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RENEWABLE ENERGY COMMUNITIES: STATE OF THE ART AND EXPERIENCES

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Abstract

Renewable Energy Communities (RECs) are entities that work together to enable the production, management and consumption of renewable energy at the local level. These communities support the transition to a more decentralized, democratic and sustainable energy system. In this article, RECs are examined in the context of international and national laws, with particular attention to the European Union's RED II Directive and the “Milleproroghe” Decree in Italy. It examines how renewable technologies and advanced infrastructure, such as storage systems and smart grids, are essential for the operation of RECs. The article highlights the environmental, economic, and social benefits offered by RECs through the analysis of significant experiences in Germany, Denmark, the United Kingdom, and Italy. These benefits include a reduction in greenhouse gas emissions, combating energy poverty, and promoting local resilience. However, RECs face technical, regulatory and economic challenges, such as integration into networks and project financing. Despite these obstacles, thanks to the evolution of energy policies and the development of new technologies, the future prospects are promising. Therefore, RECs have become an essential part of the inclusive energy transition and climate goals. Finally, a resume of an innovative research activity, which regarded the multidisciplinary assessment and improving proposal of Renewable Energy Communities, and that was carried out by the Euro Mediterranean Institute of Science and Technology in 2022-2023, is reported.

Keywords

Renewable energy communities, Collective self-consumption, Energy transition, Renewable energy sources, Distributed energy, Citizen participation, Energy

cooperatives, Energy poverty, RED II Directive

Introduction

Renewable Energy Communities (RECs) are an innovative pillar in the global energy transition landscape, because they offer a decentralized and participatory solution to address the challenges posed by climate change and the need for a sustainable energy system. RECs are groups of people who work together to produce, consume and share renewable energy locally with the aim of maximising economic, social and environmental benefits. Their structure focuses on energy self-sufficiency and sustainability, as well as democratic governance in which members actively participate in strategic decisions [1].

According to the RED II Directive (2018/2001/EU), renewable energy communities are legal entities that rely on open and voluntary participation, are controlled by local members, and focus primarily on delivering environmental, social, and economic benefits in lieu of financial profits. The idea combines technological and social dimensions through the use of renewable sources such as solar, wind, and biomass energy, and focuses on the active participation of the community. The collective function of RECs distinguishes them from other models of decentralized energy production: renewable energy production improves the quality of life of communities and reduces energy inequalities. Energy production is not the only goal of REC implementation; the implementation also includes activities related to energy efficiency, intelligent consumption management and the creation of synergies with other sectors, such as agriculture and transport. Resources are essential to promote a resilient and sustainable development model because they are widely usable [2] [3].

Fossil fuel consumption is a significant component of the current global energy system, which is a significant contributor to rising greenhouse gas emissions and global warming. The 2021 IPCC report states that the combustion of oil, natural gas and coal makes up about 73% of global CO2 emissions, which means that the decarbonization of the energy sector must be a primary goal to achieve the goals of the Electricity Accord. The transition to a sustainable energy system is now a necessity due to the growing global energy needs, which are expected to increase by 50% by 2050. Transformation of this type requires action in three main areas: increasing the share of renewable energy in the energy mix, improving energy efficiency, and making energy more accessible to all. RECs address these issues by providing a decentralized model that reduces transmission losses, promotes local energy resilience, and invites citizens to actively participate. In particular,

they ensure fair and sustainable access to energy even for disadvantaged communities through their method of cooperation, which promotes energy justice. Because they combine technological innovation, environmental sustainability and social inclusion, RECs play a key role in the energy transition. In the Clean Energy Package, the European Union has recognized the importance of RECs and defined them as an essential component to achieve the goal of reducing greenhouse gas emissions by 55% by 2030 [4][5][6].

Key benefits of RECs include:

- **Decarbonization:** RECs directly reduce greenhouse gas emissions through energy production from renewable sources, which means that our dependence on fossil fuels decreases;
- **Energy efficiency:** Overall energy efficiency can be improved through collective self-consumption and the use of smart technologies such as energy management systems and smart meters;
- **Economic benefits:** Tax and tariff incentives and energy savings make RECs cost-effective for members; they also help create new jobs in the renewable energy industry [7];
- **Social inclusion:** RECs reduce energy poverty by providing access to green and affordable energy, particularly in rural or economically disadvantaged areas [3].

Many experiences in Europe have shown that RECs are effective. Energy cooperatives, which comprise millions of citizens in Germany, have played a significant role in achieving a high share of renewable energy in the country's energy mix. Similarly, Denmark has built a model of wind cooperation that has led it to become a world leader in wind energy. The 2020 “Milleproroghe” Decree encouraged the launch of the first RECs in Italy. Among these is the Magliano Alpi pilot project, which has shown how the shared production of renewable energy can bring both economic and environmental benefits to local communities [8].

