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Renewable Energy Communities in Italy: A National Framework for Sustainable Cities

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Received: 05-20-2025 **Revised:** 07-22-2025 **Accepted:** 07-31-2025

Citation: Mutani, G., Tundo, A., & Capezzuto, P. (2025). Renewable energy communities in Italy: A national framework for sustainable cities. *Chall. Sustain.*, *13*(3), 398–411. https://doi.org/10.56578/cis130306.

Abstract: In light of the European Union's 2050 decarbonization objectives, a fundamental transformation of urban energy systems is required—characterized by decentralization, decarbonization, and digitalization. Within this context, the Renewable Energy Community (REC) model has been identified as a pivotal mechanism for enabling the integration and equitable sharing of locally generated renewable energy, while simultaneously delivering environmental, social, and economic co-benefits. A systemic and place-based approach has therefore been proposed, in which the interactions among buildings, neighborhoods, and communities are holistically considered in the design and governance of urban energy systems. The operationalization of RECs has been shown to rely heavily on the deployment of digital technologies, including Information and Communication Technology (ICT) platforms, smart metering infrastructure, automated control of energy flows, and demand response mechanisms. These technologies serve not only to optimize energy efficiency and flexibility but also to enhance user engagement and energy awareness. A national standard recently published in Italy has formalized this integrated methodology, supporting the coordinated development of smart and low-carbon cities. Concurrently, innovative tools are being developed to facilitate decision-making and strategic planning for RECs at multiple spatial scales. Among them, the Italian geo-portal for RECs and the Public Energy Living Lab (PELL) have been introduced to support the acquisition, organization, and interpretation of territorial and urban energy data. These tools have also enabled the definition and monitoring of context-specific Key Performance Indicators (KPIs), critical for assessing the performance and scalability of REC initiatives. The framework presented herein contributes to the broader objectives of Smart Cities by enabling data-driven, participatory, and resilient energy transitions in urban contexts. Particular emphasis has been placed on harmonizing spatial data infrastructures with energy governance processes, thereby laying the groundwork for replicable and adaptable REC models across diverse territorial configurations.

Keywords: Renewable Energy Community (REC); Standards; Sustainable development; Territorial scale; Holistic methodological approaches; Tools; Platform; Place-based energy modelling

1. Introduction

Urban areas are increasingly being confronted with multifaceted challenges spanning economic, environmental, technological, and social domains. These include the intensification of climate change at both global and local scales, rising energy consumption driven by urbanization and warming trends, a surge in the frequency and severity of extreme weather events, and heightened vulnerability of buildings and urban infrastructures. As a result, risks related to structural damage, energy insecurity, and the associated socio-economic costs have been exacerbated. Simultaneously, there exists an urgent need to safeguard and enhance the quality of life and well-being of urban populations. In response to these converging pressures, cities have been positioned as critical nodes of innovation and intervention within the European Commission's strategic framework. The transition toward smart, sustainable, and resilient cities has been acknowledged as a paradigm through which long-term urban challenges may be addressed in a coherent and systemic manner. Within this paradigm, energy systems have been identified as a foundational element for sustainable urban transformation.

The European Green Deal has explicitly recognized the energy sector as a strategic driver of sustainable development, with the decarbonization of energy systems deemed essential to meet the climate targets established for 2030 and 2050. To achieve these targets, a radical shift is required towards decentralized, digitalized, and electrified urban energy infrastructures. Central to this transition is the adoption of citizen-centered energy models, including Citizen Energy Communities (CECs) and RECs, which facilitate local energy sharing and collaborative energy management practices. RECs, as defined by Directive (EU) 2018/2001, represent non-profit legal entities that enable citizens, local authorities, and small businesses to jointly produce, store, distribute, and consume energy from renewable sources. Unlike broader CECs, which may incorporate fossil fuel-based systems, RECs are explicitly focused on renewable energy integration to foster clean, decentralized, and self-sufficient energy ecosystems. These communities not only support environmental goals but also enable economic empowerment, social inclusion, and energy democracy.

It has been increasingly recognized that technological innovation alone is insufficient to drive the low-carbon transition. Behavioral change among individuals, public institutions, and businesses is equally indispensable. The shift to a net-zero greenhouse gas (GHG) economy involves a profound transformation of everyday practices, labor models, mobility behaviors, and social infrastructures (European Commission, 2018). In this context, ICTs and digital platforms play a crucial enabling role, enhancing energy efficiency, fostering user engagement, and ensuring transparency in the design, operation, and monitoring of RECs.

RECs are thus integrally linked to the broader smart city agenda, serving as a practical manifestation of decentralized and participatory energy governance. A comprehensive analysis of relevant European legislative frameworks, scientific literature on energy-efficient buildings, and emerging technical standards has facilitated the conceptualization of an integrated REC model. This model is operationalized through both top-down planning tools—such as territorial energy atlases—and bottom-up, digital, and user-oriented platforms for real-time energy management. These complementary approaches are essential for embedding RECs within local contexts while ensuring interoperability, scalability, and replicability across diverse urban environments.

2. Smart Sustainable City Approach

The concept of Smart City, which is now referred to more often as a smart, resilient, sustainable city in both ISO standards and the United for Smart Sustainable Cities (U4SSC) initiative, is a paradigm that can be used, at a global level, to address city challenges in a new, more efficient, and sustainable way. The European Innovation Partnership on Smart Cities and Communities is the first initiative to have implemented the participation of citizens and stakeholders in smart city governance at a European level, and this was followed by the European Smart City Lighthouse Program, H2020 Smart Cities and Communities SCC1, in 2014-2020, and the recent 100 Climate Neutral and Smart Cities. The Path to Smart and Sustainable Cities initiative is based on a comprehensive and integrative approach to linking EU policies and resources at national, regional and local levels in order to accelerate the large-scale deployment of smart solutions to address the key societal challenges related to the Union's energy and climate objectives (European Commission, 2010; European Commission, 2012a).

Smart Cities and Communities EIP (SCC) is a partnership in the fields of energy, transport and communications, with reference to urban domains, where the production, distribution and use of energy, and of ICT, are intimately linked. Moreover, they offer new interdisciplinary opportunities to improve services while reducing energy and resource consumption, the production of GHG and other polluting emissions.

