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Renewable Energy Communities: Towards a new sustainable model of energy production and sharing

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ABSTRACT

In the context of Europe's efforts towards decarbonization, this paper introduces a novel framework for Renewable Energy Communities (RECs), validated with multiple case studies from Italy's practice. Drawing on established concepts and an extensive literature review, the framework identifies key pillars supporting its model. The paper delineates the essential features defining the conceptual model of RECs, offering a process-oriented perspective. This model serves as a tool to assess the success of existing RECs comprehensively and provides a structured pathway for the development of new projects across different countries, fostering replication within communities. An overarching framework is presented as a solution to enhance the effective utilization of renewable energy sources. Buildings, and the communities of people who live in them are considered primary energy consumers and direct beneficiaries of a REC framework. Consequently, an original pathway for the mass renovation of buildings located in highly populated areas, from the energy sources perspective, is provided.

1. Introduction

The significant global changes caused by human intervention such as the rapid growth of the population, the acceleration of technological development, and the increase in the consumption of resources, put our civilization at risk because they damage the delicate balances that make work all natural systems.

At the COP21 in Paris, as part of the climate change mitigation efforts of participating States, an international agreement was signed, committing to keep global warming below 2 °C above pre-industrial levels by the end of the century, and if possible, limiting the increase to 1.5 °C [1]. Furthermore, at the 2021 COP26 in Glasgow, participating states committed to achieving Carbon Neutrality by 2050 and reiterated the importance and urgency of combating climate change. Four high-level outcomes to combat climate change were identified: (1) eliminating net emissions globally by 2050 and aiming to limit the increase in temperatures to 1.5 °C; (2) adapting to the protection of communities and natural habitats; (3) mobilizing funding; (4) accelerating activities for tackling the climate crisis by strengthening collaboration between governments, businesses and civil society [2]. Furthermore, these outcomes can be unified into a primary objective, which is to accelerate the global energy transition towards Net Zero [3]. This supports the transition from an energy mix based on fossil fuels to one with low or zero carbon emissions, based on renewable sources.

A significant potential to decarbonization comes from the switch of energy consumption to electricity, as predominant vector [4–6]. This requires the replacement of electricity generated from fossil sources with electricity produced from renewable sources, and the provision of the improvement of energy efficiency and deep digitization of the energy networks. Thus, the energy transition is not limited to the gradual closure of coal plants and the development of clean energy, but it is a paradigm shift for the entire energy system that can bring advantages, not only for the climate but also for the economy and society. The energy transition, however, cannot be performed without the joint and interactive management of technological, environmental, economic, and social problems, given the interferences between social changes and technology. Subsequently, the activation of new forms of collective action and collaborative economies connected with the opportunities offered by new digital technologies, might constitute the bases of the energy transition. The outcomes depend on entire supply chains, from producers to consumers.

Technologically, the digitization of networks can enable smart grids

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which offer new services for consumers. Smart grids are electricity grids that are enhanced with technologies which enable the management and monitoring of electricity distribution from all sources of production. Furthermore, it satisfies the various electricity requests of connected users, producers, and consumers in a more efficient, rational and safe ways [7].

Environmentally, renewable sources reduce pollution, while fossil-fueled power plants can be integrated into a circular economy perspective, through restructuring and modernization, with the use of existing infrastructure. However, the reconsideration of the energy sources mix is mandatory, either by switching from fossil sources to renewable sources, either through the use of high energy-efficient sources, such as cogeneration, or the use of both options simultaneously. Solar and wind energy are the great protagonists of the energy transition underway. These sources were previously marginal until their exponential growth in recent decades. Between 2010 and 2019, worldwide photovoltaic capacity doubled from 40 GW to 580 GW [8]. According to IRENA [9], the costs associated with generating electricity with photovoltaic panels have decreased by 82 % in the last decade.

Economically, the circular economy approach might generate business models with enormous potential, capable of generating competitiveness by combining innovation and sustainability. To implement the circular economy model, the keywords for the production and consumption model are sharing, loan, reuse, repair, refurbishment, and recycling. In the framework of circular economy practices, the sharing economy is gaining increased approval, as it has proved to be advantageous, economically, and socially and environmentally [10]. The sharing economy is a model based on the sharing of resources so that they are available to everyone, at affordable prices. It is foreshadowed that the active subjects in managing these energy sharing processes will be the Renewable Energy Communities (RECs). For example, actors may consider the mass renovation of multifamily buildings, located in highly populated urban areas, to nearly Zero Energy Building (nZEB) or Zero-Emission Building (ZEB) targets, as required by the Energy Performance of Buildings Directive (EPBD) [11]. Currently it is clear that the effective implementation has important site limitations [12]. Therefore, RECs might be a large-scale solution, to produce the energy required by the community locally and to maximize its use. The concept of energy sharing is closely related to renewable energy and, in particular, to photovoltaic systems with storage. To maximize self-consumption, the concepts of energy sharing, and the energy community intervenes, in which the surplus energy is shared and made available for those who need it [13].

Socially, on a global scale, the citizens are harnessing new technologies to unite and assert their significance in the energy sector. Citizens are engaging in direct, participatory endeavors to foster a fairer, more sustainable society. Barroco et al. [8] estimate that a significant number of citizens of the European Union will join the energy market as prosumers, generating about 50 % of the total renewable electricity of the system. Prosumers are active participants in the management of energy flows, who are not simply consumers but who actively engages in all phases of the production process. Prosumers can be motivated by the advantages offered by participation, including a degree of independence and also economic gains.

In this multidimensional context, RECs stand as a new phenomenon for reaching energy transition by leveraging the technological, economic, and social perspective of sustainability. RECs have the capacity to introduce innovative prosumer models, enabling a collective of users to collaborate voluntarily under a contract. Their goal is to generate, consume, and oversee energy production through one or multiple local energy facilities. RECs share the same goal: to provide affordable renewable energy to their members, rather than prioritizing economic profit, like a traditional energy society [8]. Energy communities are established on the principles of decentralizing and localizing energy production. These communities, which involve citizens or small businesses in management, aim to generate, use, and share energy for self-consumption and cooperative purposes.

The main objective of this paper is to present a conceptual model for the Renewable Energy Communities, by conducting a thorough analysis of their advantages, structures, and limitations. The approach includes a comprehensive review of the concept, considering multiple perspectives. Furthermore, the proposed model is validated thorough analyses of several Italian case studies: the Energy and Solidarity Community of East Naples, the Energy Community of Magliano Alpi “Energy City Hall”, the Renewable Energy Community of Biccari and the Renewable Energy Community of Brindisi. These were chosen because specific data was available.

2. Background

We undertook the analysis of the REC state of the art in view of their history, the evolution of the regulatory framework in the European Union and, in particular, in Italy, the technologies that are currently used for the production of energy with reference to smart and technologies for storage, and their business models.

The “Energy Community” concept is not new, it emerged as a solution for isolated regions, such as the highlands or islands, even before the usage of decentralized energy resources became popular [14].

The model summarized by Gancheva et al. [15] considers an energy community effort as a shared responsibility for and enjoyment of the advantages associated with the action of producing energy. The principles of this model are centred on the fight against wasteful energy usage and the equitable sharing of a fundamental resource at a fair cost, made possible through energy market innovation.

