

Italian renewable energy communities: status and prospect development analysis

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ABSTRACT

2050 Carbon emissions have become an urgent problem for all the countries across EU. Conserving renewable energy in buildings has emerged as one of the primary strategies for reducing the greenhouse gases. Developing and spread self-sufficient energy communities integrated with renewable energy source has emerged as more impacting approach for lowering the impact of the building sector. The latest Renewable Energy Directive (RED) III published in October 2023, increased European Union's ambition for renewable energy transition. Italy keeps updating its regulations following the directive and aims to cover 55.4% of its gross final electricity consumption with renewable energy by 2030. The research aims at analyzing the policy trajectory, energy community transition status and potential challenge through policy analysis and case studies analysis. This research illustrated the process of the policy and legislation refining and regulating renewable energy communities (RECs) and compared the difference from EU to Italy. RECs database, key performance indicators configuration and data analysis were carried out to systematically conclude the REC developing status. This work presents in a unique way the state of the art of the REC, with a focus on the Italian context, and serves as a reference point that captures the current status and outlines possible future developments. Driven by incentive policies, approximately 55% of RECs in Italy are located in small municipalities with populations under 5,000. Among them, only 26.4% are project-specific RECs focused on individual buildings or energy systems. Therefore, both a general REC database and a detailed project-level database are established in this study. Through database comparison, eight key performance indicators were collected and analyzed to depict the typical RECs status in order to support policymakers and stakeholders to revise and ameliorate standards and procedures to promote and spread the transition towards renewable energy communities.

1. Introduction

WMO confirmed 2024 as the first year with global temperature exceeded 1.5 °C above the goal set by the Paris Agreement [1]. The Intergovernmental Panel on Climate Change (IPCC) emphasizes increase share of renewable can help decarbonize energy supply [2]. With the European Green Deal, the European Commission committed to carbon neutrality by 2050 [3]. These agreements and targets are primarily intended to expedite the global energy transition and reduce fossil energy consumption [4]. Urban population growing and urban areas keep consuming 75 % of global primary energy which emit more than 60 % of greenhouse gases according to the United Nations Human Settlements Program (UN-Habitat) [5]. One significant contributor to carbon emissions is the electrical energy vector, which is predominantly generated

from fossil fuels. Increasing the share of renewable energy in the energy mix can effectively reduce carbon dioxide concentrations [6] with energy community (EC) approaches to carbon emission mitigation have gained recognition as an effective strategy [7]. In the field of EC, there are many similar terms, and they have slightly different definitions defined by policies or legislations. When EC initially emerged, in 1980 s, its primary goal was on producing renewable energy, including heat and electricity [8]. As research has progressed, the concept of EC has been progressively improved and separated into detailed categories, such as Citizen Energy Community (CEC) and Renewable Energy Community (REC). CEC is a legally recognized organization enables small enterprises, local governments, citizen groups, and people to establish unified electricity market rules in 2019/944/EU Internal Electricity Market (IEM) Directive [9]. Conceptually, the REC places greater emphasis on its non-profit nature and are subject to fewer legal requirements. RECs

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Nomenclature	
ACER	Agency for the Cooperation of Energy Regulators
ANT	Actor-Network Theory
BESS	Battery Energy Storage Systems
CEC	Citizen Energy Community
DRE	Distributed Renewable Energy
EC	Energy Community
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
ERDF	European Regional Development Fund
EV	Electric Vehicles
IME	Internal Electricity Market
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
MASE	the Ministry of Environment and Energy Security
NECps	National Energy and Climate Plans
NPRR	National Recovery and Resilience Plan
PED	Positive Energy District
PNIEC	National Integrated Energy and Climate Plan
PV	Photovoltaic
REC	Renewable Energy Community
RED	Renewable Energy Directive
RES	Renewable Energy Source
SME	Small and Medium-Sized enterprise
TIAD	Text on Collective Self-Consumption
UN-Habitat	The United Nations Human Settlements Programme

offer a several community benefits, including economic development, energy resilience, and built environment sustainability. In respect to the economic development, the job creation is the main benefit. RECs not only promote sustainable energy production (mainly integrating PV technologies) but also stimulate local job creation across sectors such as system installation, maintenance and digital services. Another relevant benefit is represented by the community engagement valorizing the role of active local citizen and stakeholder participation in the RECs planning and management, which enhance social cohesion and encourages more democratic local energy governance. As major benefit the RECs can reduce energy poverty by enabling access to clean, affordable energy, especially for vulnerable and low-income populations [10]. Italy has been a forerunner within the European Union in advancing RECs at both legislative and practical levels. Accordingly, this study adopts Italy's REC development as a case study to identify underlying patterns and challenges in the legislative framework and its practical implementation. Italy has incorporated the concept of the REC into its national legislation through Legislative Decree No. 199/2021 [11]. Resolution 727/2022/R/eel [12] and Decree n. 414 of 7 December 2023 have been clarified and operationalized through the rules issued by the Ministry of Environment and Energy Security (MASE), GSE and regulatory resolutions by the national authority ARERA [13]. In this resolution, RECs are formally incorporated within the broader framework of distributed self-consumption, which delineates the scope of Distributed Renewable Energy (DRE) utilization. The resolution also establishes corresponding economic settlement mechanisms and regulatory framework to support implementation. Through a comparative analysis of distributed self-consumption configurations, this study highlights the specific distinctions among the REC and similar organizations within the Italian legal framework, focusing on aspects such as the number of users, types of production capacity, energy production typology, and incentive policies. Among the different types of configurations, Italian legislation on RECs defines a more comprehensive legal structure making RECs the configuration receives the highest concentration of policy support. At the national level, RECs are eligible for incentive tariffs on shared energy, which are subsidized through a tiered system with a total capacity cap of 5 GW. From an energy systems perspective, achieving net-zero emissions critically depends on maintaining a balance between renewable energy production and consumption. This requires a comprehensive assessment of regional energy demand and renewable generation potential to identify the necessary production capacity and to realistically evaluate the potential for decarbonization. Therefore, this study conducts a detailed analysis of the current status of RECs in Italy to assess the intermediate outcomes of policy implementation. Simultaneously, the number of RECs is analyzed to evaluate Italy's overall development process in this area. For the purpose of this study, RECs are defined according to the narrow legal framework set out in Legislative Decree No. 199/2021 [11], which provides a more specific

interpretation of community-based renewable energy initiatives in the Italian context. To reflect the unique characteristics of RECs in Italy, this study collected and analyzed data based on Italy's more detailed definitions and classifications of RECs. Additional support comes from the National Recovery and Resilience Plan (NPRR), which provided funding for municipalities with population of less than 5000 targeting 2 GW of installed capacity [14]. Tariff benefits are also available including credits through the renovation or installation of PV and energy storage facilities. Making them the most strongly incentivized form of distributed self-consumption. They may be characterized by multi-stakeholder participation and active collaboration with public institutions, local governments and educational institutions such as schools, which can participate as members. Small and medium-sized enterprises (SMEs) can participate, provided that energy production is not their main activity, while large enterprises can only support the community externally, acting as third-party producers or service providers. RECs have emerged as main actors in the transition toward sustainable energy systems. The formal recognition of RECs in RED II has catalyzed their expansion across Europe [15]. In RECs, the interaction between producers and consumers represents the core operational mechanism [16]. Sustaining a dynamic balance between production and consumption is essential for efficiency, economic viability, and grid stability. Disruptions in this balance risk dependence on external grids or inequitable benefit distribution, threatening REC durability. Achieving such equilibrium across technological, institutional, and social dimensions remains a central challenge. RECs development has been explored through governance, socio-cultural, regulatory, and technological perspectives. Studies highlights the role of innovative technologies such as blockchain, combined with the incentive mechanisms and flexible regulatory environments, in insuring REC sustainability [17,18]. Structured governance models, tailored to national contexts, have facilitated the REC deployment within Positive Energy Districts (PEDs) [19]. Municipal administrations act as key drivers of community-based and scalable initiatives [20]. Governance and policy thus provide the institutional backbone for REC growth, though models remain context-specific and their transferability uncertain. Social structures and regional cultural factors analyses demonstrate that REC pathways are shaped by local social structures and cultural norms [21]. At the regulatory level, progressive reforms—including increased capacity thresholds (200 kW to 1 MW) and the introduction of Key Performance Indicators (KPIs) demonstrate the potential of RECs to achieve CO₂ reductions of up to 64 % [22]. Complementary evidence emphasizes the importance of legislative clarity, financial mechanisms, capacity building, and public engagement [23,24,25]. Yet, policy approaches remain fragmented, with insufficient harmonization across jurisdictions and unresolved concerns regarding financial sustainability. Technological research highlights the optimization of building performance as a critical efficiency pathway [23], the role of distributed energy in enhancing sustainability and

decentralization [24], the emergence of zero-energy communities that fully meet energy needs with renewables [26,27]. While promising, this literature is predominantly techno-centric, often neglecting socio-economic, behavioral, and equity considerations. Overall, REC development depends on the integration of technological innovation, governance and regulatory support, municipal leadership, community engagement [28]. Evaluation frameworks currently rely heavily on KPIs addressing energy, economic, social, and financial dimensions [29,30]. However, much of the evidence is derived from single case studies, risking conceptual bias [31]. Critical gaps remain in the design of systematic KPIs from a building-energy perspective and in the availability of comprehensive datasets. Addressing these gaps, based on an original dataset of 212 REC cases and a tailored set of KPIs, this paper investigates the current status, structural features, and regional disparities in REC development. Different Italian regions have diverse characteristics and local standards that make complex the standardization of the technological foundation, configurations, services and other elements for REC transition. Therefore, this study provides a comprehensive analysis of Italian RECs status. The objectives in this research are primarily focusing on:

- Policy frameworks from the European level to the national and regional levels among Italy, identifying key policies and primary objectives guiding the development of RECs.
- Develop a set of KPIs for evaluating both policy and building energy infrastructure perspectives.
- Evaluate Italy's renewable energy potential by comparing the current utilization of renewable energy sources within the broader national distribution of renewable energy resources and the main targets of National Integrated Energy and Climate Plan (PNIEC) [32].
- Identify opportunities and constraints that influence the development of RECs in Italy.