These initiatives refer to the integration of smart buildings and neighborhoods, the management of local and RES, ICT solutions for design, the development of green infrastructures to reduce space heating, cooling needs and air pollution, positive energy buildings (PEBs), neighborhoods and districts, intelligent supply and demand systems and services for more informed citizens, the management of the energy demand, the transfer of data and information on energy consumption/production to citizens and end-users, transport and mobility services, smart meters and real-time energy management, all of which are the key aspects of new urban energy systems (European Commission, 2012b).

The recent "Climate-neutral and smart cities—100 Climate-neutral cities by 2030—by and for the citizens" initiative is closely linked to these issues, and it is aimed at achieving the goal of 100 climate-neutral cities by 2030.

A new model of urban governance should encourage public administration to evolve, at all levels, from a traditional work culture and organization to independent vertical segments and to a transversal, integrated, citizen-led and facilitator-based way of working. This type of model should involve moving toward the adoption of an integrated urban planning that approaches a city holistically, promotes multi-benefit solutions and breaks down traditional silos into urban projects.

The new approach to governance should also include, by definition, a community-centered approach that will take into consideration the Green Deal's warning of 'to leave no one behind' (just transition).

The IEA 2024 initiative "Empowering Urban Energy Transitions - Smart cities and smart grids" highlights that community-focused initiatives can offer multiple benefits. Community-centered approaches, such as community procurement, people-led renovation, community microgrids, energy communities, virtual community power plants and positive energy districts are increasingly being adopted to accelerate the EU's transition goals for 2030 and 2050.

2.1 EU Policies for an Integrated, Clean and Smart Energy System

The European Union has outlined a strategy, as part of the Clean Energy Package, to become climate neutral by 2050, which means that certain measures are required for the complete decarbonization of energy systems. The objective of achieving the status of the world's inaugural climate-neutral continent, along with the declaration that the 2020s will be designated as the digital decade, constitutes two of the European Commission's key strategic priorities for the forthcoming years. The term ‘toward carbon neutrality’ refers to the EU’s commitment to make a profound and systematic change to our urban, industrial, infrastructural and energy realities in order to reach a state of net-zero carbon dioxide emissions within a short period of time (Pulselli et al., 2021).

The EU strategy is outlined in a wide range of policies: e.g., the Climate Law & the Climate Pact, the EU plan for a circular economy, the European long-term strategy for 2050, the National Energy and Climate Plans, the Urban Agenda for the EU, the European Digital Strategy, Smart Specialization Strategies and platform, and the Smart and Sustainable Mobility Strategy. The Green Deal is the main set of policies that is used to promote the twin transition, that is, the green and digital transition, in urban systems, and it lists energy systems as one of its priority areas. Moreover, the aforementioned European policies also all favor a comprehensive framework for city sustainability.

Decarbonizing the energy system is key to achieving the 2030 and 2050 climate goals. Indeed, a new European energy market and new urban and smart energy systems that are fully integrated, interconnected, decarbonized and digitized, would allow an effective energy transition through the participation of citizens in the market as prosumers and active consumers. The European Union's regulatory framework governing energy communities encompasses both RECs and CECs. The Renewable Energy Directive (RED) II (EU) 2018/2001 promoted the creation in Europe of RECs and the Internal Market for Electricity Directive IMED (EU) 2019/944 the CECs. Then, the new RED (EU) 2023/2413 broadens the scope for energy communities by enabling their participation in offshore wind projects and district heating and cooling networks. Additionally, the new directives on Energy Efficiency (EU) 2023/1791 and Energy Performance of Buildings (EU) 2024/1275 (European Commission, 2024) further support energy communities. The former is for the involvement of energy communities in renewable-based heating systems, while the latter is to improve the national building renovation plans.

A smart energy system is described as a functional energy system that ensures energy transition and decarbonization. Such a system involves the use of renewable and decentralized sources of energy, an intelligent electricity grid, digital and ICT technologies at both the building and district levels, and an interconnection between buildings and the electricity distribution network (home-to-network-to-city) (European Commission, 2022). A smart energy system involves a combination of the currently isolated energy sectors, such as electricity, space heating and transport, and it includes three smart energy grid infrastructures, namely electrical, thermal and gas grids.

The diffusion of new digital technologies in buildings and in grids (smart grids), the flexibility of generators and on the demand side, ancillary services, demand response mechanisms, RES and energy communities are the drivers of a new smart energy system.

In such a system, buildings, vehicles, and other infrastructures are designed to generate, share, and store their own energy, and energy flows are optimized through intelligent systems that respond to real-time data.

Thus, RECs, which are designed according to the smart sustainable city pillars of a community-centered approach that uses smart technologies and interactions between buildings, represent a key element of smart energy systems.

3. RECs in Smart Energy Systems in Urban Contexts

In 2018, the publication of the RED II introduced RECs, just before the 2019 Internal Market for Electricity Directive defined CECs. Both directives promote the sharing of energy by identifying the central and active role of the consumers in the electricity market and support the deployment of RES-based plants through collective energy initiatives.

The possibility of self-producing and sharing energy, and the concept of RECs and citizens' energy communities, help to concretize these new urban energy systems in sustainable smart cities.

Prosumers become essential drivers of an inclusive energy system that is ready to cope with the growing shares of variable renewable energy resources in the most cost-efficient way.

Not all citizens can install photovoltaic systems on their roofs. However, RECs offer all citizens the opportunity of participating in new urban electricity systems as smart consumers, i.e., consumers who use energy intelligently and efficiently in the RECs to contribute to the reduction of energy consumption.

Thus, RECs enable all citizens to participate and contribute to the construction of a new urban energy system and to build up the trust of individuals and communities, improve public acceptance, and support affordability and equity in the clean energy transition.

The citizens who participate in the restructuring of an urban energy system through the REC concept realize the same concept as smart people, which is at the basis of the smart and sustainable city model.

City neighborhoods and districts need a holistic view to create smart and economically sustainable energy systems that have repercussions, in terms of social and environmental benefits. Spatial planning and energy planning are becoming closer and closer.

The theme of urban regeneration starts from a neighborhood scale, which allows a more significant reduction in energy input to be achieved than an individual building scale, thanks to the potential exchange of energy between buildings and the gains that can be derived from the distribution of shared local storage. It is therefore necessary to consider the interactions of RECs with modern district heating and cooling systems, combined heat and power (CHP), thermal storage, heat pumps and decentralized energy, private investments, public planning and management, and self-sufficient energy or positive energy districts (Clerici Maestosi et al., 2024).

The zero-emission buildings (ZEBs) outlined in the Energy Performance Directive and smart grids will be components of energy systems in the near future (European Commission, 2024).

