis processes. This set of KPIs includes repeated or similar KPIs, since this phase involves collecting all the KPIs defined in the analyzed articles. Of these, 138 were classified as energy, 62 as economic, 42 as environmental, and 74 as social KPIs, as shown in Fig. 3.

The presence of a predominant number of 'energy' KPIs explicitly defined through mathematical formulations and used for the analysis of RECs, might be due to the energy aspects' tendency to be mainly focussed on performance analysis, as also stated in the literature (Fouladvand et al., 2022; Canizes et al., 2023; Piselli et al., 2022). In addition, manuscripts focusing on investigating case studies have often the tendency to slightly modify and redefine some of the most commonly used energy KPIs. On the contrary, this occurs rarely in the case of economic and environmental KPIs, which tend to be more easily applicable in a variety of different case studies. Furthermore, during the *Database Creation* phase, KPIs are categorized by their *Usage*, namely the purpose for which they were used. A single KPI can be associated with more than one usage, so the sum of the frequency with which different

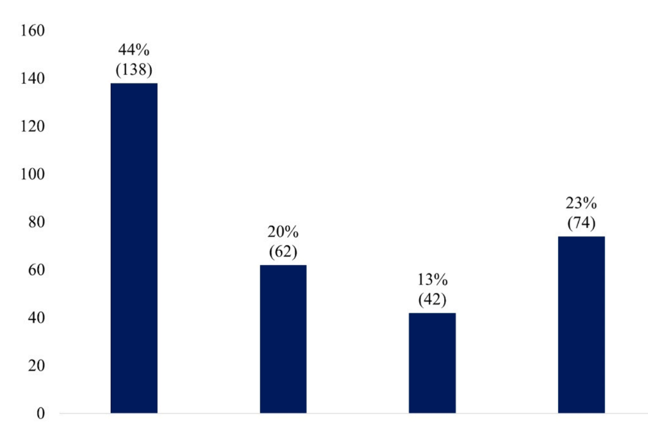

Fig. 3. Percentage based on *Sector Domains* for KPIs collected during the *KPIs Collection* phase.

Table 3
Frequency of Usage for the KPIs obtained during the Database Creation phase.

Usage	Frequency	Percentage
Monitoring	173	36 %
Operation	151	31 %
Benchmarking	69	24 %
Planning	91	19 %

usages occur can exceed the total number of KPIs identified. The results show that the most frequent *Usages* are the monitoring and operation ones, followed by benchmarking and planning, as shown in Table 3.

In addition, it was found that 191 of the 316 collected KPIs were used to analyze real case studies, showing that more than half (about 60 %) of the KPIs defined and used in articles inherent to RECs are applied to the study of an existing and operating energy community.

3.3. *KPIs Categorization and Unification*

Following the collection of KPIs defined by mathematical formulas in the analyzed papers, these KPIs are further categorized and unified according to the unification criteria outlined in Section 2.3. This process reduced the number of KPIs from 316 to 117, as reported in Fig. 4, which shows the variation in the number of KPIs across different *Sector Domains*.

As depicted, the energy KPIs experienced the most significant reduction, from 138 to 48. The number of economic KPIs also dropped substantially, from 62 to 20, and environmental KPIs saw a reduction from 42 to 7. In contrast, social KPIs underwent a less drastic decrease, from 74 to 42. Fig. 4 shows that the environmental KPIs experienced the largest reduction at nearly 81 %, followed by the economic KPIs with a reduction of approximately 68 %. The energy KPIs showed a slightly smaller percentage reduction of about 66 %, while social KPIs exhibited the smallest reduction at around 45 %. These changes in the number of KPIs, both in numerical and percentage terms, are directly related to how the unification criteria from Section 2.3 were applied. The frequency of the application of these criteria across each *Sector Domain* is summarized in Table 4. Each of the 117 unified KPIs corresponds to between one and four unification criteria, so the total unification criteria frequency count must result in a number between 117 and 468 (which is namely 136).

In general, as shown in Table 4, most KPIs are classified under the "uniqueness" criterion, with 60 instances identified. The second most frequently used unification criteria is "similarity", applied 43 times, which groups KPIs that share similar information and nearly identical mathematical formulation. The "relatedness" criterion was used 25 times, highlighting KPIs with mathematical relationships to each other, while the “equality” criterion was used 7 times. Focusing on specific *Sector Domains*:

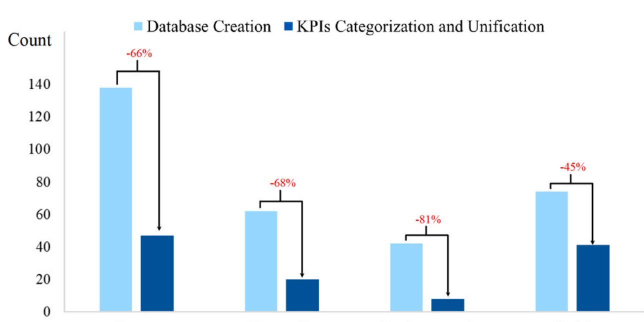

Fig. 4. Variation in the number of KPIs by Sector Domain between *KPIs Collection* and *KPIs Categorization and Unification* phases.

- Energy KPIs: The most impactful criteria are "uniqueness" (35 %) and "similarity" (33 %), followed by "relatedness" (25 %). A small portion (7 %) falls under "equality." This distribution results in a significant reduction in the number of energy KPIs between the *Database Creation* and *KPIs Categorization and Unification* phases;
- Economic KPIs: The "uniqueness" criterion predominates (46 %), while "similarity," "relatedness," and "equality" are less frequently used, each around 12–29 %;
- Environmental KPIs: Notably, no KPIs were classified under "equality," and the other unification criteria were applied only a few times, reflecting the small number of environmental KPIs collected earlier. This suggests these KPIs are more generalizable and aggregable compared to those in other sectors;
- Social KPIs: "uniqueness" is also dominant here, accounting for 52 % of the KPIs, with "similarity", "relatedness", and “equality” contributing 33 %, 13 %, and 2 %, respectively.

Additionally, Fig. 5 shows the impact of the unification process concerning each specific *Usage*. As shown, the unification process impacts KPIs across all Sector Domains and Usages fairly uniformly. However, certain cases stand out, such as environmental KPIs in planning contexts, which decreased from 10 to 1 KPI (a reduction of 90 %). Social and economic KPIs in benchmarking contexts experienced a less dramatic yet still significant reduction (from 11 to 7, about 36 %) or social KPIs in monitoring contexts (from 56 to 34, nearly 39 %). Following the methodology outlined in Section 2.3, the 117 unified KPIs are further classified based on their DP and Targets. Fig. 6 illustrates the distribution of DP among the unified KPIs.

As illustrated in Fig. 6, the REC DP is the most commonly used, applied to about 57 % of the unified KPIs, indicating that most KPIs require data from the entire REC perimeter. Around 30 % of the KPIs are limited to the REC Members DP, and only 13 % focus on the REC-to-Grid DP, which pertains to energy flows between the REC and the electrical grid. This shows that most indicators used to analyze REC projects generally require relatively extensive data knowledge. Fig. 7 shows the distribution of *Target* assigned to the unified KPIs.

The majority of KPIs are aimed at the REC or the REC manager (about 32 %), and policymakers (around 30 %), followed by stakeholders (almost 25 %). Only 13 % of the unified KPIs target community members. The sum of the assigned Targets (338) exceeds by far the number of KPIs (117), indicating that quite often KPIs serve multiple user groups. Fig. 8 shows the percentage composition of these *Targets* based on *Sector Domain*.

- Energy KPIs are primarily directed at the REC or REC manager (34 %) and policymakers (33 %), with a smaller focus on stakeholders (almost 27 %), and very little interest for REC members (6 %);
- Environmental KPIs show a similar trend, with a minimal focus on REC members (4 %), and balanced distribution among other targets (30–35 %);
- Social KPIs, however, show a more balanced distribution across REC (30 %), policymakers (28 %), stakeholders (22 %), and REC members (19 %);
- Economic KPIs are mainly directed to the REC and stakeholders (31 % each), with less focus on REC members (22 %) and policymakers (17 %).

Additionally, Fig. 9 provides further insights, showing that social KPIs dominate those addressed to REC members (52 %). Energy and social KPIs are more frequently directed toward the REC, policymakers, and stakeholders, while environmental and economic KPIs, on the other hand, are less prominent, except when economic KPIs are directed at stakeholders or REC members.

Table 4
Unification criteria utilization based on Sector Domain.

