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An Italian Geoportal for Renewable Energy Communities

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Abstract: The development and implementation of a national geoportal designed to optimize the planning and management of integrated Renewable Energy Communities (RECs) is presented in this study. This innovative tool facilitates the identification of optimal energy system configurations by selecting available renewable resources and technologies and determining community membership based on assigned input parameters. These parameters include electrical load profiles, energy prices, renewable resource availability, technological characteristics, socio-economic conditions, and territorial constraints. A multi-objective optimization framework was employed to address energy, economic, environmental, and social priorities simultaneously. The methodology adopts a place-based approach, enabling the application of energy management and optimization models tailored to the specific characteristics of each case study and the corresponding input data. The proposed geoportal incorporates features such as flexibility, scalability, and applicability to real-world territorial contexts, while providing decision support to regional planners and stakeholders. Scalability was achieved through the integration and management of spatial and temporal datasets across varying scales. The study evaluates five scenarios, including the maximum renewable energy potential utilizing solar, wind, and biomass renewable energy sources (RES) technologies, and two REC scenarios emphasizing photovoltaic (PV) energy sharing between sectors, residential prosumers, and consumers. Performance metrics and indexes were employed to assess the energy, economic, environmental, and social benefits of RES generation, distribution, and sharing. The findings indicate that REC scenarios featuring energy sharing achieve higher levels of self-consumption and self-sufficiency compared to isolated configurations. Future iterations of the geoportal aim to extend its application to additional territories, thereby enhancing the self-sufficiency of Territorial Energy Communities (TECs) and advancing sustainable energy practices on a broader scale.

Keywords: Energy geoportal; Renewable energy communities; Renewable energy sources; Energy modeling; Place-based analysis; Geographic information system; Energy performance indexes; Self-consumption; Self-sufficiency

1 Introduction

RECs represent a new and promising measure in the context of the concrete application of energy transition policies, in line with the Sustainable Development Goals (SDGs) of the 2030 Agenda [1]. The United Nations 2030 Agenda for Sustainable Development highlights the critical role of energy for the sustainable development of countries, and in particular through SDG 7, "Affordable and Clean Energy," SDG 11, "Sustainable Cities and Communities," and SDG 13, "Climate Action." By promoting local production and the sharing of renewable energy, RECs ensure universal access to sustainable, reliable, and modern energy services, reduce dependence on fossil fuels, and support competitive energy pricing and innovative energy-saving solutions. They also enhance the sustainability and reliability of energy systems through the shared management of energy resources, promote active citizen participation and social inclusion, create new "green" jobs, contribute to the reduction of greenhouse gas emissions, and drive the development of a green economy, thereby aligning with national strategic goals to achieve climate neutrality by 2050.

Italy, as a key player in the energy transition, has provided strong policy and legislative support for the development of RECs. Italy has implemented European regulatory frameworks pertaining to the creation and development of RECs through Renewable Energy Directives II and III (RED II [2] and RED III [3]), with Legislative Decree 199/2021 [4]. This legislative framework was further implemented with economic incentives by the CACER Ministerial Decree [5] and by the National Recovery and Resilience Plan (PNRR) [6]. RED III promotes the participation of citizens and local authorities in the management of energy and lays the foundations for a more decentralized and informed energy system. In terms of incentives, the CACER Decree provides specific incentives for the sharing of energy produced from renewable sources through a rewarding tariff provided by the Energy Services Manager (GSE) for energy shared among the members of a renewable energy community. CACER introduces contributions to cover the initial costs of the design and installation of plants, as well as for the digitalization and adoption of intelligent energy monitoring and management systems.

The PNRR allocates approximately €2.2 billion to support collective self-consumption and REC projects, financing up to 40% of the installation costs of PV, wind, biomass and storage systems for energy community projects in small municipalities with less than 5,000 inhabitants, thus also contributing to the revitalization of inland and rural areas.