This study contributes to the REC literature by providing the first nationwide, data-based empirical assessment of REC typologies in Italy, structured around a set of operational KPIs derived from real deployment data. For the future, this research contributes to find out key trends in Italian REC design and provides policymakers with practical insights for REC development policymaking, RECs are also categorized based on their defining characteristics, and the primary factors that have shaped the emergence of these categories are examined.

2. Materials and methodology

This paper addresses the research questions through a three-phase approach aimed at analyzing the current status and features of RECs. The methodology consists of three main stages: policy analysis, data collection and quantitative analysis, and evaluation of energy sources with data analysis. These steps provide a comprehensive review of RECs, from the policy framework to renewable energy sources, offering a holistic understanding of their status and future outlook. The first phase focuses on the relevant policy frameworks governing RECs from European level to Italian level. Timeline diagrams illustrated the progression of relevant legislation and regulation from European level to Italian regional level. This analysis offers an updated synthesis of the political and financial instruments that facilitate the growth of RECs. Through this approach, we identify the influence of legislation on REC development and provide strategic insights for areas where implementation is still in its early stages or yet to be initiated. In the second phase of the study, we collected and analyzed empirical and numerical data on RECs in Italy. To provide a more robust understanding of REC performance, this study not only identifies but also critically analyzes eight KPIs. Each KPI was selected for its dual relevance to both technical assessment and policymaking. For instance, population size directly determines eligibility for funding under Decree MASE No. 414/2023 and the PNRR, linking demographic thresholds to financial support and scalability.

Climatic zones capture regional variations in energy demand and thermal comfort needs, which are central to designing effective energy policies. The number of producers and consumers, together with PV capacity and the presence of other renewable sources, reflect the structural balance between supply and demand, informing strategies for energy autonomy and resilience. Finally, total energy consumption and the number of REC buildings provide insight into the actual integration of communities into the national energy transition. Data sources include the GSE REC registry, Legambiente's Community Energy Map, research from RSE, and the latest datasets from national grid-related entities such as TERNA. Based on this data, we defined a set of KPIs across three dimensions: (i) producers, (ii) consumers, and (iii) general community characteristics. The eight selected KPIs—population size, climatic zone, number of producers, installed PV capacity, presence of other renewable sources, number of consumers, total energy consumption, and number of REC were chosen for their policy relevance and technical significance. This framework enables a structured assessment of REC development and supports data-informed decision-making for future community planning and policy design. In the third phase, we applied a combination of quantitative and spatial analysis methods to examine potential relationships among key REC indicators. To better understand the structural and performance characteristics of existing RECs, this study employed statistical visualization techniques. Specifically, regression plots were used to examine correlations among key variables, such as population size, number of producers, and total renewable energy capacity. In parallel, boxplots were applied to illustrate the distribution and variance of energy production across REC groups categorized by structural attributes. These visualization techniques were applied directly to empirical data without the use of simulations or predictive algorithms. While the analysis is descriptive in nature, the consistency of trends observed across multiple indicators lends credibility to the findings. Finally, spatial distribution analysis was conducted to map renewable energy capacity across regions, supporting region-specific recommendations for future REC development. This phase forms the analytical basis for evaluating REC performance and projecting their policy and energy implications.

In summary, this study adopts a methodology encompassing policy analysis, database construction, and energy forecasting as shown in Fig. 1. The chosen approach ensures a comprehensive understanding of the regulatory framework, the implementation status of RECs and future development potential. This chosen methodological design provides a solid foundation for the subsequent data analysis and discussion on the performance and scalability of RECs in Italy.

3. Results

The results section provides a detailed overview of the development of RECs in Italy, with particular focus on their distribution, implementation models and policy. Key features and emerging trends are discussed to assess the effectiveness and scalability of RECs at the national level.

3.1. Policies governing renewable energy community

The policy and legislative framework at the EU level exerts a decisive influence on the formation and development of RECs [33]. It not only defines their legal status and operational boundaries but also shapes market access conditions and incentive mechanisms. To systematically capture the institutional trajectory of RECs within the EU, this study adopts a timeline-based approach to review key REC-related policies and legislative acts introduced between 2018 and 2024. This overview provides essential context for understanding the positioning of RECs in the EU's broader energy transition strategy and serves as a foundation for the subsequent analysis of Italy's national policies and case studies, given its status as an EU Member State. The EU aims to mitigate climate change by achieving climate neutrality by 2050 [34] integrating

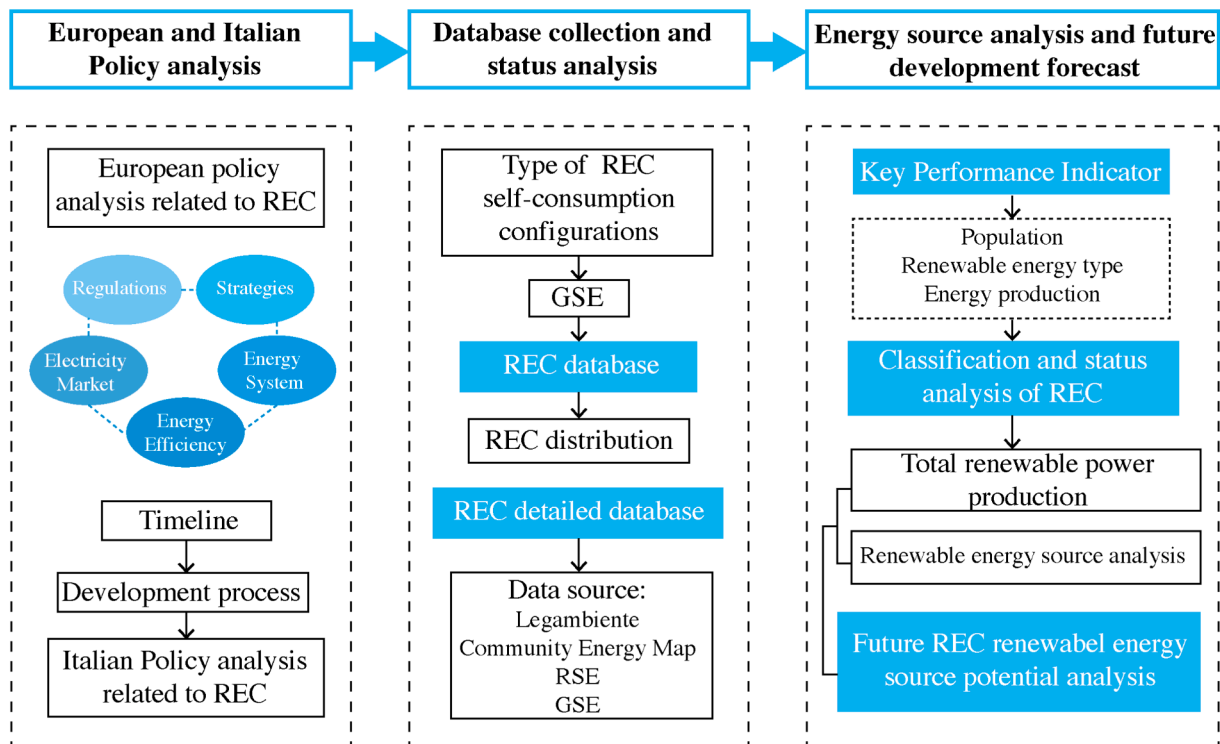


Fig. 1. Research workflow of Italian renewable energy community status and future development. Source: elaboration of the authors

renewable energy sources flexibly into the energy market [35], which forms a critical foundation for the effective implementation of RECs.

As these policies are subject to continuous updates, this study references only the most recent version available at the time of writing to ensure accuracy and relevance. Furthermore, the relevant policies are summarized through a timeline illustration, as presented in Fig. 2. In 2018, the Renewable Energy Directive II (RED II, 2018/2001/EU) formally introduced the REC concept [33], establishing a policy and legal framework for their development [36]. According to RED II, RECs aim to promote the production and consumption of renewable energy [37]. EC represent a broader cooperative approach without a strictly defined legal category [38]. CECs, originating from electricity market reforms, emphasize consumer participation and rights protection, with the ability to generate, share, and sell electricity, manage distribution networks, and deliver energy efficiency services [39]. RECs are a subset of ECs characterized by their local focus, non-profit orientation, and exclusive reliance on renewable energy sources [25]. However, these conceptual boundaries often overlap in practice, and divergent national interpretations regarding geographical scope, governance structures, and benefit-sharing arrangements reduce cross-country comparability and complicate the design of harmonized support schemes.

(i) Governance and Regulation

The Governance of the Energy Union and Climate Action Regulation (EU/2018/1999) [40] and the National Energy and Climate Plans (NECPs) [41] form the core of EU energy governance, ensuring Member States collectively pursue shared climate and energy objectives. Italy, for instance, set ambitious PNIEC targets of achieving a 40.5 % share of renewables in total final energy consumption and 65 % in electricity generation by 2030 [32]. Yet, the gap between ambition and implementation remains significant, as administrative bottlenecks, grid connection delays, and financing constraints often hinder the timely deployment of community-scale renewable projects.

(ii) Strategic and Legal Framework

The EU's strategic direction is guided by the European Green Deal [42], the Long-term Strategy [43], the European Climate Law [44], and

the "Fit for 55" legislative package [45]. These instruments define explicit 2030, 2040, and 2050 targets, with net-zero emissions by 2050 as the ultimate goal. While these top-down strategies provide legal certainty for RECs, they lack detailed mechanisms for effectively integrating small-scale, locally governed energy models into large-scale decarbonization pathways, creating a disconnect between macro-level objectives and micro-level implementation.

(iii) Electricity Markets

The Risk-Preparedness Regulation (EU/2019/941), the Internal Market for Electricity Regulation (EU/2019/943), and the ACER Regulation (EU/2019/942) establish a unified, secure, and efficient internal electricity market [46,47,48]. However, high levels of market integration may disadvantage small, non-profit RECs, which typically lack the scale and resources to compete in liberalized wholesale markets unless targeted participation mechanisms are implemented.