RECs combine technological, regulatory and social elements in a model that maximises local benefits to offer an integrated solution to the challenges of the energy transition. However, achieving them requires a clear regulatory framework, investment in innovative technologies and active community involvement. The regulatory framework, the technologies used, the experiences at international level and in Italy, as well as the challenges and opportunities for the development of RECs will be examined in detail below. The analysis will provide an overview of the current state of the art of this innovative and sustainable energy model.

Methods

A mixed strategy was used to conduct the analysis on the state of the art and experiences of renewable energy communities. This strategy combined a systematic review of the literature with a comparative study of national and international experiences. The literature review included scientific articles, institutional reports, and case studies published in the last ten years selected using academic databases such as Scopus, Web of Science, and Google Scholar. Studies addressing the regulatory, economic and social aspects of RECs have been included, with particular attention to those that analyse real cases of implementation in Europe and Italy.

Subsequently, the most important public policies and directives were examined, with particular attention to European (RED II Directive) and Italian ("Milleproroghe" Decree and PNIEC) laws. Finally, a multiple case study methodology was used to compare ERC experiences. Specific projects were selected based on criteria of operational success, sustainability and community involvement.

The methodology used made it possible to identify common dynamics and challenges specific to RECs. It was also possible to evaluate the possibility of replicating the observed patterns in a variety of socioeconomic contexts. In addition, to find the most promising technological solutions to overcome infrastructure and operational barriers, feasibility studies and technical data related to the integration of RECs into electricity grids were examined.

Historical evolution of RECs and state of the art

Renewable Energy Communities (RECs) are an innovative model of energy production, distribution and consumption in which citizens, companies, and public administrations work together to share locally produced renewable energy. RECs offer a concrete alternative to traditional centralized energy production systems, based on the principles of sustainability, participation, and decentralization. The aim of this approach is to transform consumers into active players in the energy transition, overcoming the technical, regulatory, and social difficulties that often prevent the large-scale adoption of renewable energy. RECs are legal entities that work together with a group of people (citizens, businesses and local authorities) to produce, store, consume and sell renewable energy in a way that maximises social, environmental, and economic benefits for the local community. The ability of RECs to promote self-consumption and energy autonomy while simultaneously reducing greenhouse gas (GHG) emissions and promoting social and economic inclusion is what makes them unique. RECs, according to the literature, stand out from other distributed energy production models because they focus on social goals and

community involvement. This distinguishes them from traditional energy cooperatives, which often focus on economic viability [3][2][6].

Although renewable energy communities are among the most innovative models for addressing the energy transition right now, their development has been the result of a complicated historical path that has involved technological advances, changes in laws and social changes. This chapter analyses the main stages that marked the emergence of RECs, with a focus on their development in Europe, where they found fertile ground thanks to progressive policies and the support of the population. The emergence of energy cooperatives in the Nordic countries and Germany in the late 1800s led to the first forms of collective organization for energy production. These cooperatives had the goal of supplying electricity to rural areas where there were no large electricity companies. Small hydroelectric plants and community organization made it possible to overcome infrastructural barriers, creating a model in which citizens were both producers and consumers of energy. For example, wind energy cooperatives were born in the 1970s in Denmark as a direct response to the oil crisis. The current model of RECs derives from these cooperatives, which were based on principles such as collective ownership and democratic participation. Throughout the 1990s, interest in environmental sustainability and global efforts to reduce GHG emissions increased. This has led to the development of renewable energy. The ratification of the Kyoto Protocol (1997) prompted many European nations to promote decentralized energy production, supporting local cooperative projects. During this time, Germany adopted the Renewable Energy Law, which provided tariffs to incentivize small producers. There has been a favourable environment for new community projects based on technologies such as photovoltaic (PV) and wind. In parallel, the European Union (EU) began to develop a common energy policy, culminating in the publication of the Green Paper on Energy Security, which emphasized the importance of diversification of energy sources and citizen participation. As the 21st century began, more action was needed to combat climate change, which led to an increase in policies supporting renewable energy. RECs have been officially recognized as an innovative model for promoting decarbonization. Directive 2009/28/EC (RED I), which set binding targets for the EU's share of renewable energy, marked the turning point. The basis for the inclusion of participatory models such as RECs was laid by this Directive. Directive 2018/2001/EU (RED II), which formally defined the concept of Renewable Energy Community and encouraged its integration into national energy markets, represented the culmination

of the evolution of legislation. RED II eliminated numerous regulatory and technical barriers to enable citizens to produce, consume, store and share energy [6][9][7][10][11].