PEBs constitute a relatively new energy concept that is somewhat more ambitious than nearly zero-energy buildings, NZEBs and ZEBs (Ala-Juusela et al., 2021).

By 2050, ZEBs, PEBs, smart grids and energy communities will be the drivers of the future electricity systems at the local level.

Smart microgrids could be integrated into a global smart grid at a district level to increase benefits for communities, to better balance the local energy supply and demand, and to integrate even more renewables (ATELIER EU project). The smart grid concept is based on the active involvement of users and the adoption of ICT technologies and innovative applications, advanced metering infrastructures (AMIs), large-area monitoring, power data analysis, and predictive maintenance and control.

Future urban electricity systems, consisting of RECs, existing buildings and new PEBs or ZEBs, can be defined. The large-scale integration of ZEBs, or PEBs, into smart grids could play an important role in the future of smart grids and increase the integration potential.

In short, RECs should be realistic technological models, especially in Mediterranean areas, for the sharing of energy by citizens. Moreover, they should be more easily achievable than district energy models and positive energy systems (PEDs), which are currently more widespread in northern and central Europe.

3.1 A Better Design of Smart RECs

Integrated energy planning and mapping, supported by a designated coordination unit or a public-private partnership in spatial planning, allows emissions to be reduced, renewables to be integrated and peak loads to be reduced as a result of including energy flexibility in buildings.

The analysis of energy phenomena at the urban-territorial level (atlas) makes use of analysis and aggregation tools to maximize the benefits that can be obtained by communities in order to obtain a better REC design. Urban energy management, which involves such topics as demand prevision studies, RES spatial potential, etc., together with the promotion of RECs, is generally delegated to local administrations and municipalities.

Digital tools, such as those provided by ENEA, and which are described later on in the paper, are already available to achieve a better REC design. Such tools can be used to visualize, assess and optimize individual and community energy use and flows, to visualize the (real or potential) performance of a home and/or a community on a local energy market, and to assess the economic and environmental benefits of joining or creating a social energy community.

The best technical design should consider that RECs share energy flows between buildings and the grid, in a virtual model of exchange, as defined by the Italian regulations, and data flows of energy meters from buildings to the grid (DSO and GSE body) to take part in incentive-regulated schemes.

However, it should be noted that some key technical design criteria need to be satisfied to make full use of the public incentives provided for RECs.

The energy-use profiles of residential buildings are integrated with those dedicated to the commercial and tertiary sectors to create constant and regular energy demand. In this way, peaks in demand, which generally do not coincide with peaks in production from renewable sources, are eliminated. This classification of needs makes it possible to find more effective forms of energy supply in which, over time, the availability of energy coincides with its production. The optimal combination of different types of prosumers and consumers in RECs, whether residential, tertiary, industrial or Small and Medium-sized Enterprises (SME), could be assessed from the economic standpoint as the complementarity of loads that are relevant for the optimal exploitation of dispatchable and non-dispatchable RESs. The heterogeneity of the user types that characterize an Italian case study has been recognized as having the potential to significantly enhance the flexibility and self-sufficiency of RECs.

Another design criterion that should be considered concerns the best choice for REC members in the area of the primary-energy cabin.

The primary energy-cabin area that has been defined by Italian legislation for RECs leads to a widening of the constitutional framework in order to optimize economic incentives and, at the same time, to extend the horizon for urban energy systems to include land energy systems, as for mobility domain.

A good REC design uses all the available regulatory and market solutions to create a smart energy system.

When prosumers have the possibility of monetizing their energy and flexibility resources, through an active participation in the energy market, they are encouraged not only to invest in clean energy resources and optimize their use on-site, but also to activate these resources for the benefit of the energy system as a whole.

Energy flexibility can assist in reducing GHG emissions, as it addresses the effective implementation of renewable energy generation, reduces peak loads, balances energy use in the grid and helps to reduce prices for the end users. Integrating solar energy and energy storage can also be introduced to obtain better flexibility.

The possibility of RECs "providing environmental, economic or social benefits, at the community level, to its shareholders or members", can help to make a person decide whether to participate in the ancillary services market. RECs should be designed to simultaneously make use of their distributed energy resources (DER) and demand responses to offer flexible services to the overall energy system, for example, by participating in grid operator (DSO or TSO) markets.

These services can help improve the business model of the energy community, because the stakeholders achieve flexibility, and they are the ones that value it the most. This flexibility can be achieved by the communities themselves, if they have the necessary expertise, or through partnering with a third-party, commercial aggregator.

Therefore, the constitution of RECs should overcome bureaucratic mechanisms and laws by treating energy consumption and its uses in the same way, and it should involve all the available opportunities (energy efficiency, flexibility, selling between peers, and ancillary services).

3.2. Smart Management of RECs

A collective energy management of energy can allow consumers to collectively connect and scale up their potential interactions with the electricity system.

Such schemes could, for example, allow a community to: (i) better monitor how the community is performing, in terms of energy consumption, or to (ii) share solar panels or otherwise engage in energy sharing or peer-to-peer trading of electricity produced from joint investment projects that can make them less dependent on the high electricity prices of the wholesale market.

The use of the available digital technologies in energy communities can make it easier to manage the various inverters and storage facilities located in the energy community in order to maximize the community's self-consumption and to optimize the sharing and management of production and storage in real time to maximize self-consumption.

Platform services can help REC members to visualize how electricity is being produced and consumed within a community, and some services also show how the renewable mix can be optimized at the household or community level, and how local trading could impact their economic and environmental objectives. In this way, community members can participate in the energy community and feel more engaged. Such an interface could provide community members with information regarding the performance of their individual energy assets, as well as those of the collective community.

The increased visibility of the consumption and production of energy for users, and the exploitation of high-end applications for the effective management of energy in return for financial incentives as well as environmental and social benefits, can help create “trust” and contribute to the diffusion of RECs.

Open-source and modular platforms can be used to optimize the use of local resources and enable individuals to have equitable access to energy trading, on par with large energy suppliers.

A platform can simulate a scenario with RECs, be implemented peer-to-peer, and also initiate energy trading in the community by creating active local energy markets. Platforms allow knowledge of the phenomena in the effective management of RECs to be made available, thereby providing trust and transparency for the members.

4. Italian Standardization for Smart Urban Energy System and REC Approach

The Italian Standard UNI 11973:2025 “Sustainable cities, communities and infrastructures – The contribution of buildings to sustainability – Methodological model for the integration and interconnection of sustainable buildings in cities”, which is just being published, highlights a holistic approach to the design of buildings in urban energy systems and energy communities. The approach, represented in Figure 1, considers integration and mutual interactions between buildings, neighborhoods and energy communities in a smart and resilient city (Tundo et al., 2024).