(iv) Energy Systems and Energy Efficiency

The Clean Energy for All Europeans package [45] and the REPowerEU plan [49] introduced the EC concept as a core element of EU energy market reform, accelerating the transition in response to geopolitical pressures. Yet, the accelerated deployment timelines under REPowerEU risk prioritizing large-scale, centralized renewable projects over smaller, community-driven initiatives, which often require longer development cycles but deliver broader socio-economic benefits.

(v) Buildings and Energy Efficiency

The Energy Efficiency Directive (EED, EU/2023/1791) [50], RED III (EU/2023/2413) [51], and the Energy Performance of Buildings Directive (EPBD, EU/2024/1275) [52] collectively promote energy savings, renewable deployment, and building sector decarbonization. The EED mandates an 11.7 % reduction in final and primary energy consumption by 2030 compared to 2020 levels [53]; RED III raises the 2030 renewable target to at least 42.5 % (aspirationally 45 %) and introduces "Renewables Go-To Areas" to streamline permitting [54]; EPBD revisions require all new buildings to be zero-emission by 2030 (public buildings by 2028) and mandate solar installations on both new and existing buildings [55,56]. While these regulatory benchmarks offer

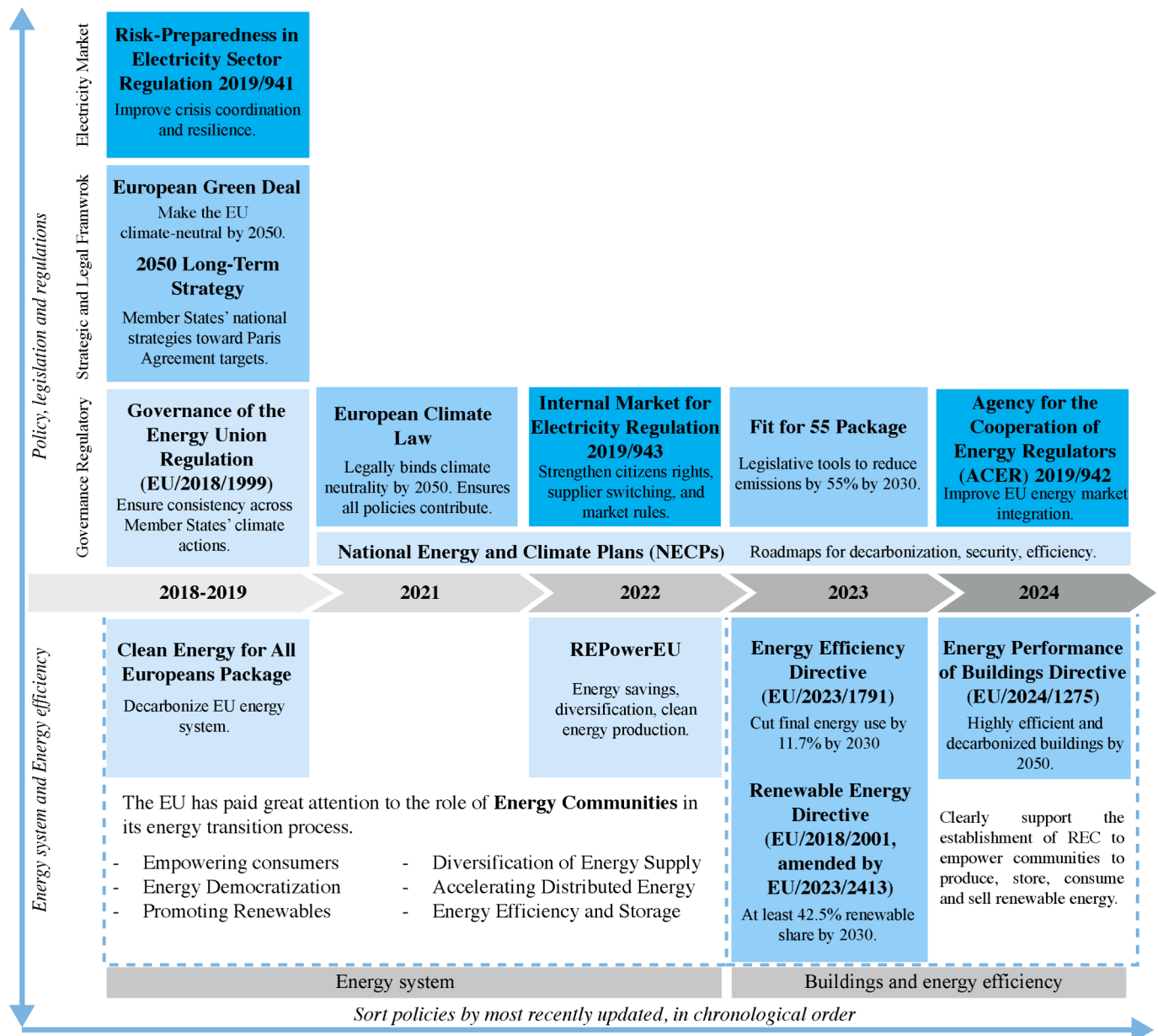


Fig. 2. Timeline illustration of European legislation and policies relevant to RECs. Source: elaboration of the authors

measurable criteria that can be adopted by RECs, compliance may impose disproportionate administrative and financial burdens on smaller initiatives in less affluent regions unless tailored support mechanisms are introduced. RECs demonstrate multi-dimensional value in reducing electricity costs, mitigating environmental impacts, creating employment opportunities, fostering regional economic growth, and enhancing public participation [10,25,57]. However, their future scalability and impact depend on addressing three structural challenges: Localism versus scale balancing community autonomy and participation with contributions to large-scale decarbonization targets. Policy coherence aligning diverse national definitions and support mechanisms to enable cross-border collaboration and comparative evaluation. Resource and market access improving access to finance, ensuring equitable grid connections, and streamlining administrative procedures. Without systemic solutions to these issues, RECs risk remaining a niche element rather than a central pillar of the EU's climate and energy strategy.

As discussed in the previous section, EU directives, most notably RED II 2018/2001/EU, the Electricity Market Directive (2019/944/EU) [58],

and the more recent RED III (2023/2413/EU) established the legal foundation for the promotion of RECs. These directives provided Member States with both definitions and guiding principles, including collective self-consumption, local ownership, and active consumer participation. The legislative trajectory of RECs in Italy can be divided into three distinct phases as shown in Fig. 3. In the initial phase (2018–2020), following RED II and the Electricity Market Directive, Italy first introduced the concept of collective self-consumption under Legislative Decree 162/2019 [59]. Shortly after, ARERA Resolution 318/2020/R/eel [60] initiated an economic settlement mechanism, marking the beginning of experimental REC implementation. However, the restrictive capacity threshold (≤ 200 kW) and complex administrative procedures limited the scale and transformative impact of this initial phase. In the second phase (2021–2022), guided by the NECP Regulation (EU/2018/1999) [61,62] and the REPowerEU initiative [63], Italy enacted Legislative Decrees 199/2021 [10] and 210/2021 [64] to stimulate investment in renewables, storage, and market reform. ARERA Resolution 727/2022/R/eel [12] subsequently consolidated rules under

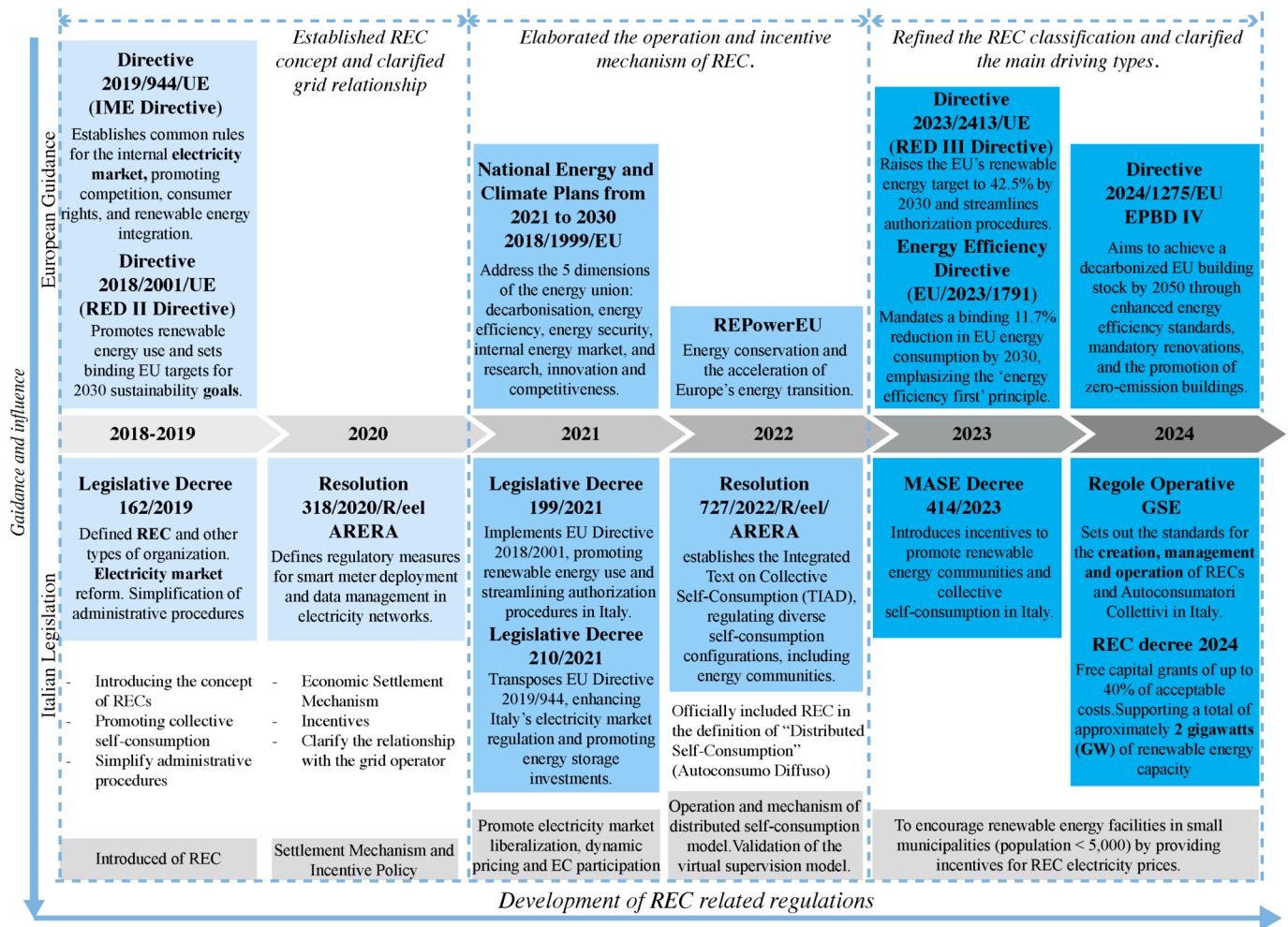


Fig. 3. Timeline illustration of legislations and policies in Italy. Source: elaboration of the authors