UnificationCriteria	Total Frequency	Frequency by Sector Domain			
		Energy	Economic	Environmental	Social
Uniqueness	60	35 %	46 %	44 %	52 %
Similarity	44	33 %	29 %	33 %	33 %
Relatedness	25	25 %	13 %	23 %	13 %
Equality	7	7 %	12 %	0 %	2 %

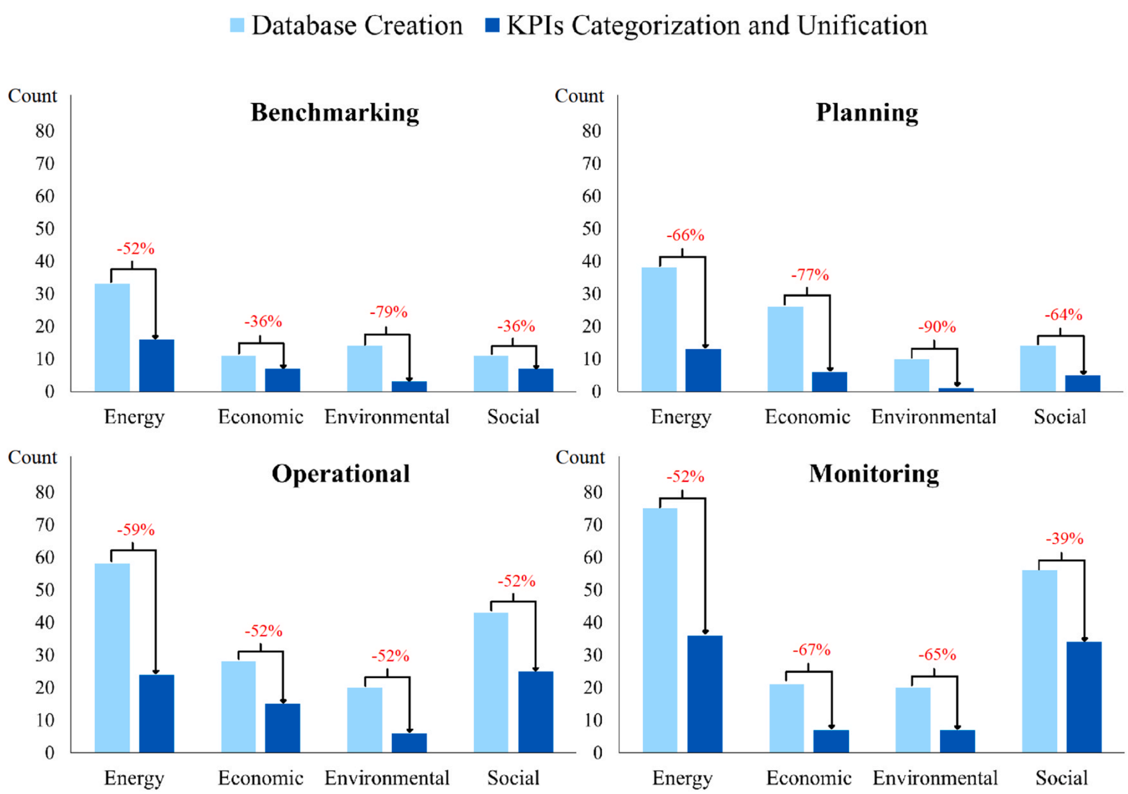

Fig. 5. Impact of the aggregation process within each *Usage* based on each *Sector Domain*.

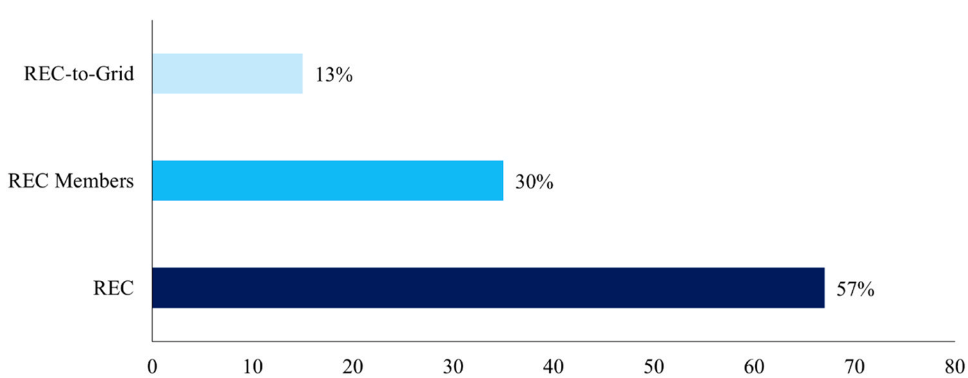

Fig. 6. Frequency of *Data Perimeters* allocated to the aggregated KPIs.

3.4. Multi-Critera Analysis

This section presents the results of the MCA described in Section 2.4. Principal variables, acronyms, and parameters used to calculate the KPIs are listed in Table 5.

Table 6 shows the application of the MCA to the energy KPIs obtained during the *KPIs Categorization and Unification* phase. The table lists the top 10 KPIs, ranked according to the performance matrix values, where the scoring and weighting processes were applied using a linear additive evaluation model. The full version of Table 6 can be found in

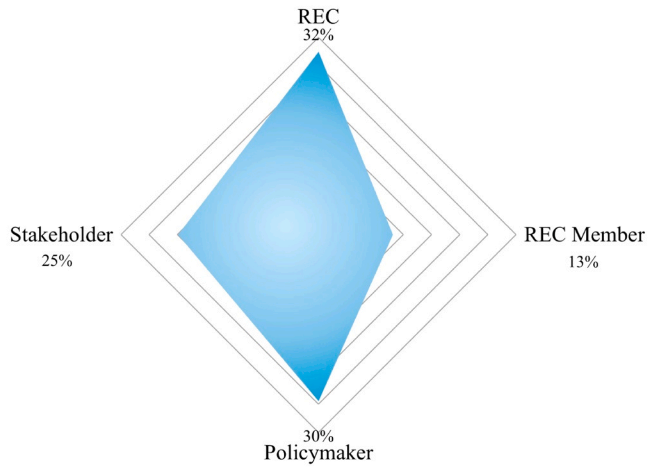

Fig. 7. Frequency of the *Targets* assigned to the unified KPIs.

(Giannuzzo et al., 2024b). Among the KPIs listed, some focus on quantifying the relationship between energy produced and consumed within the REC, such as the Electrical Self-Production Rate (ESP), Self-Consumption Rate (SCR), and Self-Sufficiency Rate (SSR). These metrics are descriptive of the general energy behavior of the community. Others, such as Total Energy Used (TEU), Frequency Standard Deviation (F_{std}), and Integration Coefficient (IC), are more specific and quantify the energy exchange between the REC and the electrical grid. Additional KPIs, like Local Storage Capacities (LSC), End-REC Members Automation (RMA), and New Energy Related Services (ERS), analyze even more specific characteristics of the REC. Meanwhile, Collective Self-Consumption (CSC) is a recurring indicator in the regulatory frameworks of some Member States. The table also highlights that the highest-ranked energy KPIs are those indicators characterized by a very high frequency, usage coverage, and target coverage. This demonstrates that these KPIs have been mathematically defined multiple times for a range of purposes (planning, benchmarking, operations, and monitoring) and have been used to communicate significant information to multiple targets (stakeholders, policymakers, RECs, and REC members). As we move down the table, the substantial difference between the top-ranked KPIs and the others appears to be related to frequency, indicating that some KPIs are less frequently mathematically defined and used, reflecting their lower relevance or a lesser need to define these indicators in detail.

The results also indicate that frequency, as defined in Section 2.4, is not the same as the number of papers in which KPIs are used. This is because it may occur that similar KPIs, which are later unified into a single indicator using the criteria outlined in Section 2.3, could be defined multiple times in one single paper, resulting in a frequency score higher than the number of papers in which the unified KPI was used. In addition, some KPIs are defined to be calculated over varying time windows, while others do not specify a particular time frame, suggesting they can be evaluated over different periods. For these latter indicators, the flexibility in their application likely leads to the omission of a specific time window in the literature.

Moving on to economic KPIs, Table 7 presents the top 10 economic indicators obtained through the MCA. The full version of Table 7 can be found in (Giannuzzo et al., 2024b). Among the economic KPIs, some are crucial for assessing the economic feasibility of implementing a REC, such as Net Present Value (NPV) and Economic Sustainability Factor (EF), while others, like Capital Expenditure (CAPEX) and Annual Energy Cashflow (AEC), are key components in these calculations. Additional indicators, such as Energy Bills Reduction (EBR), Businesses Creation (BC), and Business Diversity (BD), focus on specific economic aspects of the REC, quantifying the community's economic impact on its members. There are also KPIs like Share of Individual Savings (SIS) and Community Share of Market Savings (CSMS), which measure the benefits of developing a local energy market within the REC, as opposed to relying solely on grid energy transactions. Notably, many KPIs are defined without a specific time window for calculation, allowing for flexibility in their applications. However, certain KPIs, such as AEC and NPV, are often scaled to annual or longer time frames because they provide more meaningful insights when evaluated over these periods, although users can still calculate them over different time scales if needed.

As shown in Table 7, only AEC, CAPEX, and NPV have Frequency (F) scores different than 0.25, indicating that they are frequently defined mathematically in the literature. The remaining KPIs, although being in