The evolution of energy communities in Europe was precipitated by the decision of Arab oil-producing countries to raise oil prices by 70 % and cut output by 5 % monthly [16]. Beginning in the 70s when Denmark’s pioneered wind turbine project, the evolution was marked by citizen-driven initiatives, government support, and subsequent growth [17,18]. Germany played a pivotal role with the emergence of a bioenergy village in Jühnde in 2006 [19]. The German Feed-in Tariff was a pivotal driver, leading to widespread adoption by over 130 communities [20]. However, Germany faced a decline in communal energy initiatives after 2015 due to regulatory challenges. Radtke and Ohlhorst [21] estimate that there were around 1800 community energy projects built in Germany between 1995 and 2020, with just 71 from 2015 to 2020. In Italy, the Energy Community concept dates to the late 19th century, with a modern resurgence from 2005 to 2013, fueled by cooperative efforts and renewable energy policies. Cooperative development was largely funded by member contributions, offering residents investment returns ranging from 1 % to 8 % [22].

In summary, community-led energy initiatives have been an integral part of to the European Union’s energy framework for an extensive period. However, the term “community” in the context of energy has been used with manifold meanings and the research community still agrees that a common definition and understanding is not present so far.

Regarding the European context, there is more clarity in defining roles due to legislative restructuring. However, most of the available studies are not aligned with the new definitions.

Energy communities and collective self-consumption initiatives have recently taken a prominent position in shaping the European energy policy landscape by the recast of the Renewable Energy Directive (RED-II), 2018/2001/EU [23] and the common rules for the Internal Electricity Market Directive (IEMD), 2019/944/EU [24], as main directives for the European regulatory framework. RED-II contains the definitions of collective self-consumption and of the Renewable Energy Community, while IEMD defines the Citizens’ Energy Community. The definitions of different community led-energy initiatives are presented in Table 1.

A high similarity exists between the definition of RECs and the energy cooperative, where the latter is included in the formal REC definition.

Table 1
Current terminology related to the topic of community led-energy initiatives.

Terms	Definition and Description	Definition Source
Renewable Energy Cooperatives (REC)	A collective of individuals who voluntarily participate in a democratically managed, non-profit organization. *Main goal:* to address shared economic and social needs within the energy sector, including production, distribution, and consumption	[25]
Renewable Energy Communities (REC)	Legal entities, with voluntary and open participation managed by members or shareholders (natural individuals, SMEs, or local governments, including municipalities). *Main goal:* to provide environmental, economic, or social benefits for the community, rather than generating financial gains	[23]
Citizen Energy Communities (CEC)	Similarly defined as REC, with extended operational activity, to provide energy efficiency services or electric vehicle charging services for the members or shareholders.	[24]

For the Citizen Energy Community (CEC), the European definition was modified subsequently, with its latest form in April 2019, included in the currently in force Directive 2019/944/EU [24].

However, the CEC solely oversees electricity, regardless of its source - be it fossil or renewable. It also lacks a framework that embodies the principles of autonomy and proximity.

Regarding Italian legislation, Italy implemented the European Directives 2018/2001/EU and 2019/944/EU, through the Milleproroghe Legislative Decree 2021 [26]. Several other national legislative measures enforced and provided the legal framework for REC implementation, including the incentive tariff and the limitations related to the maximum power of plants (not to exceed 200 kW) [27]. The Arera Resolution 318/2020 [28] governs methods and economic regulation relating to electricity shared in buildings or condominiums by a group of renewable energy self-consumers who act collectively or within the renewable energy communities. Technical rules to be followed regarding collective self-consumption and energy communities were published in 2020 (GSE portal), with the role to manage the incentive mechanisms. Among the various measures adopted by the Italian government is the Ecobonus 2020 [27], which introduces a deduction equal to 110 % of the expenses related to specific energy efficiency measures and anti-seismic measures on buildings, incurred for a specific period of 2.5 years.

The basic goal of energy communities is for members and/or the local community to self-organize around an energy-related activity, to provide services or other socio-economic benefits. However, important technical challenges require consideration. Advanced activities can be done, and they usually necessitate real-time control of loads, generators, and storages to deliver improved services. This necessitates a sophisticated metering system, as well as a reliable and secure connection. It also necessitates the presence of controlled loads and actuators capable of sending commands, based on set-points determined locally or received by a central controller. The application of blockchain technology is an important advancement in this industry, considering decentralization as one of the most important components of the electrical sector's shift.

The uncertainty and discontinuity of supply from energy sources such as wind and solar, and their extreme fragmentation in small power plants, are factors that complicate their integration into the grid. To absorb the energy generated by these numerous plants along their further development, it is necessary to strengthen the grid, to modify it conceptually and to renew it technologically according to the logic of smart grids and digitalization.

Regarding the managerial problems for new and more complex technologies, a solution might be to integrate local energy operators into RECs, as shareholders. This will facilitate the required investment to be operated institutionally, rather than family driven, and will provide a proper technical assistance and maintenance for the systems.

Technologically, solar photovoltaics and wind energy technologies have been recognized as the most widely used systems in REC in the literature [29].

One way to facilitate the integration of clean and distributed energy resources into the system is to create "smart grids" and "smart meters". The European Union Commission Task Force on Smart Grids [4], defines the smart grids as cost-effective customer-oriented electrical network that incorporates the activities and behaviours of the actors linked to the grid system. Smart grids are a new trend in electricity systems; therefore, their benefits are not completely standardized. The shift from traditional grid infrastructure to smart grid architecture has increased the relevance of information and communication technologies (ICT) within the energy networks. Smart metering is an important ICT-enabled function for measuring bidirectional communication between consumers and producers, and it is an important part of the smart grid systems in enhancing energy efficiency [30].

By matching demand to the needs of the overall system in real time, digitalization opens the opportunity for consumers and producers to sell electricity or provide valuable services to the grid. Smart energy communities and blockchain are fundamentally complementary because they enable decentralization. An experiment of this type was launched in 2021 by the Italian government, namely the PlatOne project [31]. PlatOne aims to develop and test cutting-edge technological solutions to enable energy flexibility mechanisms within an open and inclusive European market. The organisation responsible for coordinating the Italian pilot project is Acea, thus becoming the first key player on the path towards defining a new smart grid energy market model.

When considering the business models for REC implementation, it is identified that a REC can take numerous forms, depending on the extent of stakeholder involvement in the project, the investment, and the peculiarities of the considered area. Every member plays a crucial role in shaping, executing, and maintaining the overall arrangement, influencing the value generation in Business Models for Energy Communities (BMEC) and the equitable distribution of risks and costs. Additionally, community members must have a financial stake, and the entire business model should be tailored to meet their specific needs and preferences [32]. The BMEC can be classified by a customer-side business model or by a third party-side business model.

While energy communities are not primarily profit-driven, they aim to secure returns for their shareholders. This is achieved through various means, such as accessing more affordable energy, selling surplus production or equity stakes or reducing reliance on the electricity grid through self-consumption. By participating in a community, members collectively share costs and risks, thereby reducing the initial cost financial barrier.

This framework is mainly addressed to authorities and decision-makers, starting from large entities (such as the European Commission) to the national level (government and local public authorities). These entities can use the framework to establish legislation and specific framework regarding RECs, where it does not exist (e.g., the case of Romania) or to enforce it (e.g., in the update of the European directives, for the implementation of later national laws).

In a wider context, the main objective of this work is to provide a solution for the mass renovation of existing and new buildings, linked with the mandatory concept of nZEB [11], which soon will be replaced by mandatory ZEB [33], to achieve zero emissions by 2050. The framework solution developed within this work, might be a clear pathway for the buildings located in highly densely populated urban areas.

3. Materials and methods

3.1. Research methodology

The main objective of this study is the substantiation of a REC model. The topic is complex and constantly changing, thus multiple approaches were required. Context also requires consideration, including a wide range of elements and characteristics.