the Integrated Text on Collective Self-Consumption (TIAD) [65], clarifying configurations for energy sharing. While this phase advanced REC institutionalization, delays in authorization and significant regional disparities, particularly between the North and South, remained strong barriers. In the third phase (2023–2024), at the EU level, RED III (2023/2413/EU) [66,67] mandated an annual 1.6 % increase in renewable energy deployment, complemented by the revised EED (EU/2023/1791). Italy responded through the MASE Decree n.414/2023 [13], which expanded the scope of RECs and supported distributed self-consumption models, and through the REC Decree 2024, which introduced incentive tariffs and capital subsidies targeted at municipalities with fewer than 5000 inhabitants [38]. In parallel, the EU’s EPBD IV (2024/1275/EU) [52] set ambitious long-term building decarbonization standards, which Italy integrated via GSE’s operational rules. From the technological advancement point of view Italy has been the first in Europe for smart metering deployment, introducing smart meters for low-voltage end-users in buildings [68]. Smart grid and meters are key technologies for RECs implementation. IoT-enabled devices, such as smart meters and sensors can provide real time feedback on energy uses, enabling consumers to optimize their use and lower their bill. Moreover, smart meters enable consumers to actively participate in RECs exchanging the energy produced when not directly used. This synthesis therefore provides the necessary background for the subsequent analysis of Italy’s REC practices and case studies.

3.2. Italian regional renewable energy community status

As highlighted also in the previous sections one important strategy to cut greenhouse gas emissions and reach the 2050 climate neutrality target is the spread of RECs [69]. Although the EU has 9252 ECs, their distribution varies significantly among member states. Germany accounts for more than half of these communities, with 4848 ECs. According to GSE statistics, till April 9, 2025, Italy has developed 221 RECs along with numerous other types of distributed self-consumption organizations [70]. The comparison of the number of RECs across EU indicates that Italy remains in a developmental phase, highlighting the need for continued efforts and policy support to scale up REC implementation. Specifically, the Ministry of Environment and Energy Security has extended the PNRR deadline for RECs from March 2025 to November 2025 [71]. This extension provides local communities with additional time to develop RECs and shared projects, thereby promoting the transition toward sustainable energy [72]. Based on the data provided by GSE on RECs across Italy, a dataset was compiled and presented in Appendix A, which includes information available as of February 2025. Although the GSE database also contains other types of self-consumption organizations, this study focuses specifically on RECs in Italy. Therefore, other forms of renewable energy applications are excluded from the scope of this analysis. The majority of REC are small-to-medium size range with the installation 10 to 100 kW. However, a few numbers of larger-scale projects exceeding 500 kW and reaching up to approximately 1000 kW have been identified (1042 kW of solar

power installed in the province of Pordenone). This trend suggests that Italy's RECs are evolving from predominantly small-scale, decentralized configurations.

To facilitate further analysis, Fig. 4 presents a regional breakdown of the data across Italy, comparing the number of established RECs in each province with their total installed capacity. Fig. 5 visualizes the geographic distribution of RECs using a choropleth map, providing a more intuitive understanding of their spatial patterns across the country. It can be observed that the regions of Friuli Venezia Giulia, Lombardia, Piemonte, and Veneto have the highest number of RECs, each with more than 20 established communities. In Fig. 5a, darker shades of blue indicate a higher concentration of RECs in a given area. It can be observed that RECs are currently more concentrated in the northern regions, with a gradual decline in their number moving from north to south. Fig. 5b shows the high correlation between population density and the number of renewable energy communities suggesting that areas with higher population density tend to have more renewable energy communities, and vice versa. This indicates that urban or semi-urban areas are more likely to develop communities compared to rural or sparsely populated regions, in fact higher population density enables easier formation of cooperatives or associations, which are essential for setting up RECs. Consequently, while renewable energy is present in the region, many of these projects do not fall under the narrow definition of RECs as defined in Italian legislation, leading to a lower number of RECs recorded in official statistics.

The scatter plot of the Fig. 6, presents the relationship between the number of renewable energy communities and global solar radiation on a horizontal surface (kWh/m^2) across various locations. The observed negative trend, as indicated by the dotted regression line, suggests that areas with lower solar radiation tend to have a higher number of renewable energy communities. Given that lower solar radiation typically corresponds to northern Italian regions, this trend reflects a stronger policy support, economic incentives, community engagement and institutional support for renewable energy initiatives in the north, despite their relatively lower solar potential.

Based on the policy landscape collected in Appendix A, the uneven development of RECs across Italian regions can be primarily attributed to four key factors: disparities in financial resources and incentive schemes, governance mechanisms and technical support capacity, the timing and maturity of legal and policy frameworks, and differences in socio-economic conditions. Northern regions, with stronger economies and fiscal capacity, are generally able to leverage both EU and national funding. By contrast, southern regions face fiscal constraints and exhibit a limited capacity to absorb EU resources. Regions such as Piemonte, Lombardia, Emilia-Romagna, and Bolzano mobilize larger budgets often

amounting to tens or even hundreds of millions of euros with diversified funding sources, whereas southern and island regions including Calabria, Campania, Molise, and Sardegna operate with limited or no dedicated funding, and in some cases provide no direct subsidies at all. Institutionally, northern regions benefit from stronger traditions of public administration and energy governance. For instance, Emilia-Romagna, Piemonte, and Lombardia have established technical committees, digital platforms, and monitoring tools, thereby achieving more mature and effective governance structures. By contrast, many southern and island regions rely on ad hoc agreements or lack formal governance mechanisms altogether, reflecting both weaker technical capacity and fragmented administrative structures. In addition, the timing of legislative action varies significantly across regions, leading to uneven experience and institutional learning. Early adopters such as Piemonte (2018), Lazio (2020), and Campania (2020) had more time to accumulate expertise and refine their frameworks, while latecomers such as Umbria (2024) and Valle d'Aosta (2024) remain in the pilot stage. Others, such as Molise, Sicilia, and Sardegna, still lack comprehensive legislation and rely primarily on temporary projects. Socio-economic conditions further exacerbate regional disparities. Northern and central regions benefit from stronger traditions of community organization, cooperative models, and citizen engagement, which facilitate the development of RECs. In contrast, southern and island regions often face limited social capital and more pronounced energy poverty, making it more difficult for communities to initiate and sustain projects autonomously.

To address these disparities, this study proposes a set of targeted policy recommendations. From a financial perspective, national authorities should ensure greater redistributive support to southern and island regions through the PNRR and structural funds, for instance by establishing a dedicated REC development fund. A differentiated subsidy system should also be introduced, granting disadvantaged regions higher levels of support, similar to the Valle d'Aosta model of offering up to 100 % subsidies. From a governance and technical perspective, the establishment of regional REC technical platforms or one-stop shops in southern and island regions is essential, complemented by interregional technical assistance schemes that link experienced northern regions with less advanced areas. From a regulatory perspective, regions that still lack comprehensive REC legislation (Molise, Sicilia, Sardegna) would benefit from the adoption of a unified national framework and guiding documents to avoid policy fragmentation, while integration between the national REC registry and regional platforms could further streamline administrative and financial processes. Finally, from a socio-economic perspective, expanding energy education and training programs in the south is crucial to enhance community awareness and technical capacity. Encouraging the involvement of cooperatives and non-profit organizations can also compensate for limited government capacity, while particular attention should be devoted to energy-poor households, ensuring they receive priority access to subsidies and REC participation. In sum, the uneven development of RECs in Italy can be attributed to disparities in fiscal capacity, governance and technical support, the timing of legislative action, and differences in social capital. Promoting a more balanced national trajectory will require strengthened financial and institutional support for southern and island regions, coupled with enhanced governance capacity and broader social participation.

3.3. Key performance indicators for Italian renewable energy community

Based on the above analysis, the current state and trends of REC in Italy have been examined. The further data was collected and consolidated to identify the key characteristics and regional variations of RECs across the country. According to data released by GSE as of March 6, 2025, Italy currently has 212 active RECs. The analysis of these RECs reveals significant variability in scale, geographic distribution, and organizational structure. Nevertheless, this results represents only 1 %

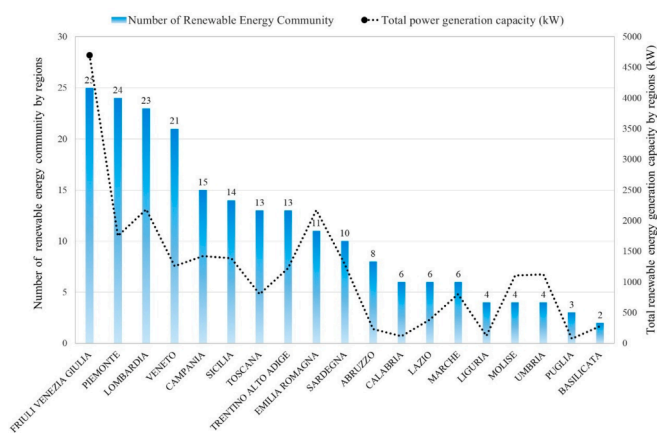


Fig. 4. Distribution of Italian renewable energy community and renewable energy generation capacity in each region, data. source: GSE, elaboration of the authors