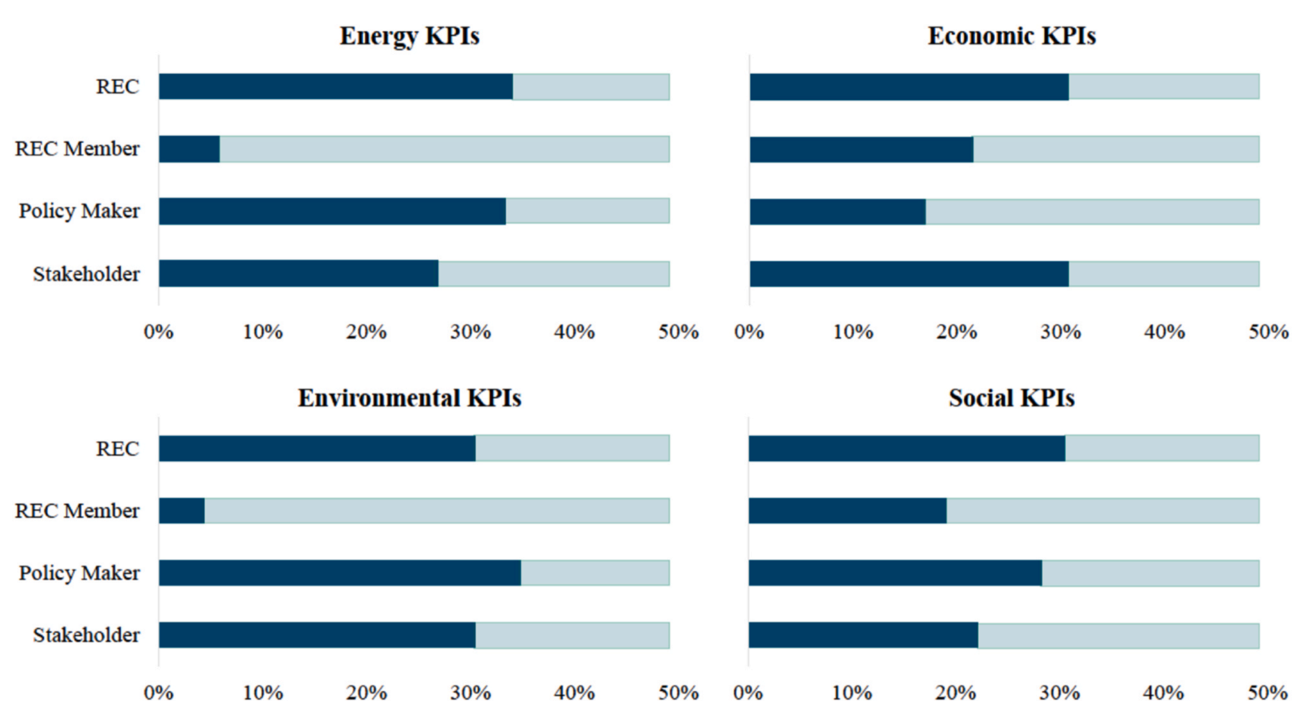

Fig. 8. Percentage composition of *Targets* based on *Sector Domain*.

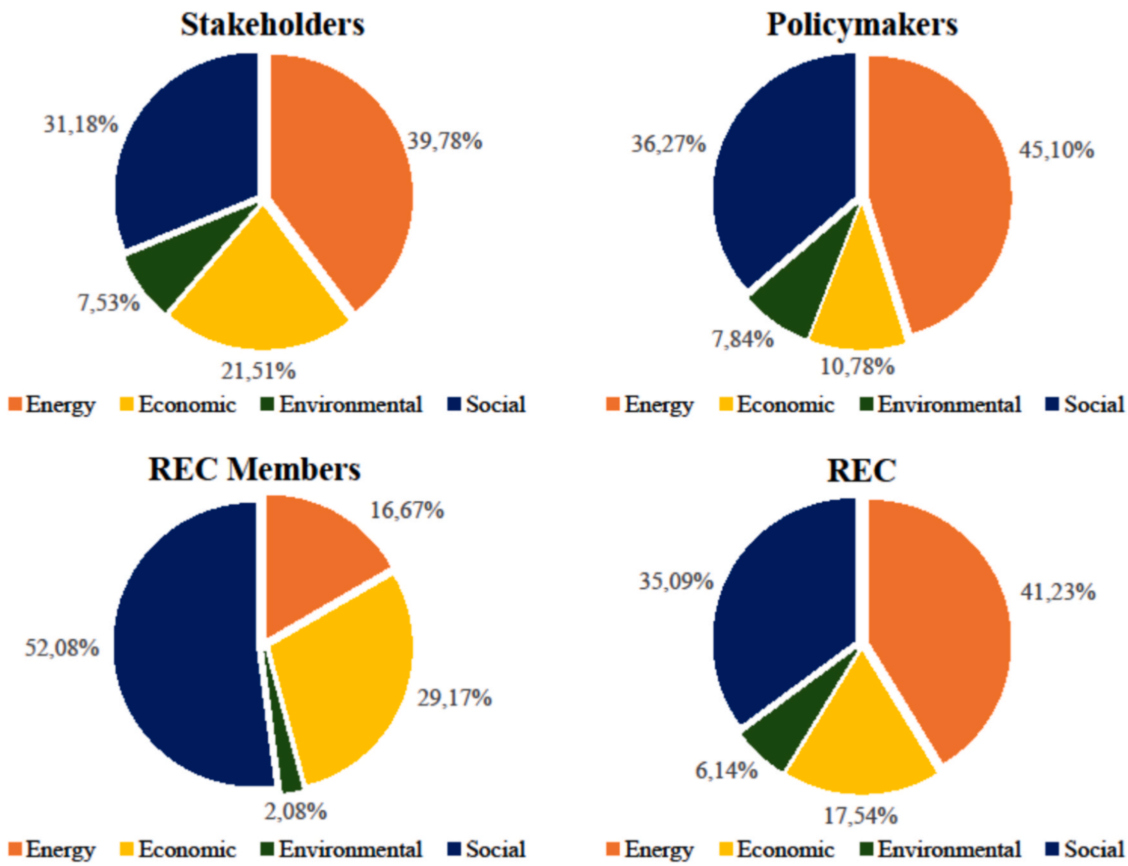

Fig. 9. *Sector Domains'* distribution based on the *Targets.*

the top 10 economic indicators, are less often mathematically defined in the literature. On the other hand, most of the KPIs have very high Target Coverage (TC) values, demonstrating their broad applicability to a wide range of objectives. The Usage Coverage (UC) scores tend to be medium, reflecting that these KPIs are commonly used for multiple purposes. Similar to energy indicators in Table 6, some economic KPIs do not specify the time frame within which they should be calculated.

Table 8 shows the results obtained by MCA for all environmental KPIs, noting that only 7 unified environmental KPIs were identified. Also, Table 8 can be found in (Giannuzzo et al., 2024b). These KPIs address various aspects, such as the impact of the REC on biodiversity (Biodiversity Impact), land use (Use of Land), noise impact on the local population (Noise Pollution Reduction), integration of electric vehicles (Low Carbon Public Transportation Vehicles Deployment Rate), and pollutant emissions (Environmental Impact and GHG Emissions). From a numerical point of view, as previously mentioned, the small number of environmental KPIs might reflect the fact that environmental impact can be summarized effectively with a limited set of indicators. It is also evident from the table that only one of the environmental KPIs (Environmental Impact) has a frequency value of 1, while the others have very low Frequency values. In contrast, the Target Coverage (TC) and Usage Coverage (UC) scores are more varied. Particularly, the TC values are very high, showing that this type of KPI generally covers a wide range of targets, while the UC values are moderate, similar to those overserved for the economic KPIs. Finally, Table 9 shows the top 10 social KPIs obtained through the MCA. The full version of Table 9 can be found in (Giannuzzo et al., 2024b).

Among these, some KPIs describe the social composition of the community (such as Stakeholders Diversity and Local Representation), while others quantify the REC's impact on the local population (such as Local Innovations, Education Programs Development, Social Energy Empowerment, and Citizens Satisfaction). As shown in the table, the top 10 social KPIs have identical MCA scores, reflecting the strong uniformity in their frequency, usage, and target coverage. Specifically, these KPIs exhibit very low Frequency, moderate Usage Coverage, and the highest Target Coverage, indicating that social KPIs are often aimed at all target groups and to about half of the *Usages* applications.

3.5. KPIs Reference List

In this section, the authors present a curated set of 25 KPIs constituting a structured framework for evaluating REC performances across energy, economic, social, and environmental domains. This comprehensive set is designed to assess various aspects of REC, offering a reference set of metrics that are categorized by sector, scope of use, target, and DP. In fact, the KPIs Reference List is intended to support different target groups through analysis across all phases of REC projects while maintaining consistency in data requirements and mathematical definitions for various applications. Although in the previous steps, the KPIs have already been categorized by *Usage* and *Target* according to how they were used in the articles previously analyzed, here the authors propose the *Targets* and *Usages* they consider most appropriate for each KPI based on their knowledge of the REC field. In addition, the authors in this list propose some new KPIs or modifications of existing ones previously identified to fill gaps in the literature and improve the effectiveness of the indicators: for example, compared to the indicators in the previous tables, in the KPIs Reference List they are defined to take into account their temporal extension within which they are calculated. Defining the time window within which KPIs can be calculated is a matter of considerable importance since many KPIs gain relevance as they are calculated over time. It is also important to note that for most KPIs, time windows of varying lengths can be used, depending on the purpose for which the KPIs are being used. The KPIs Reference List is derived from the results of the MCA and the authors' expertise,

Table 5
Principal variables, acronyms, and parameters used to define and calculate the KPIs.