The methodology that we have used for the research is the Grounded Theory, by using inductive reasoning. The Grounded Theory is a qualitative research method focused on developing theories through systematic data collection and analysis. Generally, this technique is valuable for achieving a profound comprehension of a phenomenon which allow to substantiate new theories or concepts that are firmly rooted in empirical evidence. This process involves an ongoing cycle of data collection, coding, and analysis, aiming to develop categories and subcategories rooted in data. These categories and subcategories are subsequently compared and synthesized to formulate a theory that explains the phenomenon.

However, we used this method to conceptualize a new REC, based on a significant amount of primary data.

Coding in grounded theory is a dynamic, iterative process that is essential for developing theories from qualitative data. It involves breaking the data into concepts through open coding, linking these concepts via axial coding, and ultimately choosing a core category and refining the theory during selective coding [34,35].

For the undertaken work, we grouped similar data under the same conceptual headings (open coding). Through further analysis, these concepts were combined to form categories. Through axial coding, we connected codes to their contexts, interaction patterns, and consequences. Further, through selective coding, we systematically connected the categories, validate it, and further refined and developed it. The final various categories provided the REC framework.

The organization and the qualitive analysis of the data were undertaken using Excel software.

The first step for conducting the research analysis was to examine the state of the art of the related topic and to complete a robust literature review.

The proposed concept, therefore, had to highlight the results of past research, evaluate their strengths and weaknesses and highlight open questions. Within the current work, three types of primary data sources were distinguished: (1) collection of European directives and national laws; (2) Technical Reports from National/International Energy Institutions; and (3) scientific papers. The scientific papers were the core input data in the subsequent analysis.

For the legal information, we consulted the "Official Journal of the European Union" and the Italian "Gazzetta Ufficiale". Firstly, we have identified and collected all relevant directives, laws, and regulations pertaining to RECs [23,24,26,27], from the specified legal sources. Subsequently, we have organized the collected legal documents into categories based on their relevance to various aspects of RECs, such as formation, operation, funding, and incentives. This helped in focusing the analysis on specific areas of interest, including both overarching European Union directives and specific national laws and regulations. A qualitative content analysis was performed on these legal documents to identify and categorize relevant legislative frameworks, policy objectives, and regulatory measures that directly influence the development and operation of RECs.

For technical data and reports, we consulted sources ([9,16,31,36–38]) from officially recognized national and international energy institutions and entities, including: the International Renewable Energy Agency (IRENA); the European federation of citizen energy cooperatives (REScoop,eu); the Italian Regulatory Authority for Energy, Networks and Environment (ARERA); Legambiente (an Italian environmental association); and ENEA (an Italian public research body).

These institutions and entities were chosen because they are highly respected and authoritative sources in the field of renewable energy, providing comprehensive and reliable data. The analysis of their technical reports involved extracting and synthesizing qualitative data, to assess the current state and potential of RECs.

For the scientific papers, as main data source, we performed the bibliographic review by using Scopus database. The selection criteria for the articles query were as follows:

1 the research string referred to title/abstract/keywords were the topics "renewable energy community", "renewable energy cooperative", or "renewable energy sources community";
2 the time range used was "2018-present";
3 the selected language was "English";
4 the searched subject areas were energy, engineering, social sciences, information technology, economics and mathematics.

The selective search provided 126 articles. A preliminary analysis of the titles, abstracts and keywords allowed us to make a first classification of the papers, which have been divided according to the main topics. The next step was to read the included papers, highlight the keywords and synthesize the content with respect to the main identified themes. We used different techniques for coding categories reorganizing, re-examining, merging, or separating them. The last step included finding patterns and honing the overarching themes using theoretical ideas from the literature consulted.

In carrying out the literature analysis, we found several topics to be common to most of the papers regarding REC. The most frequently encountered topics are summarized in Table 2.

The identified topics were used to categorize the main features of REC in a selected set of categories; in order to define the conceptual model for the REC. Beyond the literature review, we conducted a multiple case study analysis. The purpose of the multiple case study was to identify the patterns for the conceptual definition and creation of REC, to understand its main characteristics and features, with the purpose to identify and propose a general framework.

We analyzed the topics that emerged from the study of the literature review, to identify several distinct categories, to group them appropriately and make them effective in the construction of a conceptual model.

3.2. Validation of the model thorough several Italian case studies

Further, the proposed conceptual model was used to analyze four RECs from Italy, to validate it. The first one was the Energy and Solidarity Community of Napoli Est, in the district of San Giovanni in

Table 2
Topics addressed in the scientific literature review and the frequency of the topic's appearance.

Topics	Occurrences	Topics	Occurrences
Energy policy	49	Investments in REC initiatives	20
Economic and social effects	45	Energy production technologies	19
Sustainable development	29	Energy efficiency	18
Environmental effects	29	Energy sharing	18
Laws and legislation	25	Prosumers	17
Electric power transmission networks	25	Citizen & local participation and participatory approach	15
Photovoltaics	23	Economic viability	15
Local strengths and issues	22	Social innovation	11
Electric energy storage	21	Demand side management	10
Business models	21	Digital technologies for REC	9
Governance models	21		

Teduccio (NA). The second case study was the Energy Community of Magliano Alpi "Energy City Hall". The last two are located in Puglia and are still under development: the third was the Renewable Energy Community of Biccari and the fourth was the Renewable Energy Community of Brindisi.

Validation itself consisted in going through each pillar proposed in the concept with each case study, to check to what extent there is generalized applicability of the concept, for the various existing RECs.

The analysis of the case studies allowed to test the effectiveness of the proposed conceptual model. It was possible to verify that in the REC already well consolidated, like the first two cases, all the identified pillars are matched. Based on the analysis, it was observed that all the characteristics of the REC were well defined by the proposed model and do not exclude any fundamental aspect.

As for the REC being defined, like the two case studies of Puglia, they served to confirm the use of the pillars in the form of a process. In the case of the Biccari REC, the analysis phase has been completed and the design phase has begun. The assessment phase needs to be postponed until the renewable energy community is operational. In the case of the REC in Brindisi, the design cannot proceed until the barriers, which are part of the first phase of analysis, are overcome.

A detailed analysis of the case studies used for the REC concept validation is provided in Appendix 1 (Table A1.1 and Table A1.2).

4. Results and discussion

4.1. Literature review analysis results

An extensive literature review was undertaken with the aim of classifying the data into several pillars, which would form the basis of the REC conceptual model. The specific categories (which emerged from the frequently addressed topics related to REC) were grouped into main categories (see Table 3).

Based on the classification of the review literature and through the conducted multiple case study analysis of the selected topics, the following pillars were substantiated.

REGULATORY FRAMEWORK. This pillar comprises the directives, laws and rules that give the definitions of the REC and provide explanations about the economic incentives, the role of citizens and involved actors, as well as the legal information about the electricity market. Renewable Energy Communities are currently an important topic on the European agenda. Therefore, the regulatory framework is constantly evolving. Energy communities have been legally defined in the European "Renewable Energy Directive" (RED-II). Regarding the implemented legislation, it varies by country (e.g., for Italy's case study, a detailed assessment of the nationally applicable legal framework was undertaken in the background section of this paper).

CONTEXTUAL DRIVERS AND BARRIERS. The model of the RECs has a significant potential, as they can generate competitiveness by combining innovation and sustainability. The cost reduction of tax advantages and the efficient use of energy are among the direct advantages found in the background analysis. As reported in the literature [165], the administration or a company that chooses to participate in an energy community and therefore consumes the electricity produced by a photovoltaic system, has access to economic advantages. First, they can realize savings on their bills: direct consumption of energy leads to reductions in the variable components of the bill (such as energy quota, network charges, and associated taxes). Second, they can generate revenue from the energy they produce. Installing a photovoltaic system can serve as a source of income, if considering incentive mechanisms. Third, they might benefit from direct tax deductions, i.e., the recovery of 50 % of construction costs for installing a photovoltaic system on the roof of a building (e.g., in the case of Italy). These economic benefits can encourage the creation of RECs and are consequences of an attractive regulatory framework.