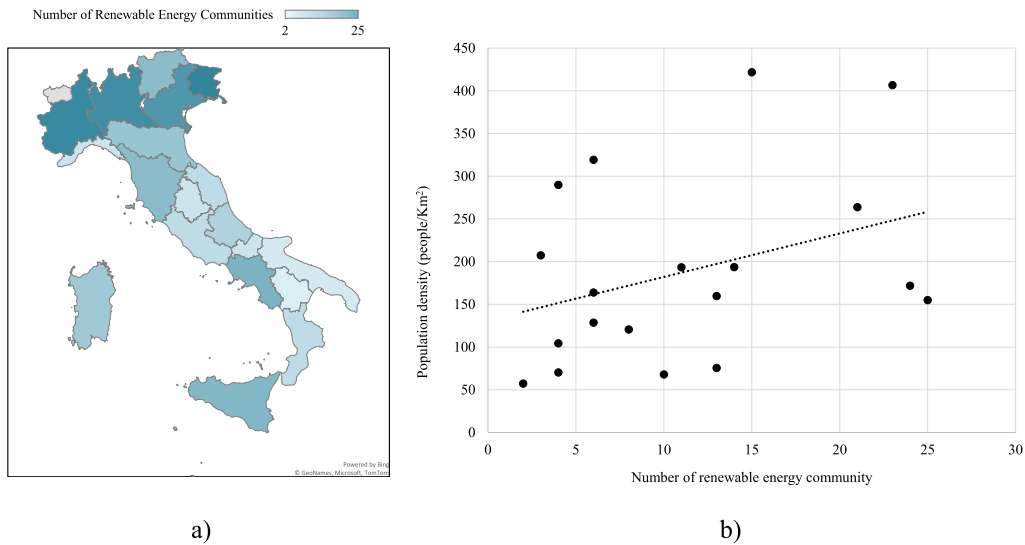


Fig. 5. A) distribution of REC in Italy by region. b) Number of REC vs regional population density. Source: GSE, elaboration of the authors

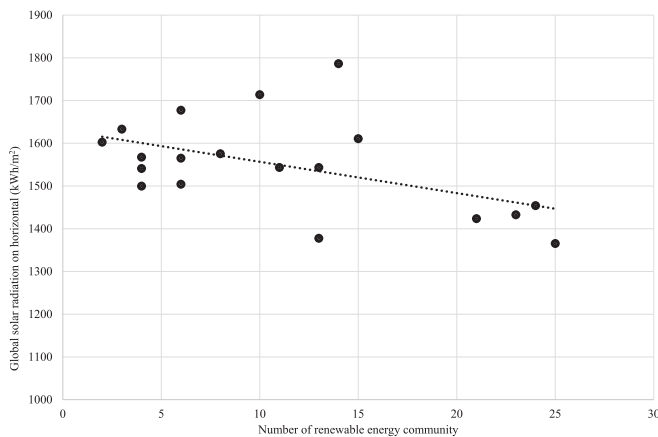


Fig. 6. Scatter plot showing the relationship between the number of renewable energy communities and global solar radiation on a horizontal surface (kWh/m²). The dotted line represents the fitted regression trend. Source: elaboration of the authors

of the target set by the PNRR, indicating that there is still a significant gap to be addressed [73]. As previously noted, the limited involvement of government agencies and social institutions in Italian RECs has made data collection particularly challenging. Official records acknowledge that it is difficult to comprehensively identify and document the distribution of RECs throughout Italy. Moreover, unlike in some other European countries, Italian RECs are required to have individual connections to the public distribution grid and are limited to managing electricity derived exclusively from renewable sources [29]. According to the latest GSE data, the Appendix B includes all currently listed in the REC category. Based on a synthesis of data from the Legambiente Reports 2022 [74] and 2024 [75], the RSE Orange Book 2022 [76], the Community Energy Map [77], and various other academic publications, 87 RECs were identified that have been officially announced and are under development and they are listed in Appendix C. In Appendix D, 56 RECs were found to have publicly available detailed and accurate information including the type of renewable energy sources, the number of producers, and the number of consumers. During the data collection process, we identified and compared the key energy-related characteristics that define RECs. The analysis highlights several critical features that serve as the foundation for proposing targeted measures to support the

future development of RECs in Italy. KPIs are widely utilized by social groups and government agencies to define renewable energy metrics, formulate strategies, and evaluate outcomes within the context of RECs. KPIs provide a comprehensive framework for assessing REC initiatives from both environmental and energy perspectives [78]. To develop an integrated evaluation system for the REC context, this study drawing upon extensive case data identifies 8 main key parameters that are closely linked to community-level energy efficiency and the overall effectiveness of REC implementation showed in Table 1.

- KPI 1 – Population: this indicator reflect the size of the RECs. According to Decree MASE No. 414/2023 [13], towns with fewer than 5000 inhabitants are eligible for funding under the PNRR to establish RECs, with capital subsidies of up to 40 %. This policy aims to promote the green transition and energy autonomy of smaller municipalities. However, starting in March 2025, this capital subsidy scheme will expand the eligible community size to 50,000 inhabitants, thereby significantly broadening the scope of RECs. This policy shift is expected to have a substantial impact on the future development of RECs in Italy. Moreover, it reflects a mature trajectory in Italy’s REC policy framework, transitioning from the initial phase of encouraging REC establishment to a more advanced phase focused on scaling up and expanding REC implementation.
- KPI 2 – Climate zones: it indicates the specific climatic condition of the RECs location. Differences in climatic zones lead to variations in thermal comfort needs and energy demands, which, contribute to substantial differences in building energy consumption. While regional policy was also reviewed during the analysis, it was not included as a standalone KPI due to the highly uneven development of REC-related legislation across Italian regions and provinces. In many cases, dedicated policies or regulations are either absent or vary significantly in scope and standardization, making consistent comparison challenging. Nevertheless, the influence of regional policy is indirectly considered through other KPIs, such as incentive structures, which reflect the practical impact of policy environments on REC implementation. Based on available data and insights from simulation models, this study identifies four key parameters related to production capacity and diversity, each represented as individual KPIs:
- KPI 3 – Number of producers: this reflects the level of community participation on the supply side and indicates the collective capacity for local energy generation.

Table 1
The Key Performance Indicator of REC in Italy.

KPIs n°	KPIs	REC characteristics
KPI 1	Population	The national energy regulations of Italy state that REC fees vary for populations under 5,000.
KPI 2	Climate zone	The maximum potential of renewable energy sources like solar and wind power is limited by the climate types in different places.
–	Regional policy	Each region has its own set of rules governing the markets for electricity and renewable energy. The policy difference becomes clearer when the regions are categorized.
Producers		
KPI 3	Number of Producers	Number of buildings equipped with renewable energy installations
KPI 4	PV (main RES)	Roof The amount of available roof space has an impact on rooftop PV installations.
		Ground The size and function of the community have an impact on ground PV.
KPI 5	Other Renewable Energy Source	The viability and potential of additional RES applications can also be tested by statistics of other RES categories, which are influenced by the local climate and geographic setting.
KPI 6	Total renewable energy generation capacity [kW]	Assess REC energy efficiency and the potential for carbon neutrality based on the extent of RES installation, and measure REC output capacity from an energy standpoint.
Consumers		
KPI 7	Number of Consumers	The community's energy usage and rooftop PV potential are determined by the total number of buildings.
KPI 8	Total energy demand [kWh]	The community's energy output goal is determined by the average yearly usage of its structures. The EU's long-term development goal is to become carbon neutral and self-producing by 2030.

Source: elaboration of the authors

- KPI 4 – Number of PV installations: this indicator captures the prevalence and distribution of PV systems within the community, distinguishing between rooftop and ground-mounted installations.
- KPI 5 – Other types of renewable energy sources: this includes installations such as wind turbines, biomass plants, and micro-hydropower systems. It reflects the technological diversification within RECs and the extent to which they expand more than solar-only systems.
- KPI 6 – Total renewable energy generation capacity: this aggregates the installed capacity (kW) across all renewable energy sources within a REC and serves as a direct measure of the community's generation potential. It is essential for evaluating the energy autonomy and scalability of a REC. Rooftop PV systems are the primary renewable energy source of REC, with their early-stage deployment heavily dependent on data and information collected from RES installations [79]. This part starts with analyzing the rooftop PV data. Not all RECs have clear rooftop PV installation statistics, according to the data that is currently available. According to Appendix D, not all RECs have clear statistics on rooftop PV installations and 52 RECs currently established the rooftop PV installations and the rooftop PVs number from one and three are currently deployed in 69.6 % of RECs. This is largely attributable to the fact that the majority of RECs the database is located in small towns at an early development stage. Only two of these communities utilize ground-mounted PV systems. Due to a limited land availability, potential landscape and ecological impacts, high initial investment costs, and the technological constraints, ground-mounted PV is rarely used in RECs. According to these statistics, rooftop PV systems offer certain benefits for the growth of RECs, including cost savings and efficient land use while

maximizing the use of available resources. However, rooftop PV is better suited for localized community use and small-scale industries. Additionally, in terms of assessment procedures and incentives, regulations such as REC III often favor rooftop solar systems. Therefore, within KPI 4, further distinguishing between different types of PV installations and introducing PV deployment as a standalone KPI were analyzed. Due to spatial limitations, rooftop PV systems are often constrained by the available surface area of individual buildings. The difference between the number of rooftop PV units and the number of energy producers can serve as an indicator of the current stage of REC development, particularly regarding scalability and system efficiency. In data analysis, PV systems are categorized into two types: rooftop PV and ground-mounted PV, allowing for a more accurate assessment of infrastructure type, spatial constraints, and expansion potential within each community. Finally, while residential population provides general insight into community size, data on consumer buildings has a more direct impact on the operation and energy dynamics of RECs. Therefore, two additional KPIs are defined:

- KPI 7 – Number of consumers: this indicator refers to the number of buildings or units participating in energy consumption within the REC. It reflects the demand-side scale of the community and is instrumental in determining the balance between local production and consumption.
- KPI 8 – Total demand energy: this represents the total electricity demand (kWh) of the REC and is essential for evaluating energy self-sufficiency, sizing of generation systems, and the potential for internal energy sharing. It also serves as a reference to KPI 6, allowing for further analysis of the self-consumption ratio and load matching within the community.