Acronym	Full Text	Unit	*(Continue)*		
A	Area/Surface	m^2	SSR	Self-sufficiency Rate	%
AEC	Annual Energy Cashflow	€	SYC	Synchronization Coefficient	%
AFA	Annual Flexibility Activated	*kWh/y*	UoL	Use of Land	m^2
BC	Business Creation	*n*	X	Pollutant Emissions	*kg/y*
BD	Business Diversity	*n*			
BI	Biodiversity Impact	*n*	**Symbols**	**Full Text**	**Unit**
CAPEX	Capital Expenditures	€	*a*	Discount Rate	%
CF	Cashflow	€	*C*	Costs	€
CFB	Consumer Financial Benefit	%	*D*	Demand	*kWh*
CS	Citizen Satisfaction	%	*E*	Energy	*kWh*
CSC	Collective Self-Consumption	*kWh*	*Exp*	Expenditures	€
CSMS	Community Share of Market Savings	%	*Inc*	Incomes	€
dB	Decibels	*dB*	*p*	Unit price	€/*kWh*
EBR	Energy Bills Reduction	%			
EF	Economic Sustainability Factor	%	**Subscripts**	**Full Text**	
EI	Economic Incentives	*n*	*avail*	Available	
ENVI	Environmental Impact	%	*bills*	Energy Bills	
EPD	Education Program Development	*n*	*ed*	Educational	
EPH	Energy Poverty Help	*n*	*el*	Electrical	
ESO	Energy Storage Opportunity	*n*	*ep*	Energy Poverty	
ESP	Electrical Self-Production Rate	%	*eq*	Equivalent	
ESR	Energy-related Services	*n*	*ex*	Before	
EVD	Event Dynamism	*n*	*excess*	Exceeded	
F/*f*	Frequency	*f*	*fg*	From the grid	
GEIF	Grid Energy Interaction Factor	%	*flex*	Flexibility	
GHG	Green House Gasses	$kg\ of eq.CO_2$	*fp*	Fuel Poverty	
IC	Integration Coefficient	%	*i*	i-th generic element	
IRR	Internal Rate of Return	%	*innov*	Innovation	
LCOEC	Levelized Costs of Energy Consumed	€/*kWh*	*j*	j-th generic element	
LDG	Local Data Governance	-	*loss*	Losses	
LI	Local Innovation	*n*	*miss*	Missed	
LPTV	Low Carbon Public Transportation Vehicle	%	*n*	n-th REC's user	
LR	Local Representation	%	*oper*	operation	
LSC	Local Storage Capacity	*kWh/kW*	*poll*	Pollutant	
NPR	Noise Pollution Reduction	%	*prod*	Production/produced	
NPV	Net Present Value	€	*red*	Reduction	
ODA	Open Data Access	%	*rep*	Represented	
PBT	Payback Time	*y*	*resp*	Responsible	
REEC	Rare Earth Element Consumption	*kg/g*	*s*	Stakeholder	
RF	Revenues from Flexibility	€	*satisf*	Satisfied	
RMA	REC's Member Automation	%	*self-cons*	Self-consumed	
SBD	Social Business Development	*n*	*spec*	Species	
SCR	Self-consumption Rate	%	*sur*	surplus	
SE	Shared Energy	*kWh*	*t*	t-th timestep	
SEE	Social Energy Empowerment	%	*tg*	To the grid	
SIS	Share of Individual Savings	%	*tot*	Total	
SSR	Self-sufficiency Rate	%	*trans*	Transmission	
SYC	Synchronization Coefficient	%	*y*	Year	

additional indicators were included to enhance the overall set's effectiveness, with clear justifications provided. Table 10 summarizes the KPIs, organized by *Sector Domains*. The 25 KPIs of the *Reference List* are divided into 8 energy, 7 economic, 4 environmental, and 6 social indicators. The energy category has the highest number of KPIs, reflecting its importance in evaluating various aspects of RECs. The selected KPIs include those that describe the energy behavior of the REC (Self-Consumption Rate, Self-Sufficiency Rate, and Electrical Self-Production Rate), quantify exchanges between the REC and the electrical grid (Grid Energy Interaction Factor), and assess the integration of energy storage systems (Batteries Integration) and ancillary services like flexibility (Flexibility Activated). Additionally, two other KPIs from the literature are included: Shared Energy, a refined version of Collective Self-Consumption that considers only the energy drawn from and fed into the grid (excluding the physical self-consumption of the members), and Synchronization Coefficient, a metric commonly used in building energy analysis but never been applied to RECs.

The Synchronization Coefficient is an indicator that is intrinsically present and is inherently reflected in other KPIs, such as the Grid Energy Interaction Factor (GEIF), Self-Consumption Rate (SCR), and Collective Self-Consumption (CSC), as it measures the percentage of simultaneous production and consumption within the REC. However, the authors believe that presenting this indicator separately offers a more intuitive and immediate understanding for users of how much the consumption is contextual to production. Furthermore, the proposed list of energy KPIs effectively covers a wide range of *Usages* and *Targets*, incorporating several KPIs from Table 6, such as Electrical Self-Production Rate (ESP), Self-Sufficiency Rate (SSR), and Self-Consumption Rate (SCR). Specifically, these last two indicators have been modified by the authors (if compared to their version in Table 6) by adding Shared Energy (SE) to the numerator. This addition provides more insight into what is happening within the REC in terms of energy flows. Since the denominator of the indicators includes the energy produced (in the case of the Self-Consumption Rate) and the energy demand (in the case of the Self-Sufficiency Rate), i.e. the energy directly self-consumed but also the energy exchange flows between the REC and the grid, by adding Shared Energy (SE) to the numerator of both indicators, it also becomes representative of the energy exchange flows between the REC and the grid. In fact, by considering in the numerator only energy directly consumed by the REC (as shown in Table 6), the indicators relate energy flows directed to the grid to energy flows within the REC, effectively comparing energy flows of different natures and related to different DPs.

Table 6
Top 10 Energy KPIs based on the obtained MCA score (where UC is the Usages Coverage, TC is the Targets Coverage and F is the frequency, namely the number of articles in which the KPI was defined through mathematical formulations).

KPI	Formula	Definition	UC	TC	F	MCA Score	References
Electrical Self -Production Rate (ESP)	$ESP = \frac{E_{el,prod}}{D}$	Ratio between the total amount of electrical energy produced on the site and the electricity demand (%). $E_{el,prod}$ is the electrical energy produced by RES within the REC, D is the electrical energy demand of the REC.	1.00	0.75	0.50	2.25	(Bianco et al., 2021; Gjorgievski et al., 2023; Dóci et al., 2015; VERDE and ROSSETTO, 1970; Chaudhry et al., 2022; Ferroni et al., 2023; Bianchi et al., 2023)
Total Energy Used (TEU)	$TEU = \sum_{t=1}^{T}(E_{fg,t} + E_{prod,t})$	Energy supply from local resources inside the community and distribution network-based supply from outside (kWh). $E_{fg,t}$ is the electrical energy taken from the grid at the timestep t, E_{prod} is the electrical energy produced with RES within the REC at the timestep t.	1.00	0.75	0.5	2.25	(Canizes et al., 2023; Couraud et al., 2023; Bianchi et al., 2023; Cutore et al., 2023b; Esposito et al., 2024; Arriaga et al., 2016)
Self - Consumption Rate (SCR)	$SCR = \frac{E_{el,self-cons}}{E_{el,prod}}$	Ratio between the electrical energy self-consumed ($E_{el,self-cons}$) and the electrical energy produced within the REC (%).	0.75	0.50	0.75	2.00	(Cutore et al., 2023a; Couraud et al., 2023; Gjorgievski et al., 2023; VERDE and ROSSETTO, 1970; Esposito et al., 2024; Bergamaschi and Gagliardelli, 2023; Sanduleac et al., 2022; Lowitzsch et al., 2020; Azarova et al., 2019; When renewable energy policy,; Moroni et al., 2019; Lazzari et al., 2023; Coignard et al., 2021)
Self - Sufficiency Rate (SSR)	$SSR = \frac{E_{el,self-cons}}{D}$	Ratio between the electrical energy self-consumed ($E_{el,self-cons}$)and the electrical energy demand within the REC (%).	0.75	0.50	0.75	2.00	(Cutore et al., 2023a; Couraud et al., 2023; Cielo et al., 2021; Guo et al., 2022; Ceglia et al., 2022; Coignard et al., 2021; Mutani et al., 2021; Okwuibe et al., 2022; Korõtko et al., 2023; Kichou et al., 2020; Mehta and Tiefenbeck, 2022; Pires Klein et al., 2021)
Local Storage Capacities (LSC)	$LSC = \sum_{i=1}^{N} Storage\ Size_i$	Total locally installed storage (kWh or/ and kW) capacities inside the community. N is the number of energy storages within the REC.	0.75	1.00	0.25	2.00	(Couraud et al., 2023; Esposito et al., 2024; Nfah and Ngundam, 2012)
Collective Self -Consumption (CSC)	$CSC = \sum_{t=1}^{T}\sum_{n=1}^{N}\min(D_{n,t}, E_{prod,n,t})$	Minimum between the REC demand and production. N is the number of REC members, T is the time window, and $E_{prod,n,t}$ is the energy produced by the n-th member within the REC (kWh) at the timestep t, $D_{n,t}$ is the electrical energy demand by the n-th member within the REC (kWh) at the timestep t.	0.75	1.00	0.25	2.00	(Couraud et al., 2023; Mustika et al., 2022)
Integration Coefficient (IC)	$IC = \frac{E_{miss} + E_{excess} + E_{loss}}{D}$	Evaluates how efficiently a REC can integrate variable RES. E_{miss} is the electrical energy which is not covered by electrical production within the REC, E_{excess} is the surplus energy produced within the REC compared to the electricity demand, E_{loss} is the electrical energy wasted due to systems' losses (%).	0.50	1.00	0.25	1.75	(Mustika et al., 2022; Denis and Parker, 2009)
Frequency Standard Deviation (F_{std})	$F_{std} = \sqrt{\frac{\sum_{i=1}^{n}(f_i - \bar{f})^2}{n}}$	Quantifies the dispersion of frequency around the target value of 50/60 Hz. A lower value of the standard deviation of the frequency indicates a stable and reliable REC. f is the frequency of the part of the electrical grid within the REC (Hz).	0.50	1.00	0.25	1.75	(Arriaga et al., 2016; Ruggiero et al., 2014; Vecchi et al., 2024)
End-REC Members Automation (RMA)	$RMA = \frac{N_{remotely\ controll.loads}}{N_{REC\ loads}}$	Percentage of REC loads (including residential) remotely controllable through an API (%).	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Energy Related Services (ERS)	$ERS = N_{services\ REC-members}$	Number of energy services provided by REC to the stakeholders and end-REC Members (market-related, remote monitoring, etc).	0.75	0.75	0.25	1.75	(Couraud et al., 2023; Nfah and Ngundam, 2012)

In the economic category, the selected KPIs highlight various aspects such as project feasibility (Net Present Value and Internal Rate of Return), local market impact (Share of Individual Savings and Community Share of Market Savings), revenues from ancillary (Revenues from Flexibility), and cost reductions for REC members (Energy Bills Reduction). Four of these KPIs were selected from the MCA results in Table 7 to ensure comprehensive coverage of the Usages and Targets. KPIs such as Annual Energy Cashflow, Capital Expenditure, and Economic Sustainability Factor were not selected because they are necessary to calculate broader KPIs like NPV and IRR, which provide more significant insights into the project's feasibility, despite lower MCA scores. Indicators like Business Creation and Business Diversity were excluded in favor of KPIs

Table 7
Top 10 economic KPIs based on the obtained MCA score.