International regulatory framework: RED II, RED III and Clean Energy Package Directive

Renewable Energy Communities are an emerging and key model for accelerating the transition to a decentralised and sustainable energy system. The growing focus on decarbonisation and energy independence in recent years has prompted governments to promote laws and policies for RECs. Advances in infrastructure such as smart grids and storage systems are also making RECs more accessible and efficient.

The RED II Directive (Directive 2018/2001/EU), which is part of the EU Clean Energy Package, has had a significant impact on the regulatory framework governing RECs internationally. This Directive, which includes specific provisions for RECs, lays the foundations for the promotion and integration of renewable energy into national energy systems. According to RED II, RECs are legal entities controlled by local members with the primary goal of providing social, economic, and environmental benefits instead of financial gains. RED II, which entered into force in December 2018, requires Member States to achieve a renewable energy rate of at least 32% of the overall energy mix by 2030. The Directive includes a number of measures to achieve this objective, including explicit support for RECs [2].

The focus of RED II is on three main elements:

- **Self-consumption:** The directive ensures that citizens and communities have the right to produce, store and share renewable energy without incurring disproportionate burdens;
- **Access to the network:** Member States are required to ensure non-discriminatory access of RECs to distribution networks, overcoming the bureaucratic and technical constraints that often prevent small producers from participating;
- **Economic support:** States are invited to promote the creation of RECs through the adoption of economic support schemes such as incentive tariffs and tax deductions.

The Clean Energy Package, approved by the European Union in 2019, incorporates the RED II standards into a broader strategy to change the European energy market. The promotion of renewable energy communities (RECs) and city energy communities (CECs) is among the most significant innovations introduced. These two communities have similar goals, but they differ based on the type of resources used and how they integrate into energy markets.

- **Renewable Energy Communities (RECs):** communities that focus on energy from renewable sources with social and environmental goals;
- **Citizen Energy Communities (CECs):** communities that can also include non-renewable sources and are mainly dedicated to improving energy efficiency and grid resilience.

The Clean Energy Package highlights the right of citizens to produce, consume and share renewable energy, recognising the fundamental role of RECs in the democratisation of energy. EU member states are required to incorporate RECs into their legislative systems, ensuring clear and favourable regulation. In particular, RED II introduces the concept of "collective self-consumption", which reduces dependence on centralized utilities by allowing REC members to share the energy produced within the same area. Ensuring non-discriminatory access to distribution networks is another important aspect, facilitating the integration of RECs into national energy systems. This measure represents a significant step towards energy equity and widespread participation, especially in rural or economically disadvantaged areas [3][6].

The RED III Directive, which was formally approved in 2023, marks a significant change in the EU renewable energy legislation. The directive updates RED II to meet the more ambitious goals of the European Green Deal and the REPowerEU plan, with the aim of reducing GHG emissions by 55% by 2030 and strengthening the EU's energy independence. According to RED III, by 2030, renewables are expected to account for at least 42.5% of the EU's total energy consumption, with an optional target of 45%. There is a significant increase from the 32% target set by RED II. In addition, the Directive sets specific targets for important sectors such as transport, heating and cooling, and industry, promoting a more widespread use of advanced biofuels and green hydrogen. An innovative aspect of RED III is the simplification and acceleration of administrative procedures for new renewable energy plants. Competent authorities must comply with maximum approval times: for renewable energy plants located in selected areas, it takes 12 months, while plants outside those areas take 24 months. This was set up to reduce bureaucracy and promote the rapid growth of renewable infrastructure. RECs play a central role in RED III. The Directive recognises them as essential tools for involving local communities and decentralising energy production. By promoting distributed energy generation, in particular through PV, wind, and biomass plants on a local scale, RECs can help achieve energy transition goals. This method contributes to the EU's climate objectives and strengthens the energy independence of communities [12] [13].

These new laws are helping RECs grow in countries like Germany and Denmark, where people have already participated in the energy market through energy cooperatives and state incentives.

Italian regulatory framework: "Milleproroghe" Decree and PNIEC

Italy has implemented the EU indications on the promotion of RECs through the "Milleproroghe" Decree (DL no. 162/2019), which introduced the concept of energy community into the Italian regulatory framework for the first time. To allow RECs to operate within a clear and defined legal framework, this decree marked a significant turning point. The "Milleproroghe" includes economic incentives for shared energy, tax exemptions and bureaucratic simplifications for the creation of RECs. The incentive tariff imposed by the Italian Energy Services Manager (GSE, Gestore dei Servizi Energetici) for each kilowatt hour of energy shared in a community is a practical example that makes participation in RECs economically sustainable for both citizens and companies [14].

The "Milleproroghe" allows energy communities to produce, consume, and share renewable energy locally by forming cooperatives, associations, or other legal entities. The most important measures include:

- the possibility of sharing the energy produced by renewable plants up to 200 kW;
- economic incentives through an all-inclusive tariff of about € 110 / MWh for shared energy:
- tax exemptions for REC members.