In summary, these eight KPIs identified provide a comprehensive framework for evaluating the structural, technical, and operational dimensions of RECs in Italy, particularly in renewable energy technology perspective. These indicators enable a multidimensional assessment of REC performance from both production and consumption perspectives, while also accounting for geographic, demographic, and infrastructural factors. In the following sections, these KPIs are applied to empirical data to evaluate current REC development and identify strategic priorities for future expansion and policy support.

3.4. The influence of renewable energy community development

Analysis of the data presented in Fig. 7, derived from 78 developed communities documented in the Appendix C database, reveals several noteworthy qualitative and quantitative characteristics of Italian RECs. A particularly significant finding is the prevalence of RECs in municipalities with limited population density, with 55 % of surveyed communities situated in towns of fewer than 5000 inhabitants. This is closely linked to national REC-related policies, such as Decree MASE No. 414/2023 [13], which has strategically incentivized REC development in smaller municipalities through targeted financial support mechanisms and simplified administrative procedures. The proportion of RECs established in municipalities with populations below 50,000 inhabitants varies considerably across geographical regions: 54 % in northern Italy, 25 % in central regions, and 59 % in southern territories. Furthermore, substantial regional imbalances are evident in the absolute distribution of RECs, with northern regions accommodating the highest concentration with 31 communities, while southern regions demonstrate significantly lower adoption rates with only 4 communities, and central regions show markedly limited REC implementation.

Fig. 7 also highlights the geographical distribution of RECs across Italy, revealing a relatively balanced presence in the northern and southern regions, while the central region demonstrates a lag. RECs in the north tend to be larger in terms of both the participants numbers and the spatial coverage. Conversely, RECs in southern Italy are generally

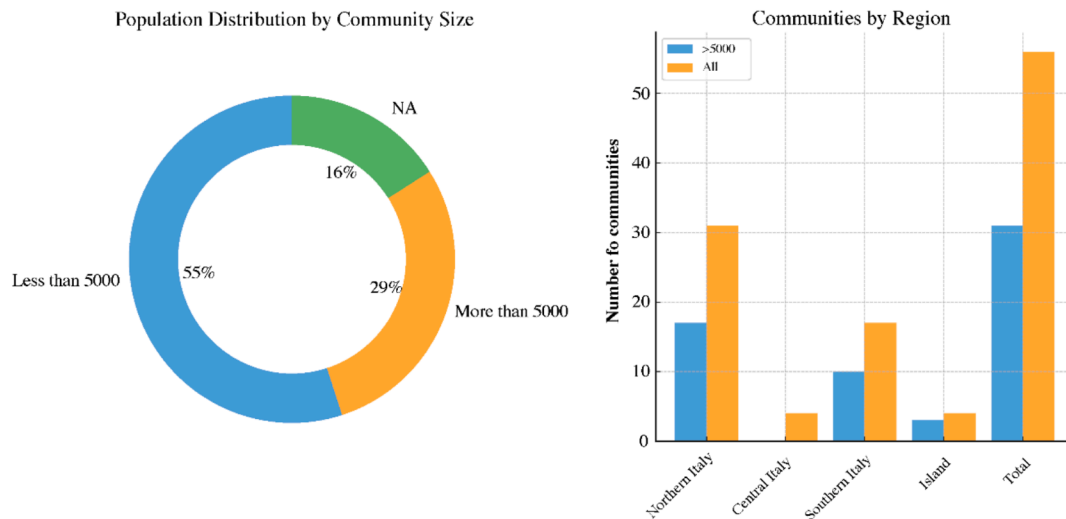


Fig. 7. REC community size categories and distribution in Italy.
Source: elaboration of the authors

smaller and more localized, reflecting differences in infrastructure, economic capacity, and levels of community engagement. Regional policy approaches to REC development in Italy also demonstrate marked characteristics across different parts of the country. In the northern regions, local governments have established dedicated funding schemes and subsidy programs to support REC initiatives. For example, Lombardia region launched the REC fund and has actively partnered with technical platforms and energy companies to facilitate the implementation. In central Italy, several provincial governments have initiated the development of technical guidelines and application platforms to support the establishment of RECs. Agencies such as the Tuscany Energy Agency (S.E.T.) have taken a leading role, while cities including Florence and Siena have launched REC pilot projects financed through EU funding mechanisms. In southern Italy, although the number of RECs is relatively limited, the potential for renewable energy development is high, owing to abundant natural resources. These regions also benefit from a higher share of national and EU funding, including allocations from NPRR. In many cases, local energy agencies and non-governmental organizations have initiated guided RECs to introduce the concept and foster community engagement. Nonetheless, the southern regions generally lack sufficient technical expertise and local public expenditure capacity, necessitating reliance on national technical assistance platforms to support REC development.

Italian regional approaches to the development of RECs reveal a complex and diverse landscape shaped by institutional capacity, funding availability, technical expertise, and policy priorities. Northern regions, with robust administrative structure and active public-private partnerships, are well positioned to advance REC implementation. In contrast, southern regions endowed with abundant renewable resources and bolstered by national-level financial support, nonetheless face substantial challenges related to technical infrastructure and local expertise. These regional disparities underline the necessity for varied policy instruments and targeted support mechanisms to ensure balanced and inclusive RECs expansion across the country. For prospective REC initiators, Italy has recently implemented several policies and regulatory measures to facilitate the integration of renewable energy sources into the national electricity system. A key framework supporting this development include the NPRR and Legislative Decree No. 28/2023, which introduces the Simplified Authorization Procedure, a mechanism designed to streamline the approval process for small-scale renewable energy projects [80]. Additionally, Italy's 2023 Grid Development Plan prioritizes enhancing grid resilience and expanding the integration of renewables through major infrastructure investments, including

enhanced interconnections and subsea high-voltage direct current transmission lines [81]. Collectively, these efforts aim to reinforce the grid's capacity to accommodate and distribute energy from diverse renewable sources. Collectively, these regulatory advancements present new opportunities for RECs in Italy, such as expedited permitting processes for small-scale renewable plants and improved grid access to national grid. Under this evolving framework, more grid-connected and operationally efficient REC models are likely to emerge. Consequently, these policies are expected to significantly support the RECs expansion by these new policies.

4. Discussion

4.1. Relationship between number of producers and total energy production

The relationship between the number of energy producers within a REC and the total amount of renewable energy produced represents a critical indicator of community-scale generation. In principle, an increase in the number of producers should exhibit a positive correlation with total energy output, particularly in decentralized systems where each producer contributes a portion of overall generation capacity, typically through rooftop PV installations or other small-scale renewable units.

To assess the correlation between community population and total renewable energy generation capacity, a simple linear regression model was applied within each subgroup of communities, grouped by the number of energy producers. The regression model used is:

$$P = \alpha + \beta \cdot N + \varepsilon$$

P = total renewable energy generation capacity (kW)

N = population of the community.

α = intercept (baseline capacity).

β = regression coefficient (change in capacity per person).

ε = residual error term.

The shaded areas represent 95 % confidence intervals. The regressions were performed using [e.g., seaborn in Python], and no causality is implied the analysis is exploratory in nature. This analysis aims to identify underlying patterns and emerging trends that shows the correlations for KPIs. The data in Appendix C were systematically screened and reclassified, resulting in the compilation of Appendix D. Fig. 8 illustrates the relationship between municipality population size, total renewable energy generation capacity per community and the

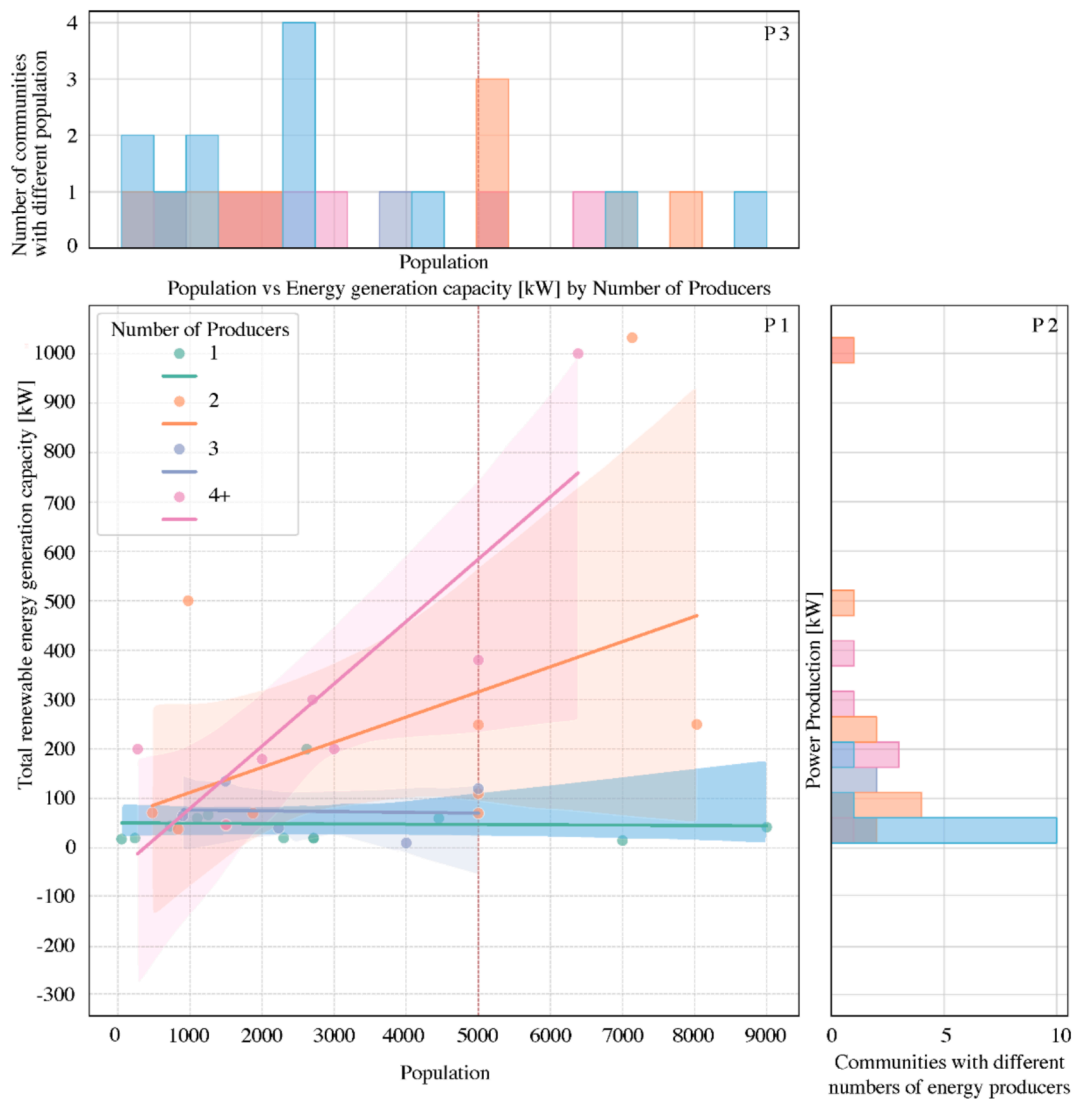


Fig. 8. Analysis of the relationship between community population, renewable energy production, and the number of energy producers. Source: elaboration of the authors