KPI	Formula	Definition	UC	TC	F	MCA Score	References
Annual Energy Cashflow (AEC)	$AEC = \sum_i Exp_i - \sum_j Inc_j$	Difference between the total yearly incomes and the expenses incurred for energy consumption and production (€/year).	0.75	0.75	1.00	2.50	(Azarova et al., 2019; Battaglia et al., 2024; Bergamaschi and Gagliardelli, 2023; Braeuer et al., 2022; Cavana et al., 2025; Cielo et al., 2021; Kaiser et al., 2022; Moroni et al., 2019; Nfah and Ngundam, 2012; Petrovich et al., 2025; Sousa et al., 2023; VERDE and ROSSETTO, 1970)
Businesses Creation (BC)	$BC = N_{bus,REC}$	Number of new businesses created within the REC design and deployment.	0.75	1.00	0.25	2.00	(Couraud et al., 2023; Herenčić et al., 2021)
Capital Expenditure (CAPEX)	$CAPEX = \sum_i C_{i,0}$	Initial costs incurred for the development, construction, and installation of infrastructure and equipment necessary to generate, store, and distribute renewable energy (€).	0.50	0.75	0.25	1.50	(Cutore et al., 2023a; Couraud et al., 2023; Bergamaschi and Gagliardelli, 2023; Azarova et al., 2019; Nfah and Ngundam, 2012; Vecchi et al., 2024)
Economic Sustainability Factor (EF)	$EF = \frac{\sum_{i=1}^{N} \frac{Inc_i}{N}}{\sum_{i=1}^{N} \frac{C_i}{N}}$	Comparison between project incomes and the system costs (%)., where N is the number of years.	0.50	1.00	0.25	1.75	(Lazzari et al., 2023)
Share of Individual Savings (SIS)	$SIS = \frac{\sum_{i=1}^{N} (P_i - P_i^*)}{\sum_{i=1}^{N} P_i}$	Percentage of savings made by an individual prosumer or consumer for trading energy in the REC as compared to trading without the REC (%), where P_i and P_i^* are the net costs for trading electricity without and with the REC, for the i-th user.	0.50	1.00	0.25	1.75	(Bergamaschi and Gagliardelli, 2023)
Community Share of Market Savings (CSMS)	$CSMS = \frac{\sum_{i=1}^{N} (P_{DSO,i} - P_{DSO,i}^*)}{\sum_{i=1}^{N} P_{DSO,i}}$	Sum of the shares of individual savings made by each local agent (DSOs) for trading energy within the REC ($P_{DSO,i}$) as compared to trading without the REC ($P_{DSO,i}^*$) (%).	0.50	1.00	0.25	1.75	(Bergamaschi and Gagliardelli, 2023)
Economic Incentives (EI)	$EI = N_{economic\ tools,REC}$	Yearly number of economic tools generated by the REC such as green or white certificates to decarbonize energy ($n_{tools}/year$).	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Business Diversity (BD)	$BD = N_{bus\ type,REC}$	Number of business types involved in the REC. It ranges between 1 and 5 based on the following typology of business within the REC: public, industrials, consulting, academics, SME, large enterprises.	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Energy Bills Reduction (EBR)	$EBR = 1 - \frac{\sum_{i=1}^{N} C_{bill,ex-REC,i}}{\sum_{i=1}^{N} C_{bill,REC,i}}$	Ratio between the energy bills before the development of the REC and energy bills after the creation of the REC. N is the total number of users within the REC (%).	0.25	1.00	0.25	1.50	(Couraud et al., 2023)
Net Present Values (NPV)	$NPV = -CAPEX + \sum_{i=0}^{N} \frac{CF_i}{(1-a)^i}$	Represents the difference between the present value of cash inflows and the present value of cash outflows over the project's lifetime (€). a is the annual discount rate and i is the year. N corresponds to the duration of the observed timeframe.	0.25	0.75	0.25	1.25	(Couraud et al., 2023; Dóci et al., 2015; VERDE and ROSSETTO, 1970; Gerundo and Marra, 2022; Battaglia et al., 2024; Coignard et al., 2021)

that offer deeper insights into the impact of local market implementation within the REC.

For the environmental domain, the authors selected 4 KPIs that capture the overall environmental impact of the REC, including land use (Use of Land), pollutant emissions (GHG Emissions and Environmental Impact), and emission reductions from electric vehicle integration (Low Carbon Public Transportation Vehicles Deployment Rate). KPIs such as Noise Pollution Reduction, Rare Earth Element Consumption, and Biodiversity Impact were excluded because they provide more specialized information and are less relevant for general environmental assessments of RECs.

Finally, the selected social KPIs are designed to quantify the REC's impact on the local population, the awareness of their role, and the benefits of the REC (such as Energy Poverty Help, Local Representation, Social Energy Empowerment, and Social Business Development). In contrast to Table 9, the authors also included indicators that address the critical aspect of monitoring and data availability over time, represented by Open Data Access and Local Data Governance.

4. Discussion

This study aimed to address the existing gaps in the literature concerning the evaluation of RECs by developing a comprehensive set of KPIs, the KPIs Reference list. The methodology involved a systematic review of over 200 research articles, followed by the categorization and unification of KPIs through a Multi-Criteria Analysis (MCA). The final output is a refined list of 25 KPIs that provide a robust framework for assessing REC performance across four key domains: energy, economic, social, and environmental. These KPIs were selected to cover various phases of REC projects, including planning, management, monitoring, and implementation, ensuring their applicability to diverse stakeholders and contexts. The results clearly demonstrate RECs are of significant scientific interest, as reflected in numerous studies (Barabino et al., 2023; Papadopoulos et al., 2023; Tatti et al., 2023; Multi-criteria analysis,). Despite this interest, only 53 of the analyzed papers included mathematical formulations of the KPIs used, which suggests a gap in the depth of analysis in many studies. This may be due in part to the reliance on well-established metrics, such as self-consumption and self-sufficiency ratios, which are widely recognized and often deemed unnecessary to redefine. However, this also indicates that only a smaller subset of articles delves into more complex and specific KPIs that require precise mathematical definitions.

Moreover, the analysis reveals that the energy and social aspects of RECs would benefit from a more diversified categorization of KPI types

Table 8
Environmental KPIs based on the obtained MCA score.

KPI	Formula	Definition	UC	TC	F	MCA Score	References
Environmental Impact (ENVI)	$ENVI = \frac{X_{poll,REC}}{X_{poll,ex-REC}}$	Environmental Impact in terms of *kg* per year of avoided X-specific pollutant (%).	1.00	0.75	1.00	2.75	(Bianco et al., 2021; Cutore et al., 2023a; Couraud et al., 2023; Multi-criteria analysis,; VERDE and ROSSETTO, 1970; Chaudhry et al., 2022; Esposito et al., 2024; Bergamaschi and Gagliardelli, 2023; Denis and Parker, 2009; Gerundo and Marra, 2022; Braeuer et al., 2022; Twum-Duah et al., 2022)
Low carbon Public Transportation Vehicles deployment rate (LPTV)	$LPTV = \frac{N_{LPTV}}{N_{REC\ public\ vehicles}}$	Assessment of the deployment rate of low carbon technologies for transport (%), where $N_{REC\ public\ vehicles}$ is the sum of total public vehicles, and N_{LPTV} is the number of low carbon vehicles within the REC.	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Noise Pollution Reduction (NPR)	$NPR = \frac{db_{REC}}{dB_{ex-REC}}$	Assesses the percentage reduction ofdB due to REC actions (%), where *dB* is the mean noise pollution registered within the REC.	0.50	0.75	0.25	1.50	(Couraud et al., 2023)
Biodiversity Impact (BI)	$BI = \sum_{i=1}^{I} S_{REC,i}$	Gathers information regarding possible disruption to biodiversity of local species as well as danger to certain animals and plants. Assessed by the number of animal species threatened by REC actions, where $S_{REC,i}$ refers to the i-th specie.	0.50	0.75	0.25	1.50	(Couraud et al., 2023)
Use of Land (UoL)	$UoL = \sum_{i=1}^{I} A_{no\ more\ avail,i}$	Surface of area no more available for agriculture or biodiversity because of REC actions (m2). $A_{no\ more\ avail,\ i}$ refers to the i-th surface within the REC no more available for agriculture or biodiversity.	0.50	0.75	0.25	1.50	(Couraud et al., 2023)
Rare Earth Element Consumption (REEC)	$REEC = \sum_{i=1}^{R} kg_{rare\ earth,i}$	Assess the resource consumption for the deployment of REC of rare earth material (kg), where $kg_{rare\ earth,i}$ refers to the i.th rare earth element used for the deployment of the REC.	0.50	0.75	0.25	1.50	(Couraud et al., 2023)
GHG Emissions (GHGE)	$GHGE = \sum_{i=1}^{I} (CO2_{eq,prod,i} + CO2_{eq,oper,i} + CO2_{eq,trans})$	GHG emissions (carbon footprint) in the community (kg of CO2-eq.) as the sum of the CO2 emission from production, operation and transportation of energy within the REC.	0.25	0.75	0.25	1.25	(VERDE and ROSSETTO, 1970; Chaudhry et al., 2022; Esposito et al., 2024; Azarova et al., 2019; Vecchi et al., 2024; Guo et al., 2022)

compared to economic and environmental aspects. This aligns with observations in the literature (Gjorgievski et al., 2021; Kouloumpis and Yan, 2021; Measuring energy efficiency, 2011), where energy and social KPIs cover more heterogeneous and multifaceted elements, whereas economic and environmental KPIs tend to focus on more straightforward, well-recognized metrics. For example, economic analysis often centers around the rate of return on investment, and environmental impact is frequently quantified through CO_2 emissions, either as an absolute value or as a reduction relative to a baseline (Ceglia et al., 2021; Liu et al., 2022).