RECs are considered a fundamental tool for achieving the 2030 climate goals, according to the Integrated National Energy and Climate Plan (PNIEC). These targets include a 33% reduction in GHG emissions compared to 1990 levels and a 30% increase in the share of renewable energy in the national energy mix [15].

The PNIEC is a strategic plan to achieve Italy's 2030 climate goals and RECs are considered essential tools for:

- Increasing the amount of energy from renewable sources, in fact the PNIEC predicts that by 2030 renewable energy sources will cover 30% of the nation's energy consumption;
- To combat energy poverty, as RECs provide low-cost energy to households in economic difficulty using energy-sharing models;
- Promoting energy efficiency, in fact, RECs help save money, reducing waste and optimizing resources.

The pilot project of Magliano Alpi, the first recognized energy community in Italy, is a concrete example of the success of these measures, because it has shown how a REC model can generate significant savings and significantly reduce local emissions.

Technologies and infrastructures for RECs

The operational heart of RECs is made up of technologies and infrastructures, which allow them to maximize the production and use of renewable energy. RECs are based on innovative technologies that enable the production, storage and intelligent management of energy. The most important of these are:

- **Decentralized renewable sources.** One of the fundamental principles of RECs is the decentralization of energy production. At the moment, PV panels, due to their versatility and low expense, are the most popular technology. However, alternative sources such as small-scale wind and biomass are becoming more popular, especially in rural areas.

  IRENA says PV is one of the most competitive technologies for RECs as costs have fallen by 90% in the last 10 years. The installation of solar systems on public and residential buildings increases the overall efficiency of the system by exploiting unused surfaces. Due to the increased efficiency of solar technologies and reduced installation expenses, the installation of PV systems on the roofs of houses, schools and commercial institutions has become particularly popular [16].

- **Energy storage systems.** Batteries and other storage technologies are essential to ensure the stability and reliability of RECs because they allow excess energy produced to be stored for use during periods of increased demand. While lithium batteries are the most widely used storage technologies, other options, such as hydrogen systems and flow batteries, are becoming more promising for improving the storage capacity of RECs. This type of system makes it possible to: minimize dependence on grid variations and ensure energy self-sufficiency even during consumption peaks. These systems are therefore particularly important for intermittent renewables, such as wind and solar [16];
- **Smart Grid.** Smart grids are crucial for the operation of RECs because they allow energy production and consumption to be managed dynamically. Smart grids can monitor energy production and consumption in real time, optimize self-consumption, and reduce grid losses thanks to technologies such as smart meters and energy management systems. Technologies such as smart meters, supervised control and data collection (SCADA) systems, and blockchain-based management platforms ensure transparency, security, and optimal use of resources [17];
- **Digital platforms for the management of RECs.** Digital tools are key to the management of RECs. Through artificial

intelligence (AI) and blockchain algorithms, these platforms make it possible to track the energy produced and shared, manage payments and optimize energy flows in a transparent and secure way. For example, the Powerpeers platform in the Netherlands facilitates peer-to-peer exchange of energy within RECs using blockchain, creating a transparent energy market at the local level [3].

Challenges and opportunities of RECs

RECs are becoming increasingly integrated with other sectors, such as agriculture and transport. Electric vehicle (EV) charging infrastructure allows vehicles to be powered with locally produced renewable energy. In addition, in agriculture, RECs can use by-products from agricultural activities to power biogas plants, creating a circular model of energy production.

Even though there is a favorable regulatory framework and significant technological developments, the implementation of RECs still faces a number of obstacles. These include bureaucratic complexity, the need for large upfront funding, and low public awareness. RECs, however, offer huge opportunities in terms of environmental benefits and social inclusion. RECs can completely change the energy system by making it more reliable, equitable and sustainable. Their ability to address existing barriers using an integrated approach that combines forward-looking policies, technological innovation and community participation will be essential to their success.

Experiences and Case Studies in Renewable Energy Communities

Renewable Energy Communities have found ground in many countries around the world thanks to innovative economic models, favourable regulatory frameworks and the active participation of local communities. We will analyze below some experiences at international level and in Italy. We look at notable cases such as energy cooperatives in Germany, wind cooperation in Denmark, and initiatives against energy poverty in the UK, as well as pilot and regional projects in Italy.

Germany and energy cooperatives

Energy cooperatives are an important part of the renewables' movement in Germany. Local cooperatives investing in solar, wind, and biomass energy have increased in the country since the enactment of the Renewable Energy Act (EEG) in 2000. A report by Bauwens et al. (2016) indicates that as of 2020, there were over 900 energy cooperatives with more than 200,000 citizens in operation. Individuals have the opportunity to invest in renewable energy projects that generate a stable economic return through German cooperatives. Schönau is an excellent example, where a community bought the local electricity grid to operate it according to a community and clean energy

objective. This growth has been accelerated by government policies and financial aid through incentives. Cooperatives are now a successful example for the energy transition. However, the increase in tariff incentives in recent years has slowed down the creation of new projects [7][18].