number of producers across Italian REC based on data from 56 developed communities included in the Appendix D database. The P1 graph demonstrates that communities with a higher number of producers generally achieve greater total energy production, with a clear upward trend particularly evident in communities 4 or more producers, as indicated by the pink regression line. Consequently, achieving carbon neutrality within RECs requires a continuous process of technological advancement and an increase in the number of local producers. This dynamic scaling-up of renewable energy infrastructure at the community level is vital for enhancing self-sufficiency and maximizing decarbonization potential. The graph P2 and P3 provide additional insights into the relationship between community characteristics and renewable energy productivity. Most communities with significant energy generation are in the mid-range of population 1000–5000, while only a small number of RECs exceed 600 kW, all of which are associated with a higher number of producers. These patterns reinforce the conclusion that both technical scale and community composition critically influence the energy productivity of RECs. Based on the data presented in P2, it is evident that most RECs in Italy remain in the early stages of development, as most communities are still characterized by having a single producer installation. However, as shown in Appendix C, there are projects where communities with only a small number of producers

demonstrate remarkably high total energy generation outputs. Upon reviewing specific information about these communities, it becomes clear that this is due to the inclusion of large-scale renewable energy production plants within the REC structure. Between 2024 and 2025, the PNRR incentive program for RECs was repeatedly extended, with the eligible community size threshold increased from 5,000 to 30,000 residents and now grow to 50,000 residents by May 2025. These extensions provide additional time for a broader range of communities to participate in the energy transition. Moreover, the expansion of the eligible community size indicates that Italy’s REC initiatives are transitioning from initial small-scale deployments to the construction of larger, more comprehensive REC projects.

4.2. Relationships between number of producers and consumers

The balance between energy producers and consumers is fundamental to the internal functioning and overall efficiency of RECs. Producers determine the local generation capacity, while consumers determine demand-side dynamics and the potential for self-consumption and energy sharing. Understanding the interaction between these two roles interact across RECs helps assess their structural diversity and operational models. In this analysis Fig. 9 offers a new perspective to

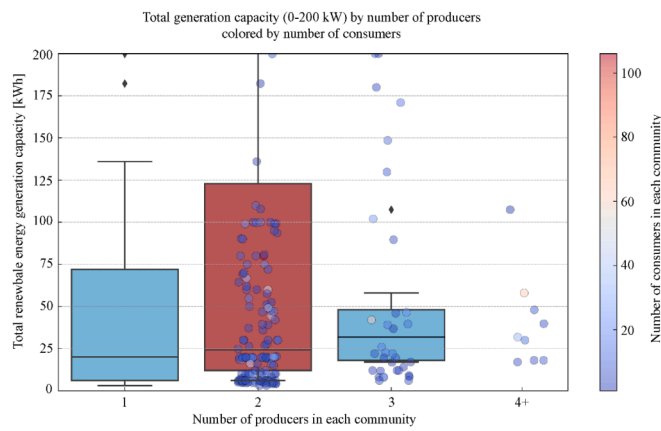


Fig. 9. Relationship between total renewable energy generation capacity (<200 kW), the number of energy producers, and the number of consumers in each community.

Source: GSE, elaboration of the authors

illustrate the relationship among producers, generation capacity, and consumers across a wider range of communities.

In boxplot-based Fig. 9, quartile-based descriptive statistics were used to summarize data, including median, interquartile range (IQR), and whisker limits, computed as:

$$IQR = Q_3 - Q_1, \text{ Whiskers} = [Q_1 - 1.5 \cdot IQR, Q_3 + 1.5 \cdot IQR]$$

Fig. 9 presents a box plot illustrating the total renewable energy generation capacity 0–200 kW range categorized by the number of producers in each community with data from Appendix D. Data points are additionally colored based on the number of consumers, providing a layered understanding of how producer–consumer relationships vary across RECs. Although Fig. 9 includes statistical distributions and individual community-level data points, it does not represent an error analysis. The figure aims to visualize the variability of total generation capacity with respect to the number of producers and the number of consumers (color-coded), rather than to evaluate model accuracy or prediction performance. This study focuses exclusively on communities with a total production capacity below 200 kW, a threshold was chosen to exclude cases in which large-scale renewable energy plants are incorporated within the REC structure, as such communities exhibit distinct characteristics and may not represent typical small-scale, community-based energy model. The resulting distribution reveals several patterns:

- To date, communities with two producers show the widest range of energy output, with a median value higher than other categories. These communities also tend to have higher consumer participation, as indicated by the red-shaded data points. While the presence of only two producers does not necessarily yield definitive quantitative insights, it does suggest that Italy’s RECs remain in an early stage of development and are gradually evolving towards configurations with a larger number of producers.
- Communities with a single producer have relatively consistent production outputs, although generally at a lower scale. They also tend to serve fewer consumers, as indicated by the darker blue shading suggesting limited internal energy sharing.
- Additionally, RECs with three or more producers exhibit lower median production levels, highlighting the presence of different development types among Italy’s RECs that warrant further categorization. For example, RECs could be classified based on their primary functional focus, such as commercial RECs, residential RECs, and industrial RECs, or according to their renewable energy deployment structure, distinguishing between plant-based RECs and

RECs with DRE systems. Further scholarly efforts are required to provide more precise definitions and in-depth discussions of these REC typologies.

This analysis indicates that an increase in the number of producers does not necessarily results in a proportional increase in total energy generation. Similarly, no clear correlation is currently observed between the number of consumers and the number of producers within individual communities. At present, the development of RECs in Italy is still at a relatively early stage, and it is premature to assess whether community-level generation can meet consumer energy demand in pursuit of carbon neutrality. To achieve the ultimate goal of zero-emission communities, it will be essential to establish a clear quantitative relationship between the number of producers and the number of consumers. Furthermore, increasing the number of producers alongside the adoption of advanced technologies will be critical for enhancing the renewable energy generation capacity of REC. With the expansion of the PNRR’s incentive scope and the sustained infusion of funding, the landscape of RECs in Italy is expected to undergo significant transformation.

4.3. Other renewable energy source application and auxiliary technologies

While PV systems currently dominate the energy mix within Italy’s RECs exploring alternative renewable energy sources is essential to promote diversification, enhance energy resilience, and align generation profiles more closely with local resource availability. A comprehensive understanding of the current deployment levels of various energy technologies within RECs when compared to national renewable energy potentials helps identify both existing limitations and future opportunities. Therefore, in this section, the national status of renewable energy utilization was compared with REC-level data compiled in Appendix D, which provides detailed information on the adoption of multiple renewable energy sources across different communities. This comparative analysis allows for an evaluation of Italy’s broader renewable energy development potential while identifying opportunities to advance technological diversification within the REC framework.

Fig. 10 compares the installed capacity (in kW) of different renewable energy technologies utilized in RECs against the national renewable energy production figures (in GW) as reported by GSE. The most significant observations from this comparison include:

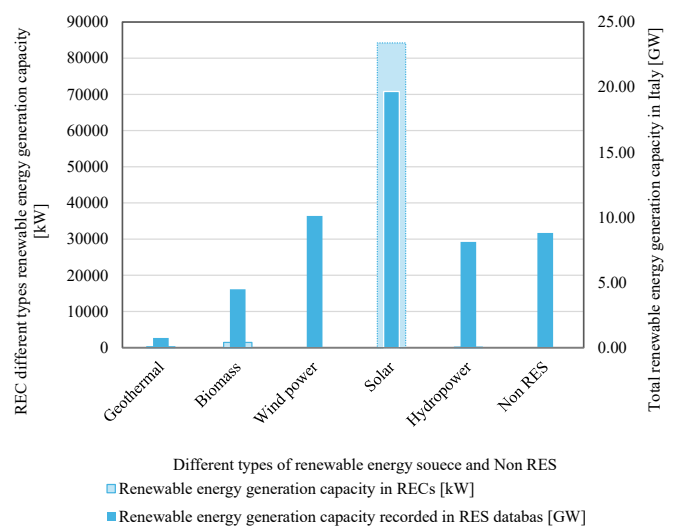


Fig. 10. Statistics on the utilization of various renewable energy sources in REC.

Source: Appendix D and GSE database [82]

- Solar energy overwhelmingly dominates REC production, presenting for the majority of installed capacity within communities. The trend reflects the accessibility and cost-effectiveness of small-scale PV systems, especially rooftop installations.
- Wind power and hydropower are integrated in REC at moderate levels, yet their presence is significantly smaller compared to their national generation potential. This suggests underutilization within community energy models, potentially due to permitting complexities, technical constraints, and the most dominated, high investment costs.
- Biomass and geothermal energy are marginally represented in RECs, despite their contribution to the national energy mix. Their limited uptake may be attributed to higher investment costs, spatial requirements, or lack of local resource availability in many communities.
- Interestingly, non-renewable energy sources (non-RES) are also present in some RECs, likely reflecting legacy systems or hybrid configurations in transition toward full decarbonization. In future research on non-RES usage trends within RECs could serve as a valuable indicator of the pace and effectiveness of community-level decarbonization. Monitoring the gradual phase-out or integration of non-renewable sources may help assess the transition trajectory toward fully renewable energy systems.