Among the indirect success factors is the quantified added value due

Table 3
Categories identified in the scientific literature review related to the REC topics.

Main Category	Specific Category	Consulted references
Current legislation framework for REC	Energy policy - involves creating strategies and regulations to guide sustainable energy production, distribution, and consumption	[39–80,81–87]
	Laws and legislation - provide the legal frameworks and regulations governing the renewable energy sector.	[41,42,52,69–71,73,76,79–81,84,88–100]
	Investments in REC initiatives -involve funding community-based renewable energy projects and infrastructure	[39,40,45,56,70,71,78,79,86,90,91,93,95,101–108]
Advantages and limitations of REC	Local strengths and issues - refer to the specific advantages and challenges a community faces in implementing RECs	[39,55,57,58,61,73,75,83,85,86,92,97,99,105,109–112]
	Sustainable development - ensures energy systems meet current needs without compromising future generations	[43,50,52,55,67,82,87,90,101,103,108,111,113–125]
	Economic viability - assesses the long-term financial feasibility of REC projects	[41,52,54,58,62,71,84,111,123,126–128]
Technologies required for supporting the REC	Electric power transmission networks - are the systems that transport electricity from producers to consumers within RECs	[51,63,66–68,75,84,88,94,104,117,128–141]
	Technology of electric storage - includes devices and methods for storing electricity generated by renewable sources	[53,57,67,84,89,113,119,127–132,134,142–148]
	Energy sharing - involves distributing locally produced energy among community members	[41,53,66,68,69,76,101,102,104,119,124,126–128,132,142,144,147,149]
	Photovoltaics - convert sunlight directly into electricity using solar panels	[42,57,58,64,71,84,88,104,105,109,113,122,124,126,127,129,134,139,142,143,146,149,150]
	Demand-supply management - balances energy production with consumption using various strategies and technologies	[72,101,102,116,118,135,143,144,147,148]
	Digital technologies for REC - optimize the management and operation of the systems	[114,127,133,145,148,149,151–153]
	Energy production technologies - include methods to generate renewable energy	[40,51,66,103,117,126–128,130,138,141,146,150,151,154–157]
Legal and structural organization of REC	Business models, governance models - define the organization and financial structure of RECs	[44,47–49,55,56,59–62,71,74,76–80,83,92–94,98,99,109,110,112,115,119,120,125,137,142,149,152,158–160]
	Citizen participation, local participation, and participatory approach - highlights the involvement of residents in REC planning and operations	[46,48,62,64,69,89,96,100,106,116,121,144,147,161,162]
	Involved actors' analysis - examines the roles and interactions of stakeholders in REC projects	[40,42,45,64,77,78,90,94,96,97,104,127,145,154,157]

(continued on next page)

Table 3 (*continued*)

Main Category	Specific Category	Consulted references
Positive and negative effects of REC	Energy efficiency - aims to reduce energy consumption by using advanced technologies and improved practices	[53,64,122,124,125,129,136,137,139,150,151,153–157,163,164]
	Environmental effects - consider the impact of REC projects on the natural environment	[41,42,54,64,66,68,74,82,87,108,110,113,121–124,126,127,135,139–141,154–156,161,163,164]
	Economic and social effects - assess the broader impacts of REC initiatives on local communities	[41],43–45,47,50,54,58–60,65,71,72,81,91,92,95,97,98,100,102,104,105,107,111,112,114–116,118,123,126,133,134,142,143,149,152,153,158–162,165
	Social innovation - involves new strategies and ideas to address social needs through renewable energy projects	[60,61,65,74,75,83,92,103,107,137]

to the project. This is considered to compensate for an eventual weak local economy. For instance, there can be a situation in which a household is unable to pay for the primary energy services (heating, domestic hot water, cooling, lighting) and electricity for appliances, needed to ensure a decent standard of living. This may be due to a combination of factors such as low-income, high-energy price and low energy efficiency of the building. The creation of an energy community is one of the solutions to alleviate the phenomenon of energy poverty. As mentioned in the literature [166], by raising awareness among consumers and allowing them to monitor and optimize individual energy consumption, it is possible to reduce household spending. Other indirect factors are related to social phenomena. Brummer [167] shows that participation in an energy community can increase acceptance of other renewable energy projects and can educate citizens on energy issues.

Despite the array of benefits highlighted earlier, the creation of an energy community might encounter several barriers along the way. These can come from diverse sources: social, geographical, economical, technical, and are influenced by direct and indirect factors, as well. As regards the direct factors, for example, the installation of new renewable energy plants may require significant investments and aspiring communities may encounter difficulties in financing the project. The consumers considered for the community could be "unsuitable" for a specific project or there could be a lack of human resources. Challenges might emerge in determining the appropriate legal structure for the community, or obstacles may arise within the national regulatory framework. Geographically, the landscape could be subject to nature protection and could have additional restrictions governing its use.

Other technical barriers relate to communication and control aspects, which result mainly from the large variety of system management and control software options, as identified within the literature [168]. In addition, regarding the indirect factors, advocates of RECs might face opposition from individuals lacking comprehensive information or understanding of intricate, innovative concepts. This resistance to change becomes more challenging to navigate when projects are situated in socially vulnerable areas. Another issue arises due to the indirect nature or the complexity in quantifying certain REC benefits, such as global emission reductions and the promotion of local economic growth. These benefits may not be readily noticeable to individuals, as identified by Timmerman [169]. Furthermore, other actors such as local authorities or stakeholders could show low or no interest in the creation of new projects.

LEGAL ARCHITECTURE. Another aspect to decide for creating an REC is which legal structure the community should take.

Firstly, the actors involved in the creation of RECs are different and can be divided into four types: (1) the end users who can be citizens, private actors, small and medium enterprises, local/regional authorities (e.g., municipal administrations), or private companies; (2) the companies that implement the project and manage the built infrastructure; (3) the financiers of the project; (4) the central and local administration that implements policies.

According to REScoop.eu [36], the small and medium-sized enterprises that can be part of the RECs are those whose participation does not constitute their primary economic activity. Furthermore, another provision in RED-II [23] requires Member States to ensure the inclusion of consumers from low-income or vulnerable families in RECs.

In general, it is possible to identify all the groups that are interested in REC projects or that can influence its outcome, with the term stakeholders, i.e., the groups (2), (3) and (4).

In particular, the stakeholders have different roles (and therefore a different involvement) in the RECs. They may have bureaucratic, political roles, and they may be experts, having different roles such as promoters, directors, or mediators.

Within the literature [170] it is revealed that the identification of stakeholders and their involvement in the public decision making is crucial because it allows for the invitation of important representatives to participate in brainstorming sessions. Consequently, Kalkbrenner and Roosen [171] highlighted that they can have a significant role in shaping the institutions, programs, and settings that have an impact on them.

According to Lowitzsch et al. [14,172], stakeholder involvement can take place in distinct phases of project implementation and in different forms. They can give and receive information about the ongoing development, they can participate in decision-making during the planning process, and they can be financially involved in the project.

As for the end users, in the context of RECs, these become prosumers. This means that the user is not limited to the passive role of consumer, but actively participates in the various phases of the production process (producer). A prosumer is an individual with ownership over their energy production facility, utilizing a portion of the generated energy for personal consumption. The surplus energy can be redirected into the grid, exchanged locally with nearby consumers, or stored for later use, to optimize consumption. Thus, the prosumer actively participates in energy flow management, and can benefit both a degree of independence and potential economic gains.