However, an integrated approach is still needed to evaluate the potential of RECs, in which technical solutions and the active participation of local actors are combined. Digital platforms are essential to managing and optimizing RECs in order to allow the real-time monitoring of energy production, consumption, and sharing. They can be used to support self-consumption and system stability and facilitate smart grid integration, communication and transparency among community members [7]. A holistic approach, based on advanced technologies, strategic planning, and the active participation of local actors, is essential for the success of RECs. Only then will it be possible to create sustainable, efficient and resilient energy communities to promote the energy transition in Italy.

Either a bottom-up or a top-down approach can be developed for pre-feasibility analyses in such platforms. Bottom-up modeling evaluates the most convenient solution to connect different members at the local scale. Top-down modeling can be used for analyses on a large territorial scale. For example, it can be used to evaluate consumption at a local scale, or the availability of RES at a territorial scale down to a local one. The latter type of analysis can also be utilized to fragment a territory into various parts in order to focus on the local scale. Bottom-up models can be used to support the technical-economic pre-feasibility phase of RECs, mainly pertaining to citizens and companies, to organize a group of members (users, consumers and prosumers), to design renewable plants (size, location and monitoring system), and to plan access to incentives and public funding. Top-down modeling can mainly be utilized by public administrations and policymakers to check the features of a territory and to boost certain clean technologies according to the actual and future energy demands. The aim of this type of modeling is to consider not only the economic convenience of RECs but also their environmental and social impacts on achieving a more inclusive and democratic governance.

The main objective of this study is to present a place-based methodology that could be used to create a national geoportal of renewable energy resources which can be useful to support the planning processes of RECs throughout Italy. Various scenarios were evaluated through the analysis of data related to electricity consumption, the actual production, and future production. The impact of the RECs on the territory was measured through energy, economic, environmental, and social indicators and indexes. Indeed, it is crucial to monitor the energy, economic, environmental, and social performances of RECs to define a long-term strategic vision and to increase the acceptance and interest of the stakeholders and the public [8]. In this regard, a recent study, conducted by Caferra et al. [9], has highlighted that one of the most relevant topics for Italian energy users concerning energy communities is, in fact, the economic performance of these initiatives. Therefore, providing a detailed overview of this topic is particularly important for the promotion of RECs.

This study is structured below. Section 2 is dedicated to the presentation of the structure of the research, and it includes the collection and pre-processing of the data and variables, energy modeling, indicators and indexes used to assess the performance of the REC scenarios. Section 3 presents the main characteristics of its geographical areas. Section 4 is dedicated to the investigation of five scenarios to boost renewables and REC solutions, considering the main technological solutions, the analysis of the consumptions and the actual-future production, and a comparison of some indexes introduced in Section 2.

2 Material and Methods

The purpose of this study is to develop a support decision tool for the sustainable energy planning of RECs in Italy. This study uses a place-based approach that focuses on the specific properties of a region. The use of a Geographic Information System (GIS) allowed the necessary data to be collected and the pre-processing to be made, which in turn consented the collected information and the obtained results to be place-based, modeled, displayed and mapped to achieve a better understanding of the outcomes. This analysis considered data and results at the municipal scale together with aggregations at the provincial, regional and national scales. The use of these boundaries was linked to the governance of the territory, and they were introduced in order to be able to elaborate energy policy reflections. Furthermore, the municipal scale is often more detailed than the primary substation areas (except in large cities) which are the conventional areas of RECs. In terms of time, all the analyses were performed considering an hour as the basic time unit, aiming to evaluate the contemporaneity of energy production, sharing and consumption. The hourly results were then aggregated by days, months or years.

The hypothetical members of an REC can be classified into users, producers and prosumers (with both consumption and production). Spatial analysis considers the buildings of the different sectors as a territorial unit as far as energy consumption is concerned; the specific energy-use profile of each sector was considered.