The study also highlights that the KPIs identified during the *Database Creation* phase are mainly used in monitoring and operations contexts, reflecting the growing interest in the literature on these two areas, as in (Cutore et al., 2023a; Ceglia et al., 2021). In contrast, planning and benchmarking aspects appear less emphasized in current research (Ceglia et al., 2022; Coignard et al., 2021; Kouloumpis and Yan, 2021; Mazzeo et al., 2021), possibly because RECs have become more established in many countries, shifting the focus towards performance monitoring rather than initial planning (Twum-Duah et al., 2022; Mutani et al., 2021). However, the infrequent use of KPIs for benchmarking between different RECs suggests a gap in comparative analyses. As RECs continue to expand globally, the importance of comparative KPIs is likely to grow, underscoring the need for a comprehensive set of indicators to facilitate performance comparison and improvement across different communities.

In light of these findings, it would be beneficial to develop a standardized benchmarking platform or dashboard to monitor the impact of energy community policies across the EU. This tool could gather and compare data from different energy communities, supporting ongoing evaluation and informed policy development.

4.1. KPIs Reference List for REC

The KPIs Reference List summarized in Table 10 provides a well-rounded set of 25 indicators designed for a comprehensive assessment of REC performance across all key sectors from a more general point of view: energy, economic, environmental, and social. This curated selection is intended to be user-friendly, offering clear and actionable insights

Table 9
Top 10 social KPIs based on the obtained MCA score.

KPI	Formula	Definition	UC	TC	F	MCA Score	References
Local Representation (LR)	$LR = \frac{N_{rep,REC}}{N_{REC}}$	Assess the representativeness of the people constituting the local governance team (%). $N_{rep,REC}$ is the number of REC members feeling representative by the governance team, while N_{REC} is the total number of REC members.	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Ruggiero et al., 2014)
Social Energy Empowerment (SEE)	$SEE = \frac{N_{resp,REC}}{N_{REC}}$	Percentage of the population feeling responsible ($N_{resp,REC}$) for their own energy consumption (%).	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Ceglia et al., 2022)
SocialBusinessDevelopment (SBD)	$SBD = B_{EP} + B_{FP}$	Number of social businesses including consideration for energy poverty (B_{EP}) and fuel poverty (B_{FP}).	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Gerundo and Marra, 2022; Ceglia et al., 2022)
Citizens' Satisfaction (CS)	$CS = \frac{N_{satisf,REC}}{N_{REC}}$	Through surveys, this KPI indicates the degree of satisfaction of the population due to RECs measures. Assessed in the percentage of the population surveyed that is satisfied ($N_{satisf,REC}$) (%).	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Ruggiero et al., 2014)
Local Employment (LE)	$LE = N_{jobs,REC}$	Number of newly created job by REC stakeholders ($N_{jobs,REC}$), that are locally developed.	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Nfah and Ngundam, 2012)
Consumer Financial Benefits (CFB)	$CFB = \frac{N_{bill\ red,REC}}{N_{REC}}$	Percentage of REC members with a bill reduction ($N_{bill\ red,REC}$) in cost per kWh (%).	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Stakeholders Diversity (SD)	$SD = N_{s\ tyoe,REC}$	Diversity of types of stakeholders ($N_{stype,\ REC}$) involved in the REC (large private companies, SMEs, public organizations, etc.), from 1 to 4.	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Local Innovations (LI)	$LI = N_{innov} + N_{patents}$	Number of innovations (N_{innov}) such as products, services; and patents ($N_{patents}$) from local community and stakeholders.	0.50	1.00	0.25	1.75	(Couraud et al., 2023)
Education Programs Development (EPD)	$EPD = N_{ed\ programs,REC}$	Number of new energy-related local educational programs ($N_{ed\ programs;REC}$) created within the REC deployment project.	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Ceglia et al., 2022)
Event Dynamism (EVD)	$EVD = N_{events,REC}$	Number of project forums, workshops, seminars ($N_{events,REC}$) within the REC.	0.50	1.00	0.25	1.75	(Couraud et al., 2023; Ceglia et al., 2022)

that can be applied to various stages of REC analysis, from planning to operations and beyond.

The energy category, with 8 KPIs, has the most indicators, reflecting the complexity and multifaceted nature of energy management within RECs. The selected energy KPIs address the REC's overall energy behavior (Self-Consumption Rate (SCR), Self-Sufficiency Rate (SSR), and Electrical Self-Production Rate (ESP)), interactions with the electrical grid (Grid Energy Interaction Factor (GEIF)), the provision of ancillary services like flexibility (Activated Flexibility (AFA)), and the integration of energy storage systems (Batteries Integration (BAI)). These indicators ensure a holistic understanding of the REC's energy dynamics, filling gaps that were not fully covered by the KPIs in Table 4. Moreover, the inclusion of Shared Energy (SE) and Synchronization Coefficient (SYC) introduces critical insights into the virtual sharing of energy within the REC and the simultaneity between energy consumption and production, key aspects that are often overlooked but essential for optimizing REC operations.

In the economic domain, the 7 selected KPIs encompass a wide range of critical aspects, from evaluating the economic feasibility of the REC project (Net Present Value (NPV) and Internal Rate of Return (IRR)) to assessing the impact of a local energy market within the community (Share of Individual Savings (SIS) and Community Share of Market Savings (CSMS)), and the financial benefits derived from ancillary services like flexibility (Remuneration from Flexibility (RF)). These KPIs also include the reduction in electricity bills for REC members (Energy Bills Reduction (EBR)), which is a direct and highly relevant benefit for individual participants. The choice of these KPIs ensures comprehensive coverage of the economic benefits and objectives associated with REC implementation. Notably, although Annual Energy Cashflow (AEC), Capital Expenditure (CAPEX), and Economic Feasibility (EF) are present in Table 7, they were not included in the final list because they primarily serve as components for broader KPIs like NPV and IRR, which offer more integrated and meaningful insights into the project's economic viability. Similarly, Business Creation (BC) and Business Diversity (BD) were excluded in favor of KPIs like SIS and CSMS, which better capture the economic impact of establishing a local energy market, a crucial aspect of REC sustainability.

For environmental performance, the authors selected 4 KPIs that provide a focused yet comprehensive evaluation of the REC's impact. Indicators such as GHG Emissions (GHGE), Environmental Impact (ENVI), and Low Carbon Public Transportation Vehicles Deployment Rate (LPTV) are crucial for understanding the broader environmental implications of REC operations, while Use of Land (UoL) offers insights into the REC's physical footprint. In contrast, indicators like Noise Pollution Reduction (NPR), Rare Earth Element Consumption (REEC), and Biodiversity Impact (BI), although relevant, were excluded because they address more specific issues that may not be universally applicable to all RECs and therefore do not provide the general insights needed for a broad environmental assessment.

The social KPIs included in the KPIs Reference List were carefully chosen to quantify the impact of RECs on local communities. Indicators such as Energy Poverty Help (EPH), Local Representation (LR), Social Energy Empowerment (SEE), and Social Business Development (SBD) provide valuable insights into how RECs influence social dynamics and community well-being. Additionally, the inclusion of Open Data Access (ODA) and Local Data Governance (LDG) underscores the importance of data accessibility and long-term monitoring, which are critical for ensuring transparency and sustained community engagement. This selection contrasts with the emphasis in Table 9, as it highlights the necessity of ongoing data collection and accessibility in assessing the social impact of RECs, which is vital for fostering trust and ensuring the success of these initiatives over time.

In real-world contexts, the relevance of these KPIs extends far beyond theoretical frameworks or academic research. The indicators delineated in the KPIs Reference List function as pragmatic instruments for decision-makers, community leaders, and stakeholders directly involved in the operation and management of RECs. These KPIs can facilitate an unambiguous evaluation of the multifaceted benefits and challenges associated with transitioning to renewable energy systems, thereby ensuring that RECs can be effectively monitored and improved over

Table 10
Final KPI Reference List obtained by combining the MCA and the author's expertise.