Denmark and wind cooperation

In response to the oil crisis, Denmark began wind cooperation projects in the 1970s. These days, communities own about 40% of Denmark's wind turbines. The example of Middelgrunden, a cooperative near Copenhagen, is an iconic model, according to Bolinger (2001): half of the 22 MW turbines are owned by a city cooperative and the other half by a local utility. National policies such as grants and regulations requiring community participation in projects have facilitated these initiatives. In addition, the Danish model has shown that shared ownership strengthens social consensus towards energy infrastructure and accelerates the energy transition [19] [20][21].

The UK and the Energy Poverty Initiative

The UK has used the REC model to combat energy scarcity. Families in need receive support from initiatives such as those supported by Energy4All or Bristol Energy Cooperative that use revenues from renewable installations. For example, the Repowering London project has built solar systems on residential buildings in London. It has allocated profits to improving the energy efficiency of homes and technical training for young people. These examples underline the potential for RECs to integrate social and environmental objectives, improving the resilience of local communities [22][23].

Case studies of RECs in Italy

The first renewable energy community recognized in Italy was located in Magliano Alpi, in the province of Cuneo. Local administration, citizens and businesses worked together to launch this pilot project in 2020. The system produces energy through PV systems, which reduces energy costs and carbon emissions. Thanks to the incentives granted by the “Milleproroghe” Decree of 2020 and the regulation established by the Regulatory Authority for Energy, Networks and the Environment (ARERA), the initiative has received strong regulatory support. The project highlighted the benefits of RECs for small rural communities and demonstrated that this model could be used in other places. Puglia has a high potential for solar and wind energy, making it an important hub for RECs. In particular, numerous municipalities participate in the "CER Salento" project to build an energy system based on shared PV systems. Their goal is to redistribute economic benefits and reduce dependence on fossil fuels. Other Italian areas, such as Trentino-Alto Adige and Lombardy, have also launched REC initiatives. The energy community of Brunico uses local

hydroelectric sources to power public and private buildings and promote sustainability at the local level [14].

From the international experiences examined, some key points for the success of renewable energy communities have emerged. First of all, a stable regulatory framework and dedicated financial incentives are essential. Germany, with its EEG, and Denmark, through participatory planning, offer clear examples of how national policies can stimulate local participation and reduce barriers to entry. Active community participation is another crucial factor. Cooperatives in Germany and wind projects in Denmark have shown that direct citizen involvement not only accelerates the adoption of renewables, but also increases the acceptance of infrastructure on the ground. Finally, training and technological support are key. Initiatives such as Repowering London highlight how projects can integrate the implementation of new technologies with vocational training and the improvement of local skills.

Experiences in Italy such as Magliano Alpi and the Apulian RECs provide important insights into understanding the opportunities and challenges of implementation. Italian legislation is changing due to the “Milleproroghe” Decree and the Integrated National Energy and Climate Plan (PNIEC). This is laying the groundwork for an expansion of RECs. However, the fragmentation of administration and the need for greater coordination between local and national authorities remain some problems. Italy has a huge potential for renewable energy, in particular PV and wind energy, and RECs could contribute to energy poverty reduction and social inclusion by promoting energy self-sufficiency in both rural and urban areas.

Advantages and challenges of RECs

RECs contribute significantly to the climate goals of Europe and the world at large, constituting an essential tool for decarbonisation. Clean energy can gradually replace fossil fuels with clean energy through the adoption of solar, wind, and biomass plants. This reduces GHG emissions both locally and globally. IRENA's report states that, through distributed generation of energy from renewable sources, RECs could help reduce global GHG emissions by 10% by 2050. This method reduces transmission losses, which, according to the IEA, make up about 5-8% of the total energy produced in centralized systems. RECs help fight energy poverty, which affects millions of households in Europe. Repowering London and other projects have shown that sharing the economic benefits of energy production can help people pay less for utilities. In addition, profits can be reinvested in improving the energy efficiency of buildings or financing social programs. The Magliano Alpi pilot project, in fact, in Italy has significantly

reduced the energy costs of families and small local businesses. This model can also be replicated in other economically fragile areas. The ability of RECs to strengthen social networks is a great advantage of them. Often, energy communities are managed collectively, which fosters inclusion and allows local members to have a voice in strategic decisions. A sense of belonging and responsibility for environmental sustainability is created through this bottom-up approach. Examples such as those of German energy cooperatives show that active participation in renewable energies increases consensus and stimulates the local economy by creating jobs and developing technical skills [22][25] [23][7][26].