The standard focuses on smart energy systems and RECs and on the sharing of data between buildings and between buildings and the grid, in an interoperable way. Such data are collected from energy meters and a community management platform to measure and distribute the economic incentives of the state, and to obtain optimal management of energy loads and supplies to the community.

The standard recommends a design of smart RECs that includes ICT platforms, smart meters, demand response schemes, automatic controls of production and consumption, and, in general, a broad accountability to increase energy consumption awareness. The use of digital technologies in such communities makes energy communities smarter, more efficient and more profitable, and it leads to greater accountability for all the members. The interactions of a REC with a city are then analyzed, in an attempt to improve benefits, achieve social and community inclusion, and combat energy poverty.

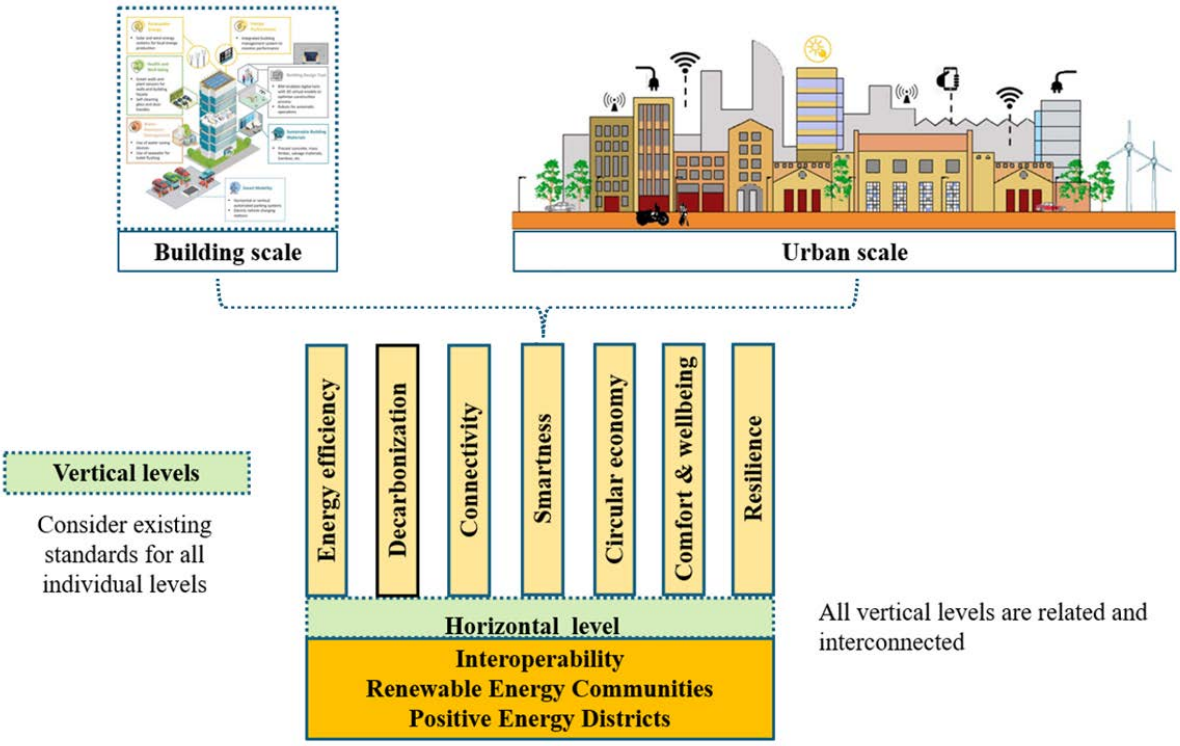


Figure 1. Methodological scheme of the Italian Standard UNI 11973:2025 on "sustainable cities, communities and infrastructures"

5. Geo-Portal for RECs

The Politecnico di Torino, together with ENEA, are developing a geo-portal, as part of joint research, to support decisions concerning the identification of the most suitable Italian areas in which to develop RECs. RECs can stimulate an energy transition at a spatial level by involving the governance of the territory and private and public actors; the aim of an REC is to develop a more sustainable energy system in which users can self-produce energy, by boosting the available renewables, and exchange energy to achieve greater self-sufficiency of the territory.

The first results of an open geo-portal, which is able to identify current and future energy consumptions and productions are presented in this paper. This geo-portal will optimize the use of renewable energy sources by exploiting the specific characteristics of each territory in Italy. The geo-portal comprises two elements: a front end, with a customized interface that different users can use to operate with the geo-portal, and a back end, with geo-databases, models and processes that allow the tool to be used.

This geo-portal is derived from a place-based approach, and it is fundamental for the analyses of territories to maintain all the geo-referenced information and to represent the spatial distribution of the data, as it is able to aggregate the information at different scales. The goal is to produce clean energy where there is an energy demand. This geo-portal could also be used to solve energy challenges in the 83 critical large cities, in which 55.9 % of the Italian population lives (Istat, 2023), and which have a very high energy use intensity (EUI) and low availability of renewable resources. The resources in the areas surrounding these large cities could be exploited to produce clean energy for the cities to offer the necessary services, and, in this way, a good level of energy and social sustainability could be achieved.

The methodology used in the back end of the geo-portal is summarized in Figure 2. One of the most important phases of any work is data collection, which is followed by the pre-processing phase and the creation of new data, the correction of the datasets and geo-referencing. After these phases, it is possible to create a geo-database, which is made up of a variety of geo-datasets on different layers, with data from the whole Italian peninsula. This geo-database format is very flexible because it allows all the data, on different layers, to be updated easily. Such a geo-database can be used to model the energy systems of the territories, from the actual consumption and production to the availability of renewable sources and, eventually, to potential future production scenarios considering all the different constraints: technical, economic, environmental and regulatory constraints (Mutani et al., 2024).

Different scenarios can be developed with this kind of geo-portal, depending on the objectives of the activities. Therefore, starting from the current business scenario as the usual (BAU) one, different future scenarios, based on the achievement of one or more energy, economic, environmental and social objectives, can be proposed, for example, reaching energy self-sufficiency and economic convenience, reducing GHG emissions, reducing energy poverty, and increasing the citizens' engagement through energy communities with different forms of spatial aggregation of the territories (from primary cabins to an area with the same governance, e.g., Mountain communities or Unions of mountain municipalities), provinces or regions.