KPI	Sector Domain	Formula	Definition	Usage	Target	Data Perimeter
Shared Energy (SE)	Energy	$SE = \min(E_{fg}, E_{tg})$	Minimum value, in every time step, between the energy withdrawn from the electrical grind and the electrical energy injected to the grid (kWh).	Planning, Monitoring	REC, Policymakers, Stakeholders	REC-To-Grid
Self – Consumption Rate (SCR)	Energy	$SCR = \frac{\sum_{t=1}^{T}(E_{el,self-cons,t} + SE_t)}{\sum_{t=1}^{T} E_{el,prod,t}}$	Ratio between the electrical energy self-consumed plus the shared energy and the electrical energy produced within the REC $E_{el,self-cons,t}$, SE_t, and $E_{el,prod,t}$ are respectively the self-consumed, the shared energy, and the electrical energy produced within the REC at the timestep t. T is the temporal extension in which the KPI is evaluated.	Planning, Monitoring, Benchmarking	REC, Policymakers, Stakeholders	REC
Self – Sufficiency Rate (SSR)	Energy	$SSR = \frac{\sum_{t=1}^{T}(E_{el,self-cons,t} + SE_t)}{\sum_{t=1}^{T} D_t}$	Ratio between the electrical energy self-consumed plus the shared energy and the electrical energy demand within the REC (%). T is the temporal extension in which the KPI is evaluated.	Planning, Monitoring, Benchmarking	REC, Policymakers, Stakeholders	REC
Electrical Self – Production Rate (ESP)	Energy	$ESP = \frac{\sum_{t=1}^{T} E_{el,prod,t}}{\sum_{t=1}^{T} D_t}$	See Table 6. T has been added as the temporal extension in which the KPI is evaluated.	Planning, Monitoring, Benchmarking	REC, Policymakers, Stakeholders	REC Members
Grid Energy Interaction Factor (GEIF)	Energy	$GEIF = \frac{\sum_{t=1}^{T}(E_{el,fg,t} + E_{el,tg,t})}{\sum_{t=1}^{T} D_t}$	Ratio between the energy taken from the grid, the energy injected into the grid, and the electricity demand of the REC (%).T is the temporal extension in which the KPI is evaluated.	Operation, Monitoring	REC, Policymakers	REC
Synchronization Coefficient (SYC)	Energy	$SYC = \frac{\sum_{t=1}^{T} E^{*}_{el,fg}}{\sum_{t=1}^{T} E_{el,fg}}$	Ratio between the electrical energy withdrawn from the grid when electrical energy is also produced by the REC ($E^{*}_{el,fg}$), and the overall electrical energy withdrawn from the grid ($E_{el,fg}$) (%). T is the temporal extension in which the KPI is evaluated.	Planning, Operation, Monitoring	REC, REC Members, Stakeholders	REC
Energy Storage Opportunity (ESO)	Energy	$ESO = \sum_{t=1}^{T} \max(0, \min(E_{REC\ sur,t}, E_{REC\ def,t}) - E_{REC\ storage,t})$	Quantifies the need for energy storage systems within the REC comparing the electrical energy surplus at the timestep t ($E_{REC\ sur,t}$), the electrical energy deficit ($E_{REC\ def,t}$) and the electrical energy charged or discharged at the timestep t by batteries within the REC ($E_{REC\ storage,t}$) (kWh).	Operation	REC, Stakeholders	REC
Flexibility Activated (FA)	Energy	$FA = \sum_{i=1}^{T} E_{flex,t}$	Annual energy used within the REC for flexibility purposes ($E_{flex,t}$) (kWh). T has been added as the temporal extension in which the KPI is evaluated.	Monitoring	REC, Policymakers	REC-To-Grid
Payback Time (PBT)	Economic	$PBT = \frac{C_0}{\overline{Inc_y} - \overline{Exp_y}}$	Refers to the period required for the savings and revenues generated from the REC project to equal the initial investment cost (y) Incomes and	Planning	REC, REC Members, Stakeholders	REC

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Table 10 (*continued*)

KPI	Sector Domain	Formula	Definition	Usage	Target	Data Perimeter
			expenses must be actualized using the discount rate.			
Energy Bills Reduction (EBR)	Economic	$EBR = 1 - \frac{\sum_{t=1}^{T} C_{bill,ex-REC,t}}{\sum_{t=1}^{T} C_{bill,REC,t}}$	See Table 7. T has been added as the temporal extension in which the KPI is evaluated.	Monitoring, Benchmarking	REC Members	REC Members
Levelized Cost of Energy Consumed (LCOEC)	Economic	$LCOEC = \frac{\sum_{n=1}^{N} \frac{I_n + M_n}{(1+a)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+a)^n}}$	Refers to the average cost per unit of energy consumed by the community over a time window (N) of the energy system. This metric considers all relevant costs, including capital expenditure (I), operation and maintenance (M), and financing, spread out over the total energy consumed by the community (E_n) (€/kWh).	Planning, Benchmarking	REC, Stakeholders	REC
Share of Individual Savings (SIS)	Economic	$SIS = \frac{\sum_{i=1}^{N} (P_i - P_i^*)}{\sum_{i=1}^{N} P_i}$	See Table 7.	Operation, Monitoring	REC, REC Members	REC Members
Community Share of Market Savings (CSMS)	Economic	$CSMS = \frac{\sum_{i=1}^{N} (P_{DSO,i} - P_{DSO,i}^*)}{\sum_{i=1}^{N} P_{DSO,i}}$	See Table 7.	Operation, Monitoring	REC, REC Members	REC Members
Revenues from Flexibility (RF)	Economic	$R_{flex} = \sum_{t=1}^{T} p_{flex,t} * E_{flex,t}$	Represents the revenues generated through flexibility services (€). $p_{flex,t}$ is a unit cost expressed in $€/kWh_{flex}$ and $E_{flex,t}$ is the energy provided at the timestep t. $p_{flex,t}$ is comprehensive both of flexibility availability and activation.	Monitoring	REC, REC Members, Policymakers	REC-To-Grid
Internal Rate of Return (IRR)	Economic	$0 = NPV = -CAPEX + \sum_{i=1}^{N} \frac{CF_i}{(1 - IRR)^n}$	It represents the discount rate at which the net present value (NPV) of all cash flows (both inflows and outflows) from the investment equals zero.	Planning	REC; REC Members, Stakeholders	REC
Environmental Impact (ENVI)	Environmental	$ENVI = \frac{\sum_{t=1}^{T} X_{poll,REC,t}}{\sum_{t=1}^{T} X_{poll,ex-REC,t}}$	See Table 8. T has been added as the temporal extension in which the KPI is evaluated.	Planning, Monitoring, Benchmarking	REC, Policymakers	REC
Low carbon Public Transportation Vehicles deployment rate (LPTV)	Environmental	$LPTV = \frac{N_{LPTV}}{N_{REC\ public\ vehicles}}$	See Table 8.	Monitoring, Benchmarking	REC, REC Members, Policymakers	REC
Use of Land (UoL)	Environmental	$UoL = \sum_{i=1}^{I} A_{no\ more\ avail,i}$	See Table 8.	Planning, Monitoring	REC, Policymakers	REC
GHG Emissions (GHGE)	Environmental	$GHGE = \sum_{i=1}^{T} (CO2_{eq,prod,t} + CO2_{eq,oper,t} + CO2_{eq,trans,t})$	See Table 8. T has been added as the temporal extension in which the KPI is evaluated.	Operation, Monitoring	REC, Policymakers	REC
Social Energy Empowerment (SEE)	Social	$SEE = \frac{N_{resp,REC}}{N_{REC}}$	See Table 9.	Monitoring	REC Members	REC
Social Business Development (SBD)	Social	$SBD = B_{EP} + B_{FP}$	See Table 9.	Monitoring	REC, REC Members	REC
Energy Poverty Help (EPH)	Social	$EPH = \frac{REC_{Inc}}{MUC * Bp_{grid}}$	Represents the ration between incomes of the REC (REC_{Inc}) and the Mean User Consumption (MUC) multiplied by the buying price of electrical energy from the grid (BP_{grid}). It assesses how many REC members in energy poverty could be helped by the REC (n).	Monitoring, Benchmarking	REC, REC Members	REC

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Table 10 (*continued*)

KPI	Sector Domain	Formula	Definition	Usage	Target	Data Perimeter
Open Data Access (ODA)	Social	$ODA = \frac{REC_{open\ data}}{REC_{data}}$	Percentage of anonymised or aggregated monitored data accessible to the public through an API (%).	Monitoring, Benchmarking	REC, REC Members, Policymakers	REC
Local Data Governance (LDG)	Social	$LDG = Yes/No$	Indicates if a committee of citizens and stakeholders (industrial, academics, social scientists, etc) has been established to work on different aspects of local data (sharing agreement, monitoring agreement, GDPR support, transparency, etc).	Planning	REC, REC Members, Stakeholders	REC
Local Representation (LR)	Social	$LR = \frac{N_{rep,REC}}{N_{REC}}$	See Table 9.	Monitoring, Benchmarking	REC, REC Members	REC

time. In the energy sector, for instance, KPIs such as the Self-Consumption Rate (SCR) and the Electrical Self-Production Rate (ESP) directly align with real-world concerns about energy independence, grid resilience, and reducing reliance on external energy sources, as demonstrated in (Ghiani et al., 2022; Mutani et al., 2021). They can play a crucial role in reducing the impact of fluctuating energy prices and enhancing the stability of the electrical grid during periods of imbalance. By effectively measuring energy performance, RECs can also ensure that the integration of renewable energy sources is optimized, benefiting not only local communities but also contributing to broader energy sustainability goals.

From an economic perspective, KPIs such as net present value (NPV) and internal rate of return (IRR) are of significant value to investors, policymakers, and energy cooperatives. These financial metrics offer clear insights into the long-term economic viability of REC projects, providing important information for securing funding and fostering public-private partnerships, as shown in (Cutore et al., 2023b). Furthermore, KPIs such as Share of Individual Savings (SIS) and Community Share of Market Savings (CSMS) illustrate how RECs can result in quantifiable financial advantages for local populations, underscoring the immediate economic empowerment of communities. This is particularly relevant in regions facing high energy costs or where economic inequality may limit access to renewable energy solutions.

Environmental KPIs, including Greenhouse Gas Emissions (GHGE) and the Low Carbon Public Transportation Vehicles Deployment Rate (LPTV), have been demonstrated to have a quantifiable impact on addressing global climate change and fostering local environmental stewardship in real-world contexts (Azarova et al., 2019). These indicators can be utilized by municipalities and regional authorities to assess the efficacy of REC-driven initiatives in reducing carbon footprints and enhancing air quality. This assessment can inform climate action plans and policy decisions at various levels of governance. The environmental benefits of these KPIs are crucial for aligning REC projects with broader national and international sustainability targets, reinforcing the role of RECs as essential components of the transition to a low-carbon economy.