From a legal point of view, the literature overview identified that citizens can participate in renewable energy projects through a variety of governance methods. They can vary in terms of governance structure, decision-making, and obligations according to the legal form selected. RECs could be entirely owned by the community or jointly produced by public or commercial actors (shared ownership) [173]. Additionally, community-managed projects come in a variety of shapes and sizes, from large cooperatives to small condominiums.

Initially, governance often initiates these developments by trialling new energy-saving technologies within individual households. This model then expands to encompass condominiums and the neighbouring community, fostering a more cohesive approach among active community members or volunteers. This shift requires that individual capabilities are pooled into a collective effort.

Subsequently, governance progresses toward establishing a collective entity such as a cooperative or an association of communities for self-governance. Another approach involves integrating existing local organizations with a community's governance principles. Consequently, a governance entity emerges, or an established one is revitalized by aligning its objectives with those of community governance. All social and structural tiers involved must continually contribute to the initial stage of governance, where citizens are intent on becoming their own users to engage in RECs.

From a legal perspective, distinct types of legal structures can be recognized, including energy cooperatives, limited partnerships, community trusts and foundations, and public-private partnerships.

Financially, within the legal structures according to the current literature [174], it can be identified eight types of energy community business models. These are: energy cooperatives, community prosumerism, local energy markets, community collective generation, third party-sponsored communities, community flexibility aggregation, Energy Service Company community and e-mobility cooperatives.

ORGANIZATIONAL STRUCTURE. In addition to the design of a suitable legal model, it is important to identify an appropriate organizational structure for the REC. While community members can only be prosumers or consumers with different capacities and various decentralized renewable installations, the diversity among community providers is greater. These can be traditional utilities companies, but also real estate companies, municipal administrations, complex technology providers, or transactive energy players.

The above-mentioned actors are inventing new models for generating and capturing value in the energy value chain, selling community-based energy services, peer-to-peer energy trading platforms, and other models.

The organizational structure is a model that should help to strike the equilibrium among the divergent design requirements of RECs, by respecting the selected legal model and the regulatory framework.

There are different ways to define an organizational structure, as identified in the consulted literature. Indirect participation through a Board of Directors [175] or direct participation through ownership and decision-making [176] are both possible. In both cases, the formation of common objectives and a shared identity for greater community empowerment and cohesiveness can benefit community energy initiatives, which serve to build social value and enable experiential learning, according to numerous research in the field [177]. The creation of middle organizations that act as knowledge brokers to promote social learning and innovation by pooling and transferring knowledge throughout communities will further promote social justice. These intermediaries help dispersed communities to come together by facilitating knowledge and idea exchanges. Some of them also provide business, technical, and financial advice.

It is identified an example of organizational structure from the literature [178] which can be suitable for the legal structures described before (the energy cooperatives being the most popular in Europe). In this example, the authors suggest the organization in two main organizational divisions, namely the Board of Directors and Management. The Board of Directors is chosen by the REC shareholders to represent their interests. The Management is selected and supervised by the Board of Directors. The management team oversees managing the project's several workflows as well as its daily operations.

According to organizational theory [179], increasing the quantity and quality of direct connections between individuals fosters cooperation. Communities are also likely to include actors with low levels of expertise in common with some being experts in energy-related areas. As a result, trust and cooperation within the community can foster knowledge exchange. Many individuals are conditional cooperators, meaning they only give to the community when they are confident that others will do the same. People are consequently inspired to participate when they have faith in other people to work cooperatively. REC members can develop creative strategies to inspire, educate, and upskill others in REC and energy conservation, within a community hub. In addition to promoting social connection, virtual communication tools and platforms can deliver useful information.

Furthermore, all individual consumers gather in the General Assembly to make major decisions. The General Assembly members must be provided with the knowledge and abilities needed to make informed decisions. Directors must put important decisions to a vote, even though they should be free to decide what they believe is best for the General Assembly based on the advice they have received.

Finally, the REC fundamental laws and regulations are found in its statutes. Yildiz et al. [173] emphasized that reaching an agreement on the community's vision, goals, and rules early on can help to prevent future disputes.

TECHNICAL ARCHITECTURE. The third aspect to decide for creating a REC is the technical architecture that the community will have. In practice, the community is a complex energy system based on renewable energy sources.

Energy systems face several spatio-temporal technical issues that must be considered. Initially, transitioning to a higher proportion of renewable energy necessitates spatial reconfiguration. Lowitzsch et al. [9] highlighted that renewable sources frequently exhibit significantly lower energy density per unit area (W/m2) compared to conventional thermal power generation (such as nuclear and fossil fuel). This reduced energy density creates new challenges in spatial utilization, requiring an integrated approach that combines spatial and energy planning. Moreover, location-specific technical generation potential may not be correlated with load centres. Additionally, it is often difficult to find space in places with high energy consumption per unit area or high human densities, such as in cities.

Lastly, there is the important problem of the intermittent renewable power generation supply to demand which varies over time. Electricity production derived from renewable sources fluctuates at an hourly, daily, and seasonal level. Therefore, the output of renewable energy sources (such as wind and solar) determines generation at any given time rather than on energy demand.

In the literature [14,180,181], three strategies were identified that can address these problems, namely complementarity, flexibility, and decentralization.

The complementary nature of renewable energy is a key tactic for raising the proportion of renewable energy in a particular energy system. It is made possible by the connectivity of several installations. The share of renewable energy in a given system can be raised even further by combining complementarity with grid flexibility alternatives like storage, demand response, and active grid management. On a temporal basis, the complementarity of a portfolio of REC, including RES sources mix, as: wind and hydroelectricity, or solar photovoltaic (PV) and wind, as well as wind, hydroelectricity and solar PV, has several advantages that make it easier to integrate higher proportions of variable sources of renewable energy into an electricity grid. Several studies [14,180] have shown that standalone hybrid solar PV and wind installations are reliable and economically viable. Briefly, the interplay between different generation resources and their locations can reduce the overall variability in electricity supply.

The second useful strategy is the flexibility of the energy system's controllable components which enables supply and demand to be balanced, which reduces the impact of variable power sources. Flexibility, in general, refers to a controllable power system component's capacity to create or absorb energy at varying rates, over a range of timescales, and in a variety of power system circumstances. According to Koirala et al. [181], there are five keyways in which flexibility could be harnessed within an energy system namely supply-side flexibility, demand side flexibility, energy storage, energy conversion as well as interconnection and grid reinforcement. A flexible energy system could adjust supply and demand to achieve energy balance. Flexibility enables energy networks to monitor energy flows and create market signals to motivate changes in energy supply and demand, integrating smart meters, smart appliances, renewable energy resources and energy efficient resources accordingly. It also enables the flows of energy through the networks to be maintained within safe limits. Energy system flexibility is also ensured via the conversion of energy into different forms. National and regional super grids play a vital role by interconnecting and fortifying grids to manage discrepancies between supply and demand across expansive geographical areas. Energy storage is a cornerstone in the construction of a versatile energy system, allowing various flexibile options to function cohesively. It integrates different sectors like heat, power, and transportation, fostering synergistic operation. The coordinated and synergistic operation of these crucial alternatives is necessary for the energy system's flexibility. Flexibility can be organized in a centralized or decentralized way.

Due to the characteristics of REC, decentralization is an important paradigm of energy networks with high-RES share. For example, concerning decentralization of electricity infrastructure, the proximity of power plants to load centres is decisive, influencing the level of transmission capacity that is needed as well as the losses that occur in the network.

TECHNICAL METRICS. To quantify outcomes of REC implementation, several technical metrics were identified within the consulted literature. The first is the increase of plant system efficiency, as a result of the increase in the efficiency of the new system plant compared to the previous one [182].