The comparison highlights a clear opportunity for technological diversification in future development of RECs. Regions with high wind, hydro, or biomass production potential could benefit from customized REC models that integrate these technologies. Thereby reduce over-dependence on solar and enhance the balance of renewable generation throughout the year. To unlock the full potential of RECs in Italy, a resource-REC matching strategy should be systematically implemented. This would involve:

- Developing a national GIS-based REC Planning Tool that overlays renewable resource maps, energy demand profiles, population density, and grid accessibility to help communities identify optimal REC configurations.
- Encouraging regional REC innovation zones, where tailored support is given for testing non-solar REC models that match regional strengths—such as wind in Apulia, biomass in Emilia-Romagna, or hydro in Trentino-Alto Adige.
- Establishing performance benchmarks for resource utilization efficiency at the community level, creating a transparent metric for assessing how well a REC utilizes locally available resources relative to its potential.
- Promoting cross-regional knowledge exchange, where successful diversified REC models can be shared and replicated in other areas with similar resource conditions but less experience.

By systematically aligning the renewable energy potential of each region with the design and implementation of RECs, Italy can move beyond the PV promoting approach and build a more resilient, inclusive, and territorially optimized community energy system. Additionally, electric vehicles (EVs) and energy storage systems although not energy sources in themselves are frequently considered integral components of REC infrastructure. Among the alternative RESs, wind energy is used in only four RECs. This limited adoption may be attributed to the geographic characteristics of small Italian towns, which are often located inland or in areas with complex topography that lack stable wind resources. Hydropower is found in just two RECs, despite Italy's advanced development in this sector. This is likely due to stringent land use and environmental regulations, as well as the scarcity of suitable sites for new small-scale hydro installations. There are three communities generate electricity from biomass, which requires a consistent and locally available supply of organic material. However, many smaller towns lack the forestry or agricultural waste infrastructure necessary to

sustain biomass systems. CHP systems are deployed in three villages, but adoption has been limited due to the relatively high capital and maintenance costs, which are often prohibitive for resource-constrained communities when compared to more accessible technologies such as solar photovoltaics. Moreover, shared Battery Energy Storage Systems (BESS) within RECs can reduce the overall deployed storage capacity while enhancing the total rate of return and improving self-sufficiency compared to individually owned systems [83]. Rather than relying on external grids, storage allows communities to retain surplus renewable electricity and use it during peak demand periods. This improves energy self-sufficiency and enhances the overall efficiency of renewable energy utilization. Energy storage systems also enable the integration of EV charging infrastructure, alleviating immediate load stress on the grid. With the growing number of electric vehicles in Italy, EVs may also serve as mobile energy storage units. Storage technologies, such as private or community-shared batteries, address the intermittent nature of renewable energy. These systems store excess power during periods of high production and release it when demand rises or generation drops enhancing grid stability and sustainability. The community's capacity peak and associated energy storage facility difficulties must be taken into account when RECs are developed further. In order to assist communities in striking a balance between energy production and sales, EVs can be utilized as mobile energy storage facilities in addition to energy storage batteries in the present REC instance. In summary, energy storage technologies are essential for the continued advancement of RECs, as they facilitate greater flexibility, enable higher levels of renewable energy integration, and support the goal of local energy autonomy. Smart grid and meters are key technologies for RECs implementation allowing consumers to actively participate in RECs exchanging the energy produced when not directly used.

Another key technology is the integration in RECs of blockchain concept for energy exchange. The technology creates a trusted and decentralised direct exchange between two parties (local producers and institutionalized energy suppliers). No intermediaries or third parties are needed in order to fulfil transactions. Moreover, the data on the blockchain are public, easily verifiable by interested parties, consistent, and always available. The data on the blockchain are also immutable providing a reliable legal point of reference.

4.4. Limitation and potential

RECs demonstrate substantial potential in advancing energy decentralization and local governance. As an institutional arrangement for implementing EU policies at the national level, RECs provide a platform for municipalities, cooperatives, and residents to jointly produce and consume renewable electricity. This not only reduces electricity expenditures, particularly alleviating the energy burden on vulnerable groups, but also enhances economic feasibility through differentiated tariffs and capital subsidies. Furthermore, RECs directly link communities to project benefits, thereby improving public acceptance and engagement with renewable energy and fostering social equity. At the environmental and energy-system levels, RECs also play a vital role by increasing renewable energy penetration, facilitating the adoption of storage and demand response, enhancing distribution grid flexibility, and supporting the achievement of EU and Italian decarbonization targets. Nevertheless, despite their considerable potential, RECs continue to face significant limitations under the current institutional framework. First, administrative and regulatory complexities remain prominent, as procedures for authorization, grid connection, and access to incentives are often lengthy and impose additional institutional costs. Second, the historical capacity cap of 200 kW during the pilot phase constrained community-scale development; although later relaxed, most RECs still struggle to contribute substantially to the national 2030 targets. Financing also represents a critical barrier: while the REC Decree and PNRR funding provide support, communities largely rely on public subsidies, with market-based financing instruments still

underdeveloped, raising concerns about long-term sustainability. In addition, within a highly liberalized electricity market, large enterprises enjoy competitive advantages, whereas small-scale, non-profit-oriented RECs lack bargaining power and face challenges in accessing higher-level markets. Most importantly, REC development exhibits strong regional disparities: northern regions, benefiting from administrative and financial advantages, have advanced more rapidly, while southern regions face governance and resource constraints that hinder widespread adoption. From a research perspective, this study also has limitations. The analyses rely primarily on publicly available datasets (e.g., GSE and Legambiente), which, while comprehensive, may not capture all ongoing REC initiatives or reflect the most recent developments in real time. Furthermore, the methodology adopted is descriptive and statistical rather than predictive; no simulation or scenario-based modeling was applied, which restricts the ability to forecast long-term REC trajectories or test alternative policy frameworks. Looking ahead, future research should incorporate dynamic modeling approaches to explore the evolution of RECs under different policy, financial, and technological scenarios. Comparative analyses across EU member states would also be valuable in identifying transferable best practices and assessing how national governance systems shape REC outcomes. Finally, interdisciplinary research that integrates technological, socio-economic, and behavioral dimensions will be essential to fully understand how RECs can scale equitably and sustainably. In summary, RECs in Italy play a significant role in advancing the energy transition, reducing costs, and enhancing social acceptance. However, their development remains constrained by structural barriers, including administrative complexity, insufficient financing, and pronounced regional disparities. Without reforms to streamline authorization procedures, optimize grid access, and develop innovative financing mechanisms, RECs risk remaining a supplementary instrument rather than evolving into a central pillar of Italy's energy transition.

5. Conclusion

This study has provided a comprehensive novel analysis of the development, characteristics, and spatial distribution of RECs in Italy, based on official data, case studies, and geospatial analysis. By constructing eight KPIs, we systematically assessed REC implementation across population scale, production capacity, energy types, consumption patterns, and community structure. The results indicate that there are currently 212 RECs in Italy, most of which include fewer than three producer. Most of the rely on rooftop PV generation with capacities below 125 kW. They are mainly located in municipalities with fewer than 5000 inhabitants (55 % of cases). These findings highlight the effectiveness of Decree MASE No. 414/2023 in supporting small-medium community participation (with the PNRR extending eligibility to community up to 50,000 inhabitants [84]). Italy is now entering a new phase of REC development, transitioning from small-scale pilots to larger-scale configurations. As a member of the European Union, Italy's RECs development has been shaped within the EU legal framework, offering valuable insights for other member states. One of the key findings of this study is that the KPI framework developed here has broader relevance, as it is grounded in the principle of balancing local generation with consumption. While solar PV remains the dominant energy source, the limited adoption of wind, biomass, and hydro reveals untapped potential, particularly in southern and rural regions. Policy reforms that promote technological diversification, streamline permitting processes, and expand financing instruments are crucial to strengthening REC scalability and equality. Differently from conventional energy models, RECs are people-centered, aiming not just to generate energy, but to empower socially and economically the actors. Community engagement is a key element of RECs, shaping both their success and sustainability, reducing energy poverty by enabling access to clean, affordable energy, especially for vulnerable and low-income populations. Though the comprehensiveness of the collected data, this

study has some limitations. First, the analysis is based on publicly available REC datasets, which may contain reporting gaps or inconsistencies across different regions. Second, the absence of simulation or forecasting models limits the ability to predict long-term impacts. Lastly, regional policy variability and incomplete standardization of REC classifications may affect the generalizability of certain findings. On the contrary, the 40 % non-repayable grant is strongly encouraging a model centered around prosumers who may eventually exit the configurations, rather than promoting models based on shared ownership of generation assets. This form of collective ownership, which can be essential to generating meaningful social and environmental impact, continues to face bureaucratic, financial, and cultural barriers. These limitations, however, do not undermine the validity of the observed trends, but rather highlight opportunities for further research. Nonetheless, RECs demonstrate significant potential for advancing decentralization, reducing costs for vulnerable groups, and improving social acceptance of renewable energy. The key lesson from this initial phase is that financial incentives alone are insufficient. The outlook from this initial implementation phase is clear: in order for RECs to become an effective tool for decarbonization and energy democratization, it is necessary to move beyond traditional economic incentives and design more systemic interventions. These should include enhanced technical and administrative support, credit access guarantees, the development of crowdfunding/investment instruments, regulatory simplification, and awareness-raising initiatives aimed at fostering trust in shared asset management. Only through an integrated vision and a genuinely community-driven approach will it be possible to transform RECs, both local and national, from isolated pilot projects into a true social and territorial infrastructure for Italy's energy transition.

CRedit authorship contribution statement

Yunxi Zhu: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Graziano Salvalai:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Paolo Zangheri:** Writing – review & editing, Writing – original draft, Validation, Supervision.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2025.116404>

Data availability

Data will be made available on request.

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