Finally, from a social perspective, the KPIs related to Energy Poverty Help (EPH) and Social Energy Empowerment (SEE) directly address the role of RECs in enhancing social equity and improving access to energy for underserved communities. These metrics facilitate the quantification of the potential for RECs to mitigate energy poverty, thereby fostering a more inclusive and affordable energy transition. Furthermore, they empower communities to actively engage in energy decisions, fostering a sense of community ownership and resilience. Furthermore, the incorporation of Local Data Governance (LDG) and Open Data Access (ODA) underscores the necessity of ensuring that these projects are transparent, accountable, and participatory, thereby fortifying community trust and transparency.

4.2. KPIs trends in the literature

A clear trend in the literature is the repeated use of similar or identical KPIs, particularly in the economic and environmental domains. This frequent overlap led, applying the methodology of this paper, to a significant reduction in the number of unique KPIs, from 316 initially identified to 117 after consolidating similar metrics. This indicates a reliance on well-established measures, especially in areas where standard metrics like economic returns or environmental impacts (e.g., CO2 emissions) are commonly applied.

Another notable trend is the strong emphasis on KPIs that require comprehensive data collection across the entire REC. Only a small portion of KPIs focus on more specific data, such as interactions between the REC and the grid or data from individual REC members. This underscores the critical role of extensive data monitoring in accurately assessing REC performance and shaping effective policies, as highlighted in previous studies (Okwuibe et al., 2022; Korõtko et al., 2023). The need for broad data coverage suggests that future policy efforts should prioritize enhancing data collection frameworks within RECs to support more detailed and effective performance monitoring.

The obtained results show that KPIs predominantly target the REC (or its manager), policymakers, and stakeholders, with only about 13 % specifically aimed at individual REC members (Fig. 8). This aligns with the literature's historical focus on optimizing REC performance at a system-wide level, especially during the early stages of REC implementation and operation (Kichou et al., 2020; Herenčić et al., 2021; Mehta and Tiefenbeck, 2022; Pires Klein et al., 2021; Dauenhauer et al., 2020; Tsolakis et al., 2020; Oprea and Bâra, 2021; Caramanico et al., 2021; Sarfarazi et al., 2020). Energy KPIs, for instance, typically concentrate on system-wide impacts such as energy consumption, self-consumption, and grid interactions, which are areas of primary interest to policymakers and REC managers. Similarly, economic KPIs often focus on financial incentives and operational costs, which are crucial for these groups. The strong linkage between energy and economic parameters, as highlighted in some KPIs, is also well-documented in the literature (Zhang et al., 2024; Uddin et al., 2023). This interdependence is particularly evident in the context of incentives for the diffusion of REC projects, which are largely managed by policymakers (Musumeci, 2022). This interdependence further underscores the focus on system-level KPIs, which cater to the interests of policymakers and REC managers, while the specific needs of individual REC members, such as personal energy savings and social benefits, remain underrepresented, as shown in Fig. 8. This gap suggests a need for developing more user-friendly KPIs that can better engage REC members, enhancing their participation and contributing to greater energy efficiency within the community. Based on this analysis, energy KPIs appear to be of limited relevance to individual REC members, as indicated in Fig. 8. In contrast, economic KPIs, particularly those related to reduced energy bills, and social KPIs, seem to resonate more with this group. To shift this perspective, it is crucial to develop easy-to-understand KPIs tailored for community end users. Such KPIs would help increase awareness, involvement, and engagement with energy-related aspects, fostering greater energy literacy and participation within the community.

4.3. MCA Findings

The MCA results highlight the importance of certain KPIs that effectively address a wide range of *Targets* and *Usages* across the identified *Sector Domains*. As shown in Table 6, the top-ranked energy KPIs, such as Electrical Self-Production Rate (ESP), Self-Sufficiency Rate (SSR), Self-Consumption Rate (SCR), and Total Energy Used (TEU), are particularly valuable, accordingly to what was demonstrated in (Cavana et al., 2025; Petrovich et al., 2025; Branchetti et al., 2025). These KPIs offer essential insights into the energy dynamics within the REC, which are crucial for stakeholders, policymakers, and REC members in various activities, including planning, monitoring, benchmarking, and operations. Interestingly, looking at the obtained KPIs definition in Table 6, a few of the top energy KPIs focus specifically on the interaction between the REC and the electrical grid. For example, the Grid Energy Interaction Factor (GEIF), later included by the authors in the KPIs Reference List, does not appear among the highest rankings, unlike Frequency Standard Deviation (F_{std}), which is notable for indicating potential blackout risks within the REC, an issue of concern for multiple user groups. Other KPIs, such as End-REC Members Automation (RMA) and New Energy Related Services (ERS), provide detailed insights but may not significantly impact the overall understanding of REC performance, although they remain relevant to certain users. Additionally, widely recognized KPIs in REC energy analysis, like Self-Sufficiency Rate (SSR) and Self-Consumption Rate (SCR), do not rank as highly, likely because the MCA frequency criterion is based on how often a KPI is explicitly defined using mathematical formulations. Many studies employ these metrics directly without redefinition, as seen in works like (Cosic et al., 2021; Masip et al., 2023), which may explain their lower ranking despite their extensive use.

Among the economic KPIs presented in Table 7, there are indicators of a more heterogeneous nature, ranging from pre-feasibility study assessments like Net Present Value (NPV) and Economic Feasibility (EF) to metrics measuring the economic impact of the REC over time, such as Energy Bills Reduction (EBR). The analysis shows significant relevance in evaluating the implementation impact of a local energy market within a REC, as reflected in the presence of indicators like Share of Individual Savings (SIS) and Community Share of Market Savings (CSMS), which aligns with findings in the literature (Mengelkamp et al., 2019; Capper and Gorbatcheva, 2022). In addition, indicators such as Capital Expenditure (CAPEX) and Annual Energy Cashflow (AEC) are among the most valued and frequently used in the literature. However, Table 7 does not include indicators related to the economic analysis of ancillary services offered by the REC, such as flexibility services, indicating that this topic is still underexplored economically compared to others. Furthermore, KPIs such as Business Diversity (BD) and Economic Incentives (EI), while applicable to different types of users, do not provide significant insight into the economic performance of the REC. Instead, they tend to be descriptive of certain aspects of the REC's economics. Similar to the energy KPIs, economic KPIs that one would expect to dominate due to their frequency of use, such as NPV, Internal Rate of Return (IRR), CAPEX, and Value Added Net (VAN), do not top the MCA score rankings because many articles use these indicators without necessarily redefining them mathematically.

Finally, most of the social indicators obtained from the MCA have the same MCA score, highlighting that most of them are primarily aimed at the same types of users, are almost always used for the same purposes, and are used a comparable number of times in the literature. Many of the KPIs, Citizens Satisfaction (CS), Local Representation (LR), Education Programs Development (EPD), and Event Dynamism (EVD), focus on quantifying the degree of interaction between REC members and REC governance. While these indicators capture related yet distinct dynamics, they often result in some redundancy. In contrast, there are fewer indicators that assess the REC's broader impact on the community, such as Energy Poverty Help (EPH), or address crucial issues like accessibility and data collection within the REC, such as Open Data Access (ODA) and Local Data Governance (LDG). These aspects, though less frequently quantified, are equally important and warrant greater attention in REC performance evaluations.

5. Conclusions

This study takes a thorough approach to improving the assessment of Renewable Energy Communities (RECs) by systematically reviewing and categorizing key performance indicators (KPIs) across the important areas of energy, economics, social impact, and environmental sustainability. Maintaining in the analysis simultaneously different domain sectors allows to capture the complexities of these communities, and to avoid restricted and partial conclusions when taking into account only few and inappropriate KPIs. As RECs are set to play a transformative role in the global shift towards cleaner energy, this paper offers an essential set of tools for evaluating and enhancing these communities. Through an extensive literature review, we identified and collected 316 KPIs from 200 research papers, which were then thoroughly analyzed, unified, and refined. This process led to the development of a streamlined set of 117 unified KPIs, capturing the essence of REC performance while eliminating redundancies. Each KPI was further categorized by its intended audience, whether policymakers, stakeholders, REC managers, or community members, and by the data required for accurate calculation. A Multi-Criteria Analysis (MCA) was conducted to prioritize the most effective KPIs, identifying those with the versatility to serve multiple purposes and benefit a diverse array of users. The final contribution of this work is a curated list of 25 KPIs, the KPIs Reference List, which we propose as a robust and practical framework for comprehensively evaluating RECs. These indicators are designed to provide clear and actionable insights that are essential for guiding REC planning, operations, monitoring, and benchmarking. Notably, the obtained results underscore the importance of energy KPIs in understanding REC dynamics, while also highlighting the need for more targeted indicators that address the economic and social dimensions, particularly those relevant to individual REC members. However, while this study offers a solid foundation, the reliance on existing literature means that emerging trends and newly developed KPIs may not yet be fully captured. Additionally, the current focus is predominantly on system-wide performance, suggesting a need for future research to develop more user-friendly KPIs that engage individual REC members and enhance their active participation. We suggest future work to expand upon this framework, exploring the economic impacts of ancillary services within RECs and developing KPIs that are better tailored to the needs of community members. By continuing to refine and expand the results obtained in this research work, we can ensure that RECs not only thrive but also become models of sustainability and community empowerment in the energy landscape.

CRediT authorship contribution statement

Angelo Frascella: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation. **Andrea Lanzini:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Conceptualization. **Lorenzo Giannuzzo:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Demetrio Minuto:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Schiera Daniele:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlo Petrovich:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Samuele Branchetti:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Nicola Gessa:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

I have shared the data using a zenodo link (see Reference [50] in the manuscript)

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