The integration of distributed generation into existing energy grids is one of the main technical challenges for RECs. Conventional grids, which are designed to provide power in one direction only, need to be modified to handle energy flows in both directions, so that they can balance supply and demand in real time. According to the GSE, to ensure grid stability and operational efficiency, the adoption of technologies such as smart grids and storage systems is crucial. In addition, innovative energy management solutions, such as digital monitoring platforms and advanced forecasting algorithms, are needed due to the intermittency of renewable sources such as wind and solar. RECs often have difficulties in obtaining the necessary funds to start projects, especially in the early stages. Although projects such as Horizon Europe and Next Generation EU offer funding opportunities, complicated procedures and the scarcity of specific skills in local communities are two major issues. Public awareness is another issue: many communities are unaware of the benefits of RECs or how they work. A study by IRENA states that awareness and training campaigns have the potential to increase adherence and engagement, which could accelerate the spread of these models around the world [27].

Future perspectives of RECs

Policies to support renewable energy communities (RECs) are constantly evolving to meet global sustainability and energy transition goals. The milestones in the development of RECs were the European RED II Directive and the Clean Energy Package. However, with RED III, the European Commission aims to strengthen the role of citizens and local communities in energy management. The need to simplify access to finance and reduce administrative barriers will have an impact on the future of REC policies. IRENA says that integrated policies at European level could enable the expansion of RECs through incentives for storage, distributed generation and smart use of energy. Germany and Denmark, as widely seen above, have already launched pilot

programs to increase the involvement of energy cooperatives.

Technological innovation is essential to increase the efficiency and sustainability of RECs. Smart grids, advanced storage systems, and AI-powered digital platforms for real-time monitoring are among the most promising emerging technologies. According to the Politecnico di Milano, the implementation of Internet of Things (IoT) technologies has the potential to optimize energy distribution and consumption, minimizing losses and maximizing self-consumption. Energy storage technologies, such as the latest generation of lithium-ion batteries and redox flow technologies, are another important sector that allows for the integration of intermittent renewables and greater grid stability. In addition, advances in green hydrogen offer new prospects for the long-term storage and decarbonisation of the most energy-intensive industrial sectors. RECs are already becoming models of energy self-sufficiency thanks to smart buildings and blockchain-backed microgrids for transparent management of energy transactions. These technologies can be used in conjunction with energy efficiency programs to make sure that energy is used to the fullest, increasing the economic and environmental sustainability of communities [28][27][25].

RECs have the potential to significantly increase local energy resilience. This is an important aspect in a context where extreme weather events are becoming more frequent and there are disruptions in the energy supply. The decentralized approach allows communities to reduce their reliance on centralized suppliers and reduces blackout effects. In particular, hybrid microgrids powered by PV, wind, and storage systems can operate in "island" mode during emergencies, providing the energy needed for vital services such as hospitals and educational institutions. Finally, the ability of communities to face future challenges can be improved by the interaction between RECs and climate adaptation strategies, such as the promotion of green infrastructure and sustainable drainage systems [22].

IEMEST thematic group “Comunità Energetiche” research activity

Considering the relevance of the topic, in the period 2022-2023 the Euro Mediterranean Institute of Science and Technology set up a multidisciplinary thematic group on RECs called “Comunità Energetiche”.

Thematic group methodology

The thematic group consisted of periodic meetings between researchers and consultants from different scientific areas (energy, engineering and architecture, science computing, law, social sciences and psychology). Its goal was to assess the status of art and future perspectives of Renewable Energy Communities through a

multidisciplinary approach (regulative, social, and technical) towards identifying open issues and so, new research lines. Each meeting was organized with presentations by each member, based on its own skills, experience, competence and individual research, and then, group discussion to find synergies, drawbacks and challenges trajectories.

Thematic group findings

The carried-out research activity highlighted that the constitution of a REC is a quite hard task comprising multisectoral complexities, mainly from the economic and organisational perspective. Moreover, it represents the first step toward the transition to smart city, hence it requires even more complexity and foresight in the design phase.

From a technical perspective, the hard matching between the renewable energy production side, which is generally characterized by an aleatory and intermittent nature, and the variable demand side load profiles, including the bidirectional flows from prosumers, needs a comprehensive collection and interoperability of accurate energy data from the community and the adoption of expensive and large technologies for assuring the energy balance. Digitalization of the energy sector and built environment to acquire real data is, therefore, an unavoidable pillar of the energy transition but it needs a harmonized framework. However, data availability in EU is still strongly affected by fragmentariness, low level of detail, and obsolescence; also, their speed improvement is hampered by bureaucracy and public administration work overload issues.