The flowchart in Figure 1 illustrates the approach used in this study, with its structure divided into three main phases:

a) Data pre-modeling: The first stage was data collection and pre-processing, which served as the basis for all the other subsequent analyses. Important data were gathered by examining international and national databases to identify the main energy characteristics of the Italian territory. This included geographical, climatic, environmental, social, and economic aspects, as well as energy-related data such as human activities, energy consumption, the availability and distribution of renewable energy resources, and information on the actual plants/systems.

b) Modeling: The second phase focused on developing statistical models to define the hourly profiles of electricity consumption, the actual production, and future production. These data were uniformly generated, using time frames (year, month, day, hour) and geographical scales (region, province, municipality) to create geo-packages for the Italian geoportal. Particular attention was paid to understanding the constraints that influenced the accessibility to resources and the availability of suitable sites for the installation of energy plants/systems to create more feasible scenarios.

c) Scenarios: The final phase involved developing scenarios. Some indicators and indexes were used to evaluate the performance of the actual and future scenarios. The different REC scenarios were evaluated by considering their energy, economic, environmental, and social impacts.

In addition to the three operational stages described above, Figure 1 divides the document into three key parts: consumption, actual production, and future production.

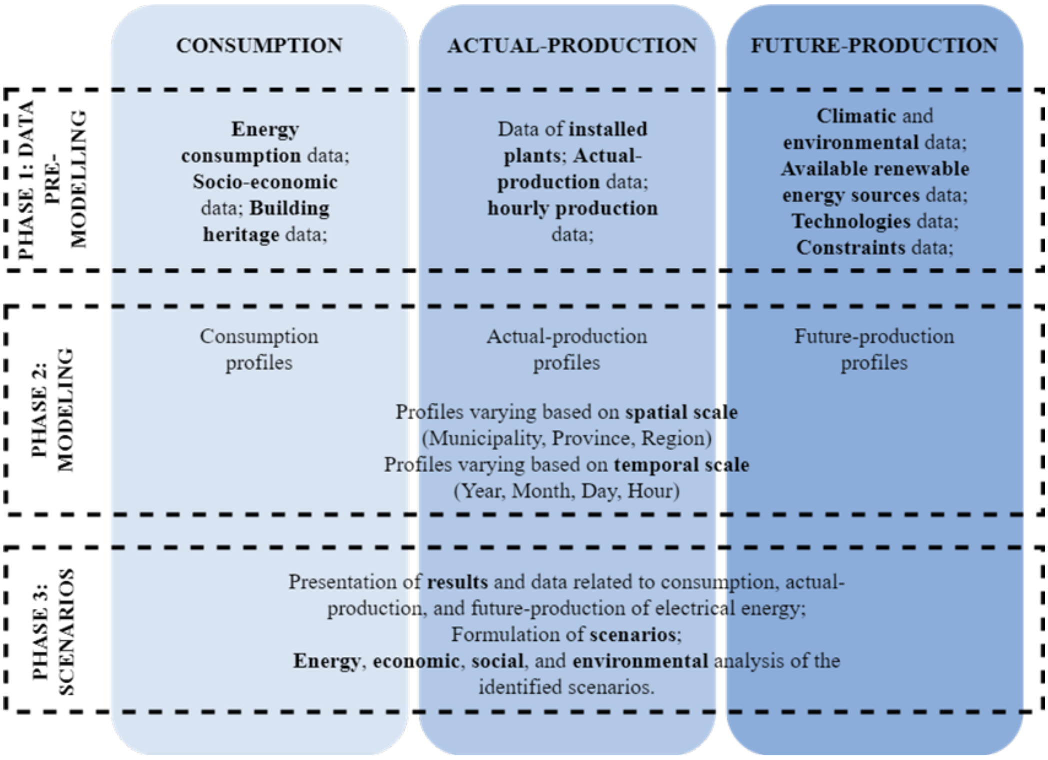


Figure 1. Methodology flowchart

2.1 Data and Geo-Datasets

The pre-modeling phase is described in this section together with the sources of the data and the pre-processing procedure used to correct and complete the datasets for the subsequent phase on energy modeling and scenario planning. Energy modeling is inextricably connected to the characteristics of the investigated territory and its features, and special care was therefore taken in the creation of the geo-datasets that served as the basis of the energy modeling. The used data were the result of a thorough search, as well as the collection, completion and correction of regional, national and international databases. Table 1 contains information about the collected databases and the geo-datasets, and it includes the sources, spatial scale, and the reference year (the most recent year) used in this study.