Another technical indicator used to assess the technical impacts of community energy projects is the Loss-of-load probability (LOLP) index [133,183]. The LOLP index determines the amount of time in which the power generated by Renewable Energy Sources (RES) does not meet the demand at the desired level of reliability.

Several studies [184,185] show how to compute the physical impacts of RECs on voltage and power quality and therefore the reduction of grid losses. From a technological standpoint, solar PV technologies have been recognized as the most widely used systems in REC in the literature [29]. Photovoltaic panels must comply with a series of requirements, they must be able to transmit the correct nominal power guaranteed in consideration of the different weather conditions and they must be reliable and long-lasting, so that the investment made is repaid by a high yield.

In addition to these benefits, given that the REC are aggregates of producers and consumers who act collectively in local energy projects (with less transit on the infrastructure and a degree of flexibility) they can have positive effects for the national electricity system such as less stress on the distribution network, as identified by Fichera and Volpe [186].

SOCIAL METRICS. Among the social objectives given by the European Directives concerning the RECs, it is possible to identify the following three, which are linked with quantifiable outcomes.

Firstly, a REC should have a prior interest in increasing community membership. Secondly, it should achieve a fair distribution of community benefits. Thirdly, it must accomplish high community openness. The first goal can be measured by analysing the percentage change in the number of the REC members. The second goal can be monitored by the interviews with the actors, by checking the perceived fairness score in the surveys. The third measure can be found by computing the percent of vulnerable consumer ownership. This is a simple formula that can be taken from the IRIS Catalog of Metrics [187], which is a database of quantitative and qualitative impact measures, created by the Global Impact Investing Network. The percentage is computed by dividing the number of total shares owned by minorities by the number of total shares. Being closer to the social goals corresponds to maximizing these three quantities.

In addition to these parameters, other social impacts can be assessed, such as the acceptance of renewable energy technologies by key stakeholders and public opinion, and in general by the actors involved. These analyses can be made through surveys of the actors.

Most of the literature on this topic focuses on wind projects, since it tackles the topic of whether wind energy is inherently more contentious than biomass or solar-based energy or only more frequently created at a large corporate scale. For example, in three subregions of the Upper Rhine, Schumacher et al. [188] conducted a poll on public approval of a range of technologies, resulting in a dataset of 495 German, 501 French, and 493 Swiss residents. The authors discovered that the type of technology had a significant impact on popular acceptance (e.g., opposition is greater for biomass and wind than for large solar installations, and resistance was minimal for smaller solar plants). Moreover, according to certain research, there are disparities in acceptance between long-term residents, who are generally more accepting and newcomers, who often worry that renewable energy projects may ruin their idealized view of the local environment [189]. Contrarily, second-home owners tend to have a more favourable attitude toward such initiatives than residents, according to Johansen and Emborg's research [190].

ECONOMICAL METRICS. The way to quantify the economic benefits is more concrete because the topic is inherently about costs and earnings. The first quantifiable data includes the reduction of overall energy cost. This can be obtained by computing the percentage change in energy cost. The same percentage can be used to ensure limited increases in the cost of energy below 3 %, as identified by Ref. [178].

Moreover, each European country has implemented the European directives through its own laws. In the previous sections various pieces of legislation were already highlighted, that regulate the incentives linked to energy communities. Another well-liked criterion frequently mentioned in the literature [191], is determining when positive and negative cash flows are equal is the payback period computation. This signifies the point at which the costs have been paid off and the profit has materialized. If there is a preference to shorten the payback period, this criterion provides investors with rapid insight. The payback period is calculated by dividing the investment costs with the annual savings on energy expenditure.

In addition to these advantages, there are savings on import costs, as energy communities can guarantee the country's greater energy self-sufficiency. These are not quantifiable as benefits for the community but are still an important impact of them. There are also direct benefits that can be assessed at a global level. Globally, the use of RES shows increases in the gross domestic product, job creation and human welfare benefits, as reported by the studies undertaken within IRENA [37]. For example, the IRENA study [37] estimated that in 2020 around 12 million people were employed worldwide in the renewables sector, which has increased up from 7.3 million reported in the first annual assessment in 2012. The most rapid expansion occurred in the solar photovoltaic industry, which employed close to 4 million people in 2020, putting it ahead of bioenergy, hydropower, and wind power. The data was collected from 126 countries from all over the world. Costs continue to decrease, particularly for solar and wind technologies. Lower expenses have resulted in broader deployment due to reasonably consistent annual investments. Increasing investments would encourage the creation of new jobs in the future and could even permit rising labour productivity.

ENVIRONMENTAL METRICS. The REC's environmental benefits can be evaluated by monitoring the goal of reducing greenhouse gases. This can, once again, be quantified using the IRIS Catalog of Metrics [187] and computing the greenhouse gas emissions mitigated in metric tons of CO_2 equivalent. Analogously, it is possible to quantify the local NOx emissions reduction in kg per year and the local PM10 emission reduction. The latter are both intended to be reduced by the REC impact. NOx produces toxic pollution that affects the health of individuals, also harming the environment, climate, and vegetation. This implies that there is an indirect impact on the social health of communities. PM10 emissions are caused by the burning of fuel and heavy industrial processes and are very harmful to human health. The literature shows [192] that these emissions cause lung diseases, heart attacks and arrhythmias, cancer, atherosclerosis, childhood respiratory disease, and premature death.

Another benefit that can be calculated is the primary energy saving, considering the consumers (the supplied buildings). In terms of metrics, this refers to the computation of the primary energy that is saved when a new plant is built, considering its lifecycle or the operational period of the buildings that are directly supplied with energy. It is linked to the renewable nature of the investment (for the energy sources) and to the interventions on the building envelopes, firstly to reduce its energy demand for heating/cooling, to reduce its energy consumption.

The assessment (including the energy sources) can be performed by using specialized software or by using the energy performance of buildings calculations CEN European standards (M/480 CEN/CENELEC package). Within the building's energy performance analysis, the energy balance that is performed requires inputs like the building's material types, layer thicknesses, thermal transmittances, internal surface resistances, solar and internal heat gains etc. [182,193].

4.2. A new conceptual model for renewable energy communities

Based on the literature review and the conducted multiple case study, this research aimed to identify a set of concepts that include all the steps and tools that constitute a REC.

All the features of the proposed REC conceptual model are summarized in Fig. 1. These are divided into nine boxes based on the mentioned scopes.

The features described in Fig. 1 clearly relate to each other in terms of influences but also in terms of temporal succession.

Most of the analyzed literature focuses on the prerequisites for a successful community. For example, in Ref. [38], the following steps are proposed: to start from the analysis of the regulatory framework, then to move to the identification of the involved actors. Subsequently, to go to the analysis of possible proposals for overcoming some constraints. Further, is the study of the involved technologies and the technical characteristics of the plants. Finally, it is presented the economic incentive criteria which is dependent on the applicable regulatory framework.

Similarly, Cappellaro et al. [165], present the regulatory framework and propose a phase in which analyzing the legal form that the community can assume, the involved technologies, and the involved actors. They list a set of possible environmental, economic, and social benefits as well.

In [175], the authors start from the analysis of the regulatory framework. Then are presented the legal structures of the energy communities. Further, the benefits of the communities are analyzed in terms of social and environmental implications.

Based on the results obtained within the analysis of the literature, it is possible to formulate that the establishment of a REC goes through three main macro phases:

1 the analysis of the enablers of a REC project, in terms of regulatory framework and macro or micro context in which the community is developed;
2 the design and the setup of the REC project including all technical, organizational, and legal aspects;
3 the assessment of the REC project including continuous monitoring of the concrete achievement of the REC with all the related benefits (measurable or not).