Despite this, REC really offer the opportunity to test innovative and advanced technologies to maximise the renewable energy production and self-consumption with low impact and efficient solutions. After a deep analysis of more innovative existing technological solutions, the thematic group focused on some solutions which are at the same time proven, sustainable, and at out of the box compared to the current status of urban works i.e., bifacial PV panels, which allow to catch also the solar energy reflected by the panels support, micro-wind turbines, which could be suitable for windy urban dense areas, and coatings for improving PV panels performances and durability.

From the organizational perspective, the involvement of several actors (investors, energy companies, citizens, public administration, etc.) requires a robust and clear governance model. It was assessed that REC models generally refer to one of 3 main governance models. The “public administration driven” model foresees a strong public participation, has a strong social mission, and the revenues are generally shared by members or reinvested in the community itself. In the “service provider driven” model, the funds and revenues are

shared by the energy player company and the members and it is more business-oriented. The “users driven” model is funded by SMEs and citizens with the goal of reducing energy bills and revenues are shared by them. So far, although RECs are entities mainly devoted to a private community, the organizational and business models are far to be largely adoptable without a strong public participation while. Indeed, only 154 RECs were set up in Italy against 400 estimated; more interest was in the self-consumption model as more profitable.

Thematic group outcomes

Based on the thematic group findings, some outcomes were delivered, two of which are here discussed.

First outcome regards the development of an early-stage analysis model of a building block (i.e., that including the IEMEST building) to test the possibility of accurately simulating the complex economic and technical working of a REC (Figure 1). A preliminary assessment of the building features, users’ composition and energy consumption of the intended building block was carried out. To that end data from the Municipality of Palermo [30], the National Statistics Institution [31], the Database of Building Energy Certificates from ENEA [32], CRESME [33], and metered data [34] were used.

Subsequently, the building block energy use was simulated with the ENEA simulation tool “Renewable Energy Community ecONomic simulator - Tool for the economic evaluation of Renewable Energy Communities” (RECON) [35]. RECON is a web application created by ENEA and aimed at supporting preliminary energy, economic and financial assessments for the creation of renewable energy communities or self-consumers of renewable energy that act collectively. In the used release, RECON analyses only residential users up to 100 homes, and provides as outputs the energy yield of the PV system, self-consumption and energy sharing, energy self-sufficiency, reduction of CO2 emissions, revenues and costs, discounted cash flows and the main financial indicators (net present value, payback time).

As a second output of the thematic group and its findings, a research project proposal was written and submitted to the call Fondo Italiano per le Scienze Applicate (FISA) 2023. The proposal goal, named ECSEDRA (Renewable Energy Communities through Sharing Accurate Energy Data), was aimed to define and set-up a model to support the emergence and the long-term management of the renewable energy communities through development of three tools affecting three dimensions (governance, digitalization, and technologies).