In Figure 2, it is possible to observe a contemporary spatial-temporal analysis, across both time on the left, and space on the right. The aim was to obtain the instantaneous supply of energy in each area through the use of renewable sources. In Italy, the sharing of energy among members of a community in the same High-Medium voltage cabin area is economically incentivized to encourage a higher energy self-production and self-sufficiency throughout the territory using the available local renewable sources. This can only be achieved, albeit to a limited extent, in large cities, because the high energy demand of an REC within High-Medium voltage cabin areas cannot be satisfied. The share of energy between different RECs can then be investigated considering the renewable energy territories (RETs).

The front end of the geo-portal consists of a customized interface, which is based on the different types of users of the geo-portal and their different objectives, and also has various levels of depth (citizens, companies, public administrations, policy makers).

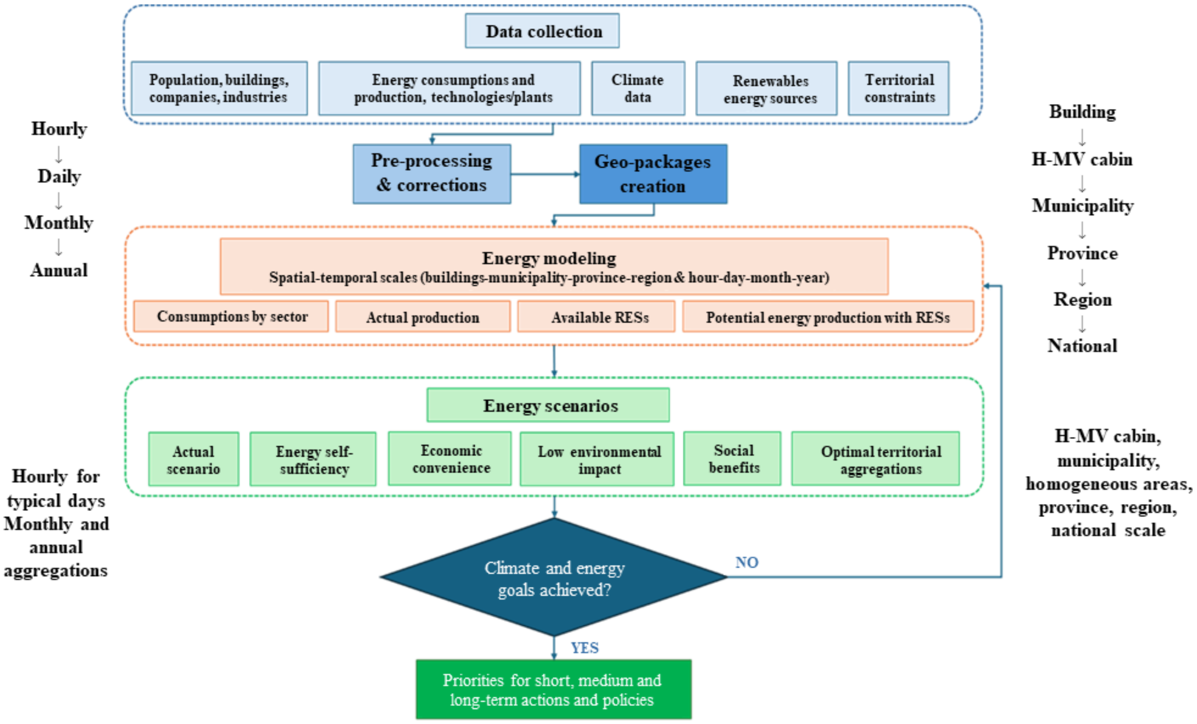


Figure 2. Methodological scheme of the geo-portal for RECs

5.1 The Italian Territory

Italy is a peninsula that develops along latitudes 36 to 47 °N and it is subject to important territorial and socio-economic differences. Table 1 describes some of the characteristics of the Italian territory. Almost half of the territory is in a plain area (45.3% below 300 m a.s.l.), a third is occupied by mountains (29.8% above 600 m a.s.l.), and about 4 % of the urban and built-up areas. Moreover, only 0.04 % of the territory consists of urban green areas, while 1% is made up of rivers, lakes, estuaries and lagoons.

Table 2 describes the characteristics of the Italian population, which consists of around 59 million inhabitants. Given the low birth rate and high mortality rate, the number of inhabitants is almost constant, in part because of the compensating migratory flow of foreigners. The median age is 46 years, and the old-age index (the ratio between the over-65 population and that of below 15) is 187.6%, relatively high, with a consequent alarming structural dependence index of 57.5% (the ratio between non-active people and active-working people in Europe should be 33%).

Significant disparities have also been observed between Northern and Southern Italy. For instance, in 2022, approximately 40% of individuals at risk of poverty or social exclusion resided in the Southern regions, while around 10% were located in the Northern mountainous areas (Mutani et al., 2024).

Table 1. Spatial characteristics pertaining to the Italian territory in km^2 and %

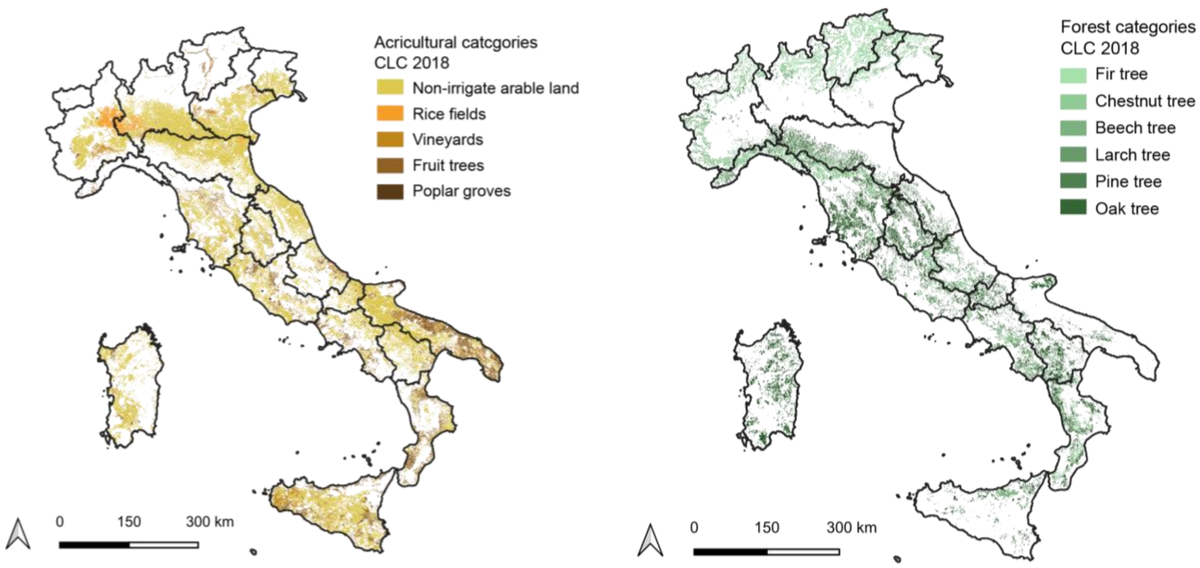
Landforms Zones	**km^2**	**%**	**Land Use**	**km^2**	**%**
Mountain areas (≤ 600 m a.s.l.)	89,778	29.8	Urban fabric, roads, rails, ports, airports	12,656	3.94
Hilly areas (>300, <600 m a.s.l.)	75,041	24.9	Green urban areas	115	0.04
Plain areas (≥ 300 m a.s.l.)	136,542	45.3	Water courses and bodies, coastal lagoons, estuaries	4,015.4	1.0