Table 1. Data collection information

Source	Data	Scale	Year
Autorità di Regolazione per Energia Reti e Ambiente (ARERA)	Electricity consumption by sector	Provincial	2022
	Consumption profile of the domestic sector	Provincial	2022
Copernicus	Corine Land Cover - Land use	Municipal	2018
Ente Nazionale Meccanizzazione Agricola (ENAMA)	Biomass Project	National	2010
Agenzia Nazionale per le nuove tecnologie, 1 'Energia e lo sviluppo economico sostenibile (ENEA)	Italian Solar Radiation Atlas	Municipal	2022
	Consumption profile by sector	National	2018
Geopportale Nazionale	Water Bodies - DB Prior 10k project	Municipal	2007
	Incentives for self-consumption configurations	National	2024
	Territorial constraints ("vincoli in rete" in Italian)	Municipal	2024
Global Wind Atlas	Wind variables - wind speed, capacity factor	Municipal	2019
Atlaimpianti, Gestore dei Servizi Energetici (GSE)	Electricity consumption by sector	Municipal	2015
	RES Plants/Systems	Municipal	2021
	Statistical report on renewable sources - hours of use	Regional	2021
	Solar PV statistical report - hours of use	Provincial	2023
	Monthly energy price by time slot and market zone	National	2024
Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)	Areas exposed to flood risks	Municipal	2020
	Areas exposed to landslide risks	Municipal	2021
	Urban Waste	Municipal	2023
	Territorial constraints - PITESAI	Municipal	2024
	Air quality measurements ($\mathrm{NO_2}, \mathrm{PM_{10}}, \dots$)	National	2022
Istituto Nazionale di Statistica (ISTAT)	Statistical atlas of municipalities	Municipal	2020
	Census of the population and housing	Municipal	2011-21
	Census of Italian industries and services	Municipal	2011
	General agriculture census	Municipal	2010
Joint Research Centre (JRC)	PVGIS - Solar irradiation, diffuse / global ratio, solar irradiance, electricity production	Municipal	2020
Meteotest	Linke Turbidity Factor - Meteonorm	Municipal	2019
Ricerca sul Sistema Energetico (RSE)	Wind variables - AEOLIAN National Wind Atlas	Municipal	2019
Trasmissione Elettrica Rete Nazionale (TERNA)	Electricity consumption by sector	Provincial	2015-22
	Consumption profile of the secondary sector	Regional	2022
Tinitaly	Digital Terrain Model - DTM 10 m and 20 m	Municipal	2022
Organizzazione delle Nazioni Unite per l'Educazione, la Scienza e la Cultura (UNESCO)	Territorial constraints - World Heritage Sites	Municipal	2024

After the data-collection phase, the databases and geo-datasets were corrected by detecting any missing outliers, averaging with the nearby technique, and homogenizing at the spatial territorial unit level of the municipalities. The obtained information was completed with an evaluation of the other energy-related variables in order to create three geo-packages (at a municipal scale) containing data for the energy modeling phase:

a) Energy consumption by sector of use (domestic, primary, secondary, and tertiary sectors).
b) The actual energy production by RES with the most frequently used technologies.
c) Future energy production, considering the availability of the RES and territorial constraints.

2.2 Constraints

Territorial constraints can seriously limit or prevent the realization of RECs, and they are therefore considered in this section [10]. Territorial constraints can be categorized into six typologies considering the technical, environmental, landscape, hydrogeological, economic, and governance aspects:

a) Technical constraints are related to those aspects that influence the effective provisioning of RES or the technical installation of the REC plants. The accessibility and availability of renewable energy resources are just a few examples of the technical constraints that can affect the potential and effectiveness of REC projects.

b) Environmental constraints are related to the conservation of natural ecosystems and biodiversity, and they include conservation areas, such as parks and reserves, as well as Ramsar sites, which are wetlands of international significance. Natura 2000 areas and Important Bird Areas (IBAs) were considered in this work for habitat and species conservation. Areas with critical air quality and severe noise pollution were also taken into consideration to ensure compliance with the environmental requirements.

c) Landscape constraints are related to the protection of the landscape and cultural heritage present in a