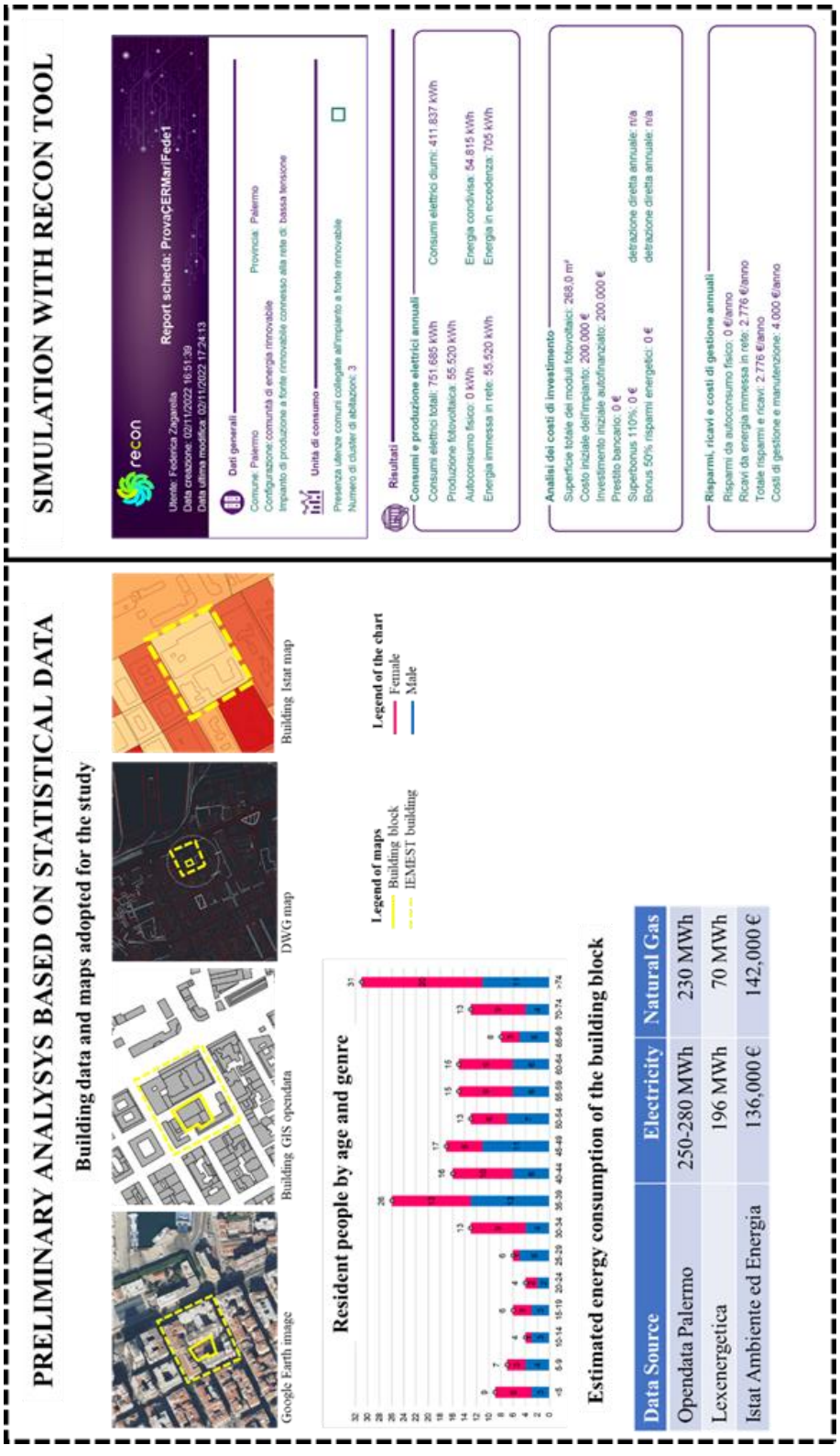

Figure 1. Scheme of the developed early stage model.

Conclusions

Renewable Energy Communities represent an innovative and essential paradigm for addressing the energy transition and climate problems. The analysis conducted in this study has clarified the importance of RECs as tools for distributed generation and energy autonomy, as well as a catalyst for social, economic and environmental benefits. RECs demonstrate an incredible ability to adapt to local contexts. Danish wind cooperation models and energy cooperatives in Germany are examples of international experiences that underline how important community participation is for the success of these initiatives. RECs support a decentralised and democratic energy management model that reduces inequalities and promotes social inclusion. These characteristics are also highlighted by the actions taken in the UK to combat energy poverty. The potential of RECs to improve energy efficiency and increase the resilience of local communities is demonstrated both in the pilot project in Magliano Alpi in Italy and in other regions of the south, such as Puglia. To ensure long-term sustainability, these projects have shown that the integration of advanced technologies such as smart grids and storage systems is critical. RECs are key to a future energy system based on sustainability, equity and resilience. They are in line with the goals of the United Nations 2030 Agenda, in particular goals 7 (Affordable and Clean Energy) and 13 (Climate Action), supporting the transition to renewable sources and reducing GHG emissions. RECs offer significant economic benefits. Reducing energy costs through self-consumption and sharing the energy produced is a powerful tool to combat energy poverty, a problem that still afflicts millions of households in Europe and around the world. In addition, the installation and maintenance of renewable plants create local jobs that improve the economy of the communities involved. From a social point of view, RECs foster the active participation of citizens in energy governance and increase the sense of belonging in the community. This factor is particularly important in rural and peripheral areas, where RECs can help revitalize both the economy and society. However, a number of problems need to be solved to make the most of the potential of RECs. Integration into existing energy grids is critical, as is overcoming regulatory barriers and financing projects in resource-constrained areas. Simplifying bureaucratic procedures and promoting awareness-raising programmes are two important ways to increase the uptake of RECs [7][20] [23][14][28][27][29][12][16].

The adoption of coherent and forward-looking policies will be key to the success of RECs in the future. The RED III Directive, which is currently in place, aims to increase the role of energy communities in the EU, promoting greater energy autonomy and accelerating the transition to a system entirely based on

renewables. In addition, continuous technological progress creates new opportunities. RECs will be increasingly efficient and resilient in energy ecosystems thanks to technologies such as AI, blockchain and advanced storage systems. To create replicable models on a global scale, it will be crucial that the interaction between technological innovation and community participation takes place in this context. While RECs are a viable and scalable solution to address climate change challenges, they require joint engagement from governments, industry, and citizens. Their success will be an important step towards a more sustainable, inclusive and resilient future for the entire planet, not just for the energy sector.

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