The *regulatory framework* and the study of the *contextual drivers and barriers* together form the **Analysis** step. The inspection of these two aspects provides a clear preliminary idea of the specific context of action and helps to clarify if the REC project is favourable or not. The presence of tax incentives, such as those present in the Italian case study, can guide all the design choices and especially the different types of legal structures that can be created, the organization models or the technical and technological features. Also, the preliminary analysis of the context requires the investigation and prediction of the positive factors but also the examination of the barriers and limitations of the existing background, to mitigate the potential risks that would endanger the implementation of REC at an early stage.

The second phase is then the **Design and Setup**: once it is established that the new project is possible, it is important to provide the knowledge to implement it. Based on the background analysis, it is possible to select a suitable legal structure for the community from among the existing models. In this phase, the stakeholders who can participate in the communities and which roles they can assume are clearly defined. The

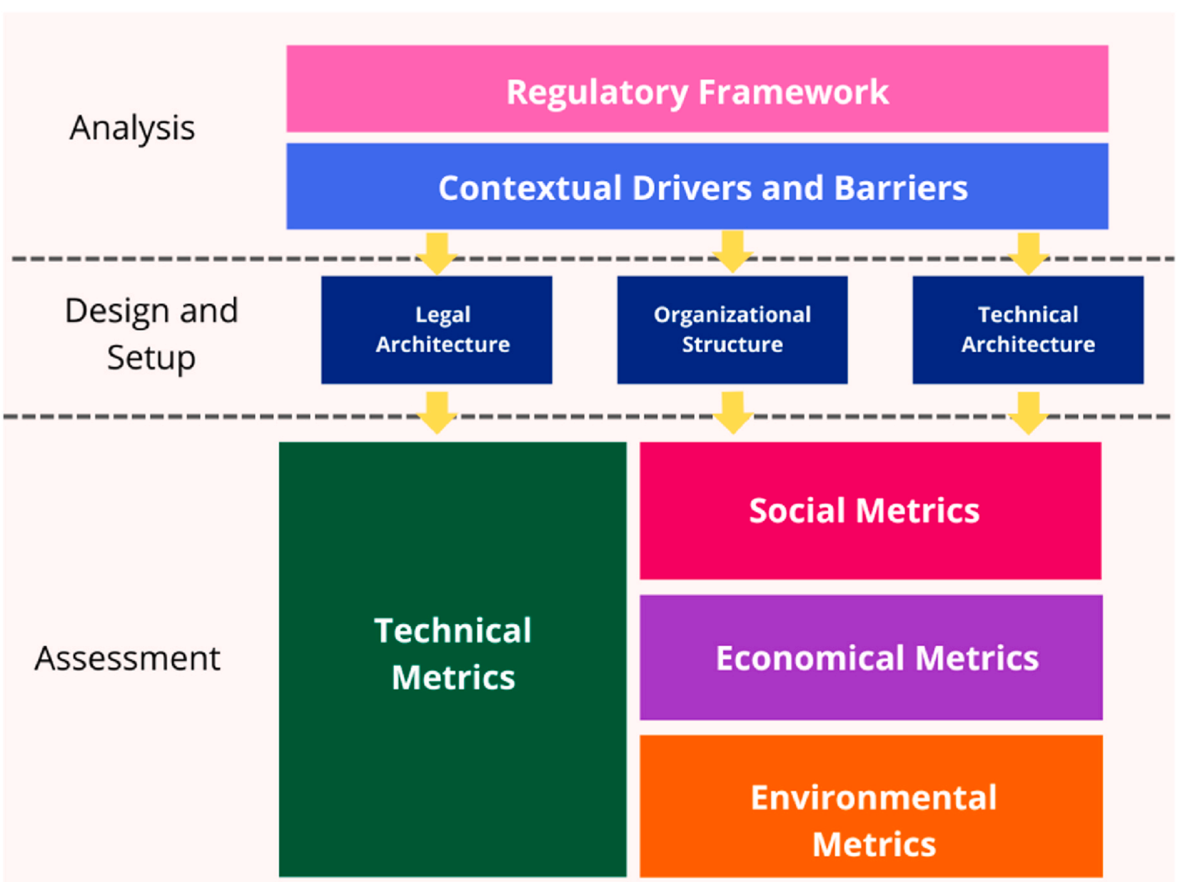

Fig. 1. REC fundamental aspects.

actors are manifold, and their involvement in the project and their roles in the creation of value must be clear. Finally, in the design phase, it is fundamental to define the technical framework in which the REC can operate, as it is important to be aware of the conditional spatio-temporal technical issues. Based on a proper design and setup, the REC can be implemented and operated.

Thus, after a REC is functioning, it is essential to be able to measure its impact at various levels to monitor its development process. The measurement can occur if correspondence is found between the initial goals and quantifiable outcomes. This is the **Assessment phase:** the phase of the monitoring and control of all the crucial aspects of the REC. This phase is characterized by the measuring and assessment of the social, economic, environmental, and technical metrics.

Constantly monitoring and controlling a project requires being able to identify the new barriers, limitations, considering its aging, as well as knowing the state of the art of similar monitored projects. This phase is essential to identify new improvements and adjustments that the community can achieve. Thus, the last phase can be a starting point to new phases of analysis and design.

4.3. Limitations

While the proposed conceptual model for RECs offers a comprehensive framework for their development and evaluation, several limitations must be acknowledged. These limitations, spanning regulatory, technical, economic, and social domains, can impact the effectiveness and scalability of RECs and should be considered carefully.

From a regulatory perspective, the inconsistency in the implementation of European directives across member states can create challenges and complicate the standardization of practices.

Technically, the maturity of some critical technologies (such as advanced energy storage systems and smart grid components), remains a significant challenge. High costs and technical complexities can pose substantial barriers, particularly for small communities with limited resources.

Economically, accessing energy markets and securing fair pricing for the energy produced can be challenging for small-scale RECs due to market regulations and the dominance of large energy providers.

Socially, ensuring that RECs are equitable and inclusive, providing benefits to all community members, and including marginalized groups, are other significant challenges.

Future research should focus on developing solutions to these challenges, ensuring the RECs successfully contribute to the energy transition.

4.4. Final remarks

The added value of the proposed framework consists precisely in the way in which it was substantiated, through the use of Grounded Theory being directly connected to the current response of society to the topic of renewable energy communities and their status quo. The resulting framework is strongly grounded in the society's current reality on this topic, being its result.

Also, the use of this research method, rather characteristic for the Human Sciences, to investigate such a complex and primarily technical subject, is innovative.

The specific advantages of our framework include its empirical foundation, context-sensitivity, and adaptability. By being rooted in a thorough analysis of diverse data sources, it provides practical insights and actionable recommendations. Its consideration of evolving regulatory contexts ensures relevance in different jurisdictions. Lastly, its adaptability to incorporate emerging technologies and business models makes it a flexible tool for stakeholders aiming to develop or enhance RECs.

Other identified limitations of our work refer to the non-exhaustive list of consulted primary data, the method used assuming an aggregation of input data to obtain a research result.

5. Conclusions and policy implications

In this paper, a conceptual model for the Renewable Energy Communities is proposed, by conducting a thorough analysis of their advantages, structures, and limitations. To substantiate the conceptual model, an analysis of the state of the art has been performed, by considering and analyzing information about the evolution of the Energy Communities, the current regulatory framework in force in Europe and, more specific, in Italy. Furthermore, a brief description of the technologies involved, and the definition of possible business models were included.