Table 2. Some characteristics pertaining to the Italian population (Istat, 2023)

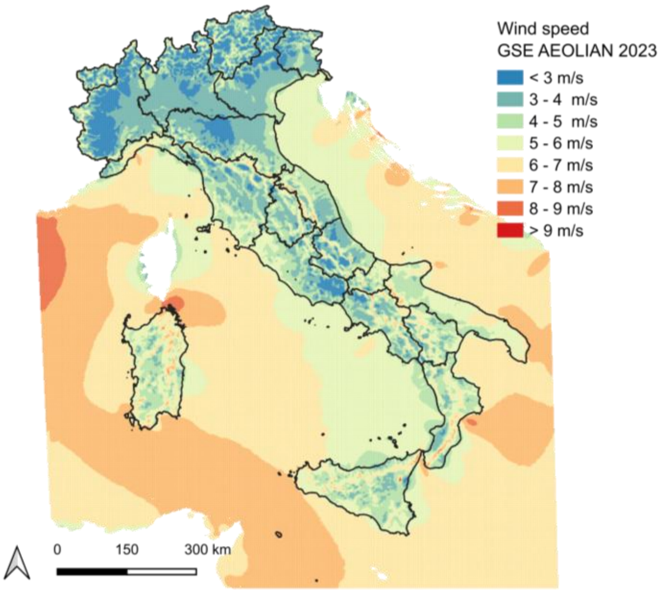
Demographic Indicators	**Number**	**%**	**Demographic Indicators**	**Number**	**%**
Population	58,989,700		Migration rate from abroad	259,588	4.4/10
Birth	395,281	6.7/10	Average age	45.9	
			Old-age index		187.6
Mortality	713,866	12.1/10	Structural dependence index		57.5

5.2 Availability and Constraints of Renewable Resources

The Italian territory is very diversified and, consequently, the available renewable sources are also diversified. In general, there are more hydroelectric sources in the North, more wind and solar sources in the South, more forest biomass in the mountains, and more agricultural biomass in the plains. Waste-to-energy and solar (roof-integrated) sources are the most important renewable sources in the cities. Figure 3 describes this complementarity of resources that characterizes the different territories. Each territory needs to exploit its available resources. It is possible to clearly observe the Po Valley in Figure 3, which has a great availability of resources from agricultural waste; for example, it is possible to observe rice fields around Vercelli and Novara (indicated in orange). Alternatively, there is a great availability of forest biomass in hilly and mountainous areas. In the coastal areas of Puglia, Calabria and the islands, wind is certainly an important resource of energy; furthermore, wind, unlike the sun, is stronger in winter than in summer.



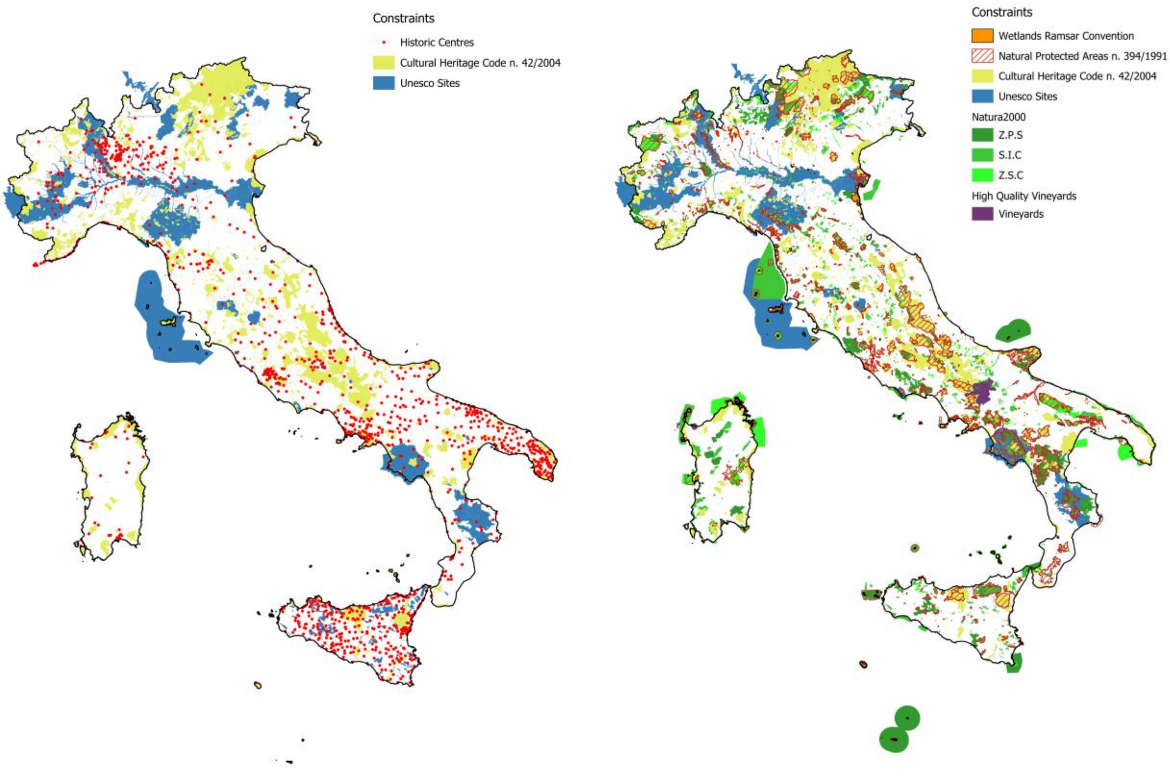
(a) (b)