The methodology followed the Grounded Theory method, to substantiate a REC conceptual model. An extensive literature review was performed, followed by multiple case studies, which aimed to identify a set of concepts that include all the steps and tools that constitute a REC. In carrying out the literature analysis, several topics were found to be common to most of the papers regarding RECs. The identified topics were used for the definition of a set of pillars characterizing all the REC papers: the regulatory framework, the contextual drivers and barriers, the legal architecture, the organizational structure, the technical architecture, and the technical, social, economic, and environmental metrics. The identification of the pillars allowed for the substantiation of the REC framework in a process pathway.

Furthermore, the proposed conceptual model was validated through the analysis of several Italian case studies.

The energy transition is an ongoing phenomenon in Europe, and consequently, the proposed model may also undergo changes in the future. For example, any updates to European directives may require the need to change some design phases such as the choice of possible legal models or organizational structure. The technologies involved are also being studied in the scientific community and could be replaced. In any case, the proposed model is based on well-chosen and well-substantiated fundamental pillars. It was decided not to consider very detailed aspects and therefore subject to possible future changes. Small variations in technologies or European directives are expected not to change the model's fundamental structure.

Based on the analysis of the case studies, it is possible to conclude that the proposed conceptual model can be used to evaluate the success of existing REC in all their aspects and also to represent a clear pathway and the process to be followed in the development of new projects across different countries.

This framework is primarily addressed to authorities and decision-makers, starting from large entities (such as the European Commission) to the national level (government and local public authorities). These entities can use the framework to establish legislation and specific framework regarding RECs, where it does not exist (e.g., the case of Romania) or to enforce it (e.g., in the update of the European directives, for the implementation of later national laws).

In a wider context, the main objective of this work was to provide a solution both for the mass renovation of existing and new buildings, linked with the mandatory concept of nZEB, which soon will be replaced by mandatory ZEB (including for existent buildings), in order to achieve zero emissions by 2050. Existent buildings represent one of the major producers of CO_2 emissions globally. Therefore, large-scale solutions and clear pathways must be developed for this crucial energy consumer.

The framework developed within this research is intended to provide a clear pathway for the public authorities, to tackle the required and still very slowly implemented large-scale deep renovations within countries. For the buildings located in highly densely populated urban areas, where both important site limitations and limited technical options have to be considered, a REC might be one of the few feasible mass solutions (from an energy sources perspective), to achieve the zero-emission target after a process of deep renovation.

The significance of a REC framework in public policies is noteworthy, emphasizing the multifaceted context essential for the establishment of energy communities. The foundation of the proposed model hinges on the need for a supportive legislative framework to be adopted at the country level, eventually guided by a larger entity such as the European Commission for the European Union.

CRediT authorship contribution statement

Sajjad Ahmed: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Visualization. **Ancuța Maria Măgurean:** Methodology, Validation, Formal analysis, Resources, Data curation, Writing – review & editing, 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.

Data availability

Data will be made available on request.

Appendix 1

Table A1.1
Proposed REC framework implementation for several Italian case studies: analysis and design & setup phases.

REC case study	Regulatory framework	Contextual Drivers and Barriers	Legal Architecture	Organizational Structure	Technical Architecture
1. Energy and Solidarity Community of East Naples	- RED-II; - IEM directives; - Milleproroghe Decree; -Campania Region own measures.	-Social and economic depression; - Environmental pollution; - Energy poverty; - Landscape constraints; - High social involvement of the foundation Famiglia di Maria.	- Community trusts and foundations.	-The Famiglia di Maria foundation serves as mediator among all involved parties; -The Fondazione Con Il Sud entity is the main financial partner; -The environmentalist group Legambiente provides solutions for the environment; -The “3eee” Supplier is the technical partner of the project.	- Photovoltaic system made up of 166 panels; - Each PV panel has a power of 330 W; −60 cells of 158.75 cm^2 made of monocrystalline silicon PV panels; -An accumulation system can store energy and supply the network with the additional production.
2. Energy Community of Magliano Alpi “Energy City Hall	- RED-II; - IEM directives; - Milleproroghe Decree; -Piemonte Region own measures; -Manifesto of Energy Communities for an active centrality of the citizen in the new energy market.	-Citizens easily reachable through a direct relationship with the Administration; -Technicians and officials on the Administration staff open to innovation; -Support of the Polytechnic of Turin; -Pre-existing environmental sensitivity; -Problems with connection and electrical blackouts; -Limit number of MV/LV substations of 13 units.	-Public-private partnership; - Energy City Hall is in the form of an association, registered with the Agenzia delle Entrate.	-The entire management and maintenance chain of the plants is located in the territory of the Municipality; -The association Renewable Energy Community Energy City Hall has its own statute, consisting of 22 articles; - The organizational structure is constituted by: founders, ordinary and honorary members.	−20 kW photovoltaic system positioned on the roof of the Municipality’s building; -A platform for the control of withdrawals and injections has been developed and made available to community members; -Consumption is monitored by smart meters positioned at the POD; -The data are collected by the Energy4com.eu online platform and transmitted to the GSE.
3.Renewable Energy Community of Biccari	- RED-II; - IEM directives; - Milleproroghe Decree; - Regional law 45 of 2019.	-Rigorous economic investment framework by the Municipality; -Budget funds for the feasibility study and engineering analyses; -Request for funding to the Puglia Region; -Sense of community well consolidated thanks to past projects; -The territory already had solar panels on public buildings.	-To be defined.	-The Municipality of Biccari is the political protagonist of the transition path; -The cooperative “ènostra” is the supplier who developed feasibility studies and provided technical assistance for REC implementation; -Agreement between the Regional Agency for Public housing and living (ARCA Capitanata) and the Municipality for the PVs installation on two condominiums.	-Photovoltaic systems of 200 kW; -Two plants are being designed on pitched roofs of two public residential condominiums owned by Arca Capitanata; -Two 10 kW systems on the roof of the municipal library and the “Sala Bollenti Spiriti” (not connected yet); −35 kW system installed on the roof of the nursery school.
4.Renewable Energy Community of Brindisi	- RED-II; IEM directives; -Milleproroghe Decree; -Regional law 45 of 2019; -POR PUGLIA, PNRR; -Cipe Resolution no. 127.	- Energy poverty; - Pollution; - Bureaucratic slowdowns.	N/A	N/A	N/A

Table A1.2
Proposed REC framework implementation for several Italian case studies: assessment phase.

REC case study	Technical metrics	Social metrics	Economical Metrics	Environmental metrics
1. Energy and Solidarity Community of East Naples	Not identified.	-Strong positive bonds and trust between the families and the foundation; -New active people in the foundation; -Strong feeling of community extended beyond financial and environmental objectives; -Families involvement in the decision process is limited.	-The proceeds will be distributed among the participating families; -An income of 300–400 euros per year is estimated for each family.	-The electricity produced by the REC's PV facility has an overall average reduction in impacts of 76 % when compared to the mix of Italian electricity; -Reductions in ionizing radiation (IRP) and terrestrial ecotoxicity (TETP); -Reductions in freshwater (FETP) and marine ecotoxicity (METP).
2.Energy Community of Magliano Alpi "Energy City Hall"	-The total installed power is close to 29 kW.	-The municipality supports a short supply chain of technicians, designers, installers, and maintenance personnel; -The REC supports the development and employment in the post-pandemic phase, through required skills for implementation.	-The PV system produces around 24198 kWh per year, which is enough to meet 46 % of overall demand or 85 % of daytime usage; -REC members reduce energy expenditures by 21 %.	-Reduction of emissions of approximately 10.75 tCO_2 (assuming an emission factor of 444,4 gCO_2/kWh).
3.Renewable Energy Community of Biccari	N/A	N/A	N/A	N/A
4.Renewable Energy Community of Brindisi	N/A	N/A	N/A	N/A

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