(c)

Figure 3. RES distribution throughout the Italian territory:
(a) Agricultural biomass; (b) Forest biomass; (c) Wind speed at 50 m

Figure 4 shows some constraints concerning the use of RES in the various territories. Some of these constraints are of a technical nature, such as the presence of well-exposed roofs for solar panels, of an environmental nature, for example, dust-carbon pollution as a consequence of the use of biomass in cities that have low air-quality indexes, of an economical nature, for example, high payback times in areas where RES production is not convenient, and of a regulatory nature, for example, historical or landscape constraints that limit the installation of RES technologies or plants in protected territories.



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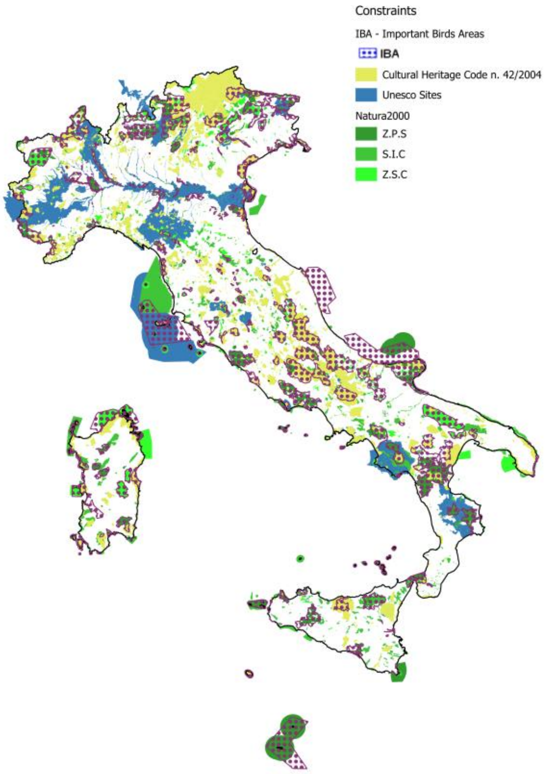

(c)

Figure 4. Territorial constrains pertaining to the use of RES throughout the Italian territory: (a) Solar; (b) Biomass; (c) Wind

5.3 The Suitability of a Territory for Renewable Communities

The suitability of territories for the creation of RECs should be assessed considering various aspects. For example, Italy's dependence on both foreign countries and on fossil fuels could be solved (at least partially) by self-producing energy and achieving energy self-sufficiency through the setting up of local energy communities (EUROSTAT, 2023; Todeschi et al., 2020), or by considering the economic convenience of such communities, compared to the price of withdrawing energy and the sale of energy injected into the grid.

The environmental impact is another important aspect that should be considered: GHG emissions and landscape conservation, for example. The share of renewables that should be reached is one of the pillars of an energy transition.

Finally, the spatial aggregation of RECs in RETs could be a solution for critical urban areas with a low availability of resources and high energy use. A first attempt has been made in the Pinerolo area (Brunetta et al., 2021) and in other areas in the Piedmont Region (Guelpa et al., 2017; Mutani & Todeschi, 2018; Mutani & Todeschi, 2021), in North-West Italy.

6. Bottom-Up Tools to Support the Establishment of RECs

The Tools and Services used by the Critical Infrastructure and Renewable Energy Community Division (TERIN-ICER-CROSS) of the Department of Technologies and Renewable Sources of ENEA are introduced in this section to support the design, implementation and management of RECs in Italy (Tundo, 2023). The common factor that characterizes all these applications is their ability to manage a considerable amount of data, while resorting to interoperability schemes (Gozo et al., 2024).

The following technologies in the applications all meet the REC requirements:

- Analyzing strategic data;
- Developing standards and enabling pathways;
- Providing technical and technological support to the institutions;
- Promoting the exchange of experiences and good practices.

The aim of the Division is to provide digital tools that can be used to initiate, promote and evaluate RECs, while leaving the managerial aspects to the market participants. The aim is also to facilitate a transition to Smart Energy

Communities, on the basis of the active participation of citizens and the development of shared local economies.

A list of Digital Tools developed by ENEA and used to Support CERs is presented hereafter:

- CER Simulator: RECON Technical-Economic Feasibility Analysis;
- DHOMUS & SIM Platform: support for home energy management;
- CRUISE and SIMUL dashboards: monitoring and optimization of energy performances;
- RES Atlas: support for the generation of renewable energy;
- Local Token Economy: the remuneration of energy virtuosity through tokens.

Digital technologies have been applied in some pilot REC configuration cases. Among these, mention can be made of the most significant cases:

- Magliano Alpi (CN), that is, the first REC established in Italy;
- Termoli (IS), which won first place in the national competition promoted by the Ministry of Education and Merit and AsviS (Italian Alliance for Sustainable Development) "Let's make 17 Goals: the School and the UN 2030 Agenda for sustainable development";
- Territorial RECs, which cover several municipalities: Garda Bresciano and Biellese;
- Lignano Sabbiadoro (UD), an area that is of particular importance because of the type of consumer, that is, of a receptive nature;
- Anguillara Sabazia (RM), an example of Solidarity REC;
- Roma Capitale, which is considered significant because of the launch of 15 CERs with public drivers and schools.

For example, Magliano Alpi is a small agricultural municipality in the province of Cuneo, Piedmont, that has become a pilot case for RECs. Following the COVID-19 pandemic, the Energy Center of Politecnico di Torino proposed REC as a new business and financial model to reach a more energy self-sufficient community through the collaboration of public bodies, citizens, and private companies. Following the first REC, "Energy City Hall," in 2020, two new RECs, "Energy Sporting Center" and "Industrial Facility," are being planned.

6.1 Renewable Energy Community ecONomic Simulator RECON

RECON2 (https://recon.smartenergycommunity.enea.it/) (Caldera et al., 2024) is a web application developed according to the MASE Decree, which came into force on January 24, 2024. This decree facilitates the creation of RECs, in alignment with Legislative Decree 199 of November 8, 2022, by implementing the REDII Directive. The project is supported by the Ministry of Environment and Energy Security under the Electricity System Research PTR 2022-2024 – Project 1.7 "Technologies for the efficient penetration of electric carriers in end uses".

It is used to support various user profiles, including consumers, prosumers (producer-consumers), and producers. It includes profiles for residential, condominium, and tertiary buildings (offices, commercial), for schools, for the industrial/artisanal sectors, and for the generic profiles. It can be used to assess multi-section photovoltaic systems (up to 2 sections) for roof or ground installations. Moreover, it provides such options as operating lease, leasing, purchasing with equity and debt, capital grants (PNRR and others), tax deductions, and purchase through an electricity supplier.

The following outputs can be obtained: incentives for self-consumption, contributions for self-consumed energy, plant efficiency, energy self-sufficiency, CO_2 emission reductions, savings and revenues, costs and financial indicators (VAN, TIR, WACC, payback time).

RECON2 facilitates the creation of RECs and GACs, as it promotes informed decision-making and active citizen involvement in energy transition.

6.2 Smart Sim Workflow

Smart Sim (https://www.smarthome.enea.it/smartsim/) (Romano, 2023) is a web tool that was created to raise consumers' awareness of their energy consumption. It allows users to perform self-assessments and simulate their consumptions and costs.

No specific skills are required to use this tool. The users just need the energy bills of the previous year and information about their homes, systems and appliances. Smart Sim refers to high-energy macro-users including lighting and electric appliances (Lo Verso et al., 2015). It can be used to compare energy purchase costs with the best contracts available via the ARERA portal.

It provides the following benefits:

- Strategies that can be used to reduce energy consumption;
- The possibility of creating and managing energy communities;
- The possibility of collecting and organizing information on energy flexibility for the users;
- Statistical data and KPIs for residential users.

Smart Sim helps citizens to obtain a better understanding of their energy consumption and promotes efficient energy use.

6.3 Data HOMes and USers DHOMUS

DHOMUS (https://dhomus.smartenergycommunity.enea.it/) (Romano et al., 2024) is an ICT platform that was created for the advanced data management of residential users: it provides educational feedback and supports the management of home energy. The architecture was developed on two different levels for two types of users:

- General User: homes without specific smart devices;
- Smart Home User: homes with sensors and actuators managed by an energy box.

The central core of DHOMUS is the aggregator layer, where data aggregation, synchronization and analysis occur. It assesses the overall flexibility of an energy system. DHOMUS interfaces with third parties, such as service providers and smart city platforms, thereby supporting urban initiatives at a District level. The functions of DHOMUS are:

- Collecting and aggregating home energy data;
- Providing detailed monitoring of the consumptions;
- Analyzing data in order to offer educational feedback;
- Supporting the management of dynamic consumption and market participation.

DHOMUS is able to integrate with other ENEA platforms to enhance functionality and promote energy efficiency and sustainability. In short, DHOMUS represents an advanced and integrated system that can be used for the management of residential energy, which utilizes state-of-the-art ICT technologies to promote energy efficiency and sustainability in order to improve the quality of life in urban communities.

6.4 SIMUL

SIMUL (Branchetti, 2023; Branchetti et al., 2024) is a digital tool that can be used to manage energy communities. It utilizes real data, including load curves, electricity production, and storage. SIMUL can perform the following activities:

- Collecting real-time and historical data from smart meters and consumption portals;
- Simulating photovoltaic production using weather data and real-time production data;
- Comparing the energy behavior and impact of different configurations (Scenarios).

The possible applications of SIMUL are:

- Tests on pilot cases for RECs and collective self-consumption;
- The support of strategic decisions through the simulation of different scenarios.

Moreover, it was designed for reuse in various contexts and applications. SIMUL can be used as an aid to promote energy efficiency and self-sufficiency within communities. Finally, the components of the system were designed to be reusable in different contexts and applications to support the evolution of energy communities and, in the future, to be integrated with other applications via API, according to interoperability protocols. Its ability to simulate evolutionary scenarios and support strategic decisions makes it a valuable tool for promoting energy efficiency and self-sufficiency in modern communities.

6.5 Smart Energy Interactive Dashboard CruISE

CruISE (D'Agosta, 2023) is an advanced web application that can be used to manage energy communities. It offers easy configuration and visualization of energy data. CruISE is a tool that can be used to support the RECs management by assisting the energy community management group and promoting monitoring and interactions with users, to encourage virtuous energy behavior. The key Features of CruISE can be used to:

- Support the management of multiple communities simultaneously;
- Provide the visualization of clear energy data to encourage sustainable practices (User-Friendly Interface);
- Collect data from various sources, analyze performances and define benchmarks.

The benefits are:

- Maximizing renewable resource use;
- Optimizing energy consumption;
- Encouraging investments in storage solutions.

CruISE simplifies energy management practices, and it makes them accessible and engaging for all its users and also collects energy production and consumption data from different sources, analyzes performances, defines benchmarks and visualizes the energy behaviors of user groups.

6.6 Local Token Economy LTE

This model for Energy Communities makes use of blockchain technology to create a Local Token Economy in order to promote socio-economic and environmental development. LTE (Massa & Meloni, 2023) offers the following features:

- Traceability and Transparency, thanks to Blockchain, which ensures secure and transparent transactions;
- A Token Economy, which uses tokens to optimize economic processes within a shared economy;
- Active Citizen Participation, which encourages citizens to participate in energy management and share economic benefits.

The LTE model supports sustainability and resilience, and it facilitates fair and transparent exchanges within communities.

7. Conclusions

This study demonstrates a correct approach to building a new urban energy system and its elements, through the use of clear research and empirical evidence, references and the exploration of practical implementations. Italian standards provide a holistic approach to RECs, whereby the integration of and reciprocal interactions between buildings, districts, and energy communities are considered for a smart, sustainable and resilient city.

The Design and management of smart RECs both require ICT platforms, smart meters, demand response schemes, automatic controls for production and consumption and, in general, a wide empowerment for energy consumption awareness. The use of digital technologies in such communities makes energy communities smart, more efficient and profitable, and it allows greater accountability for all the members.

The combined use of top-down and bottom-up tools allows the use of energy resources to be optimized and a greater involvement of all the actors throughout the territories, in particular citizens. Such citizens will then be able to decide whether to become part of an energy community and share energy.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Acknowledgements

The authors are grateful to prof. Enrico Lorenzini for his insightful feedback and formal suggestions regarding the revisions adopted in this work.

Conflicts of Interest

The authors declare no conflict of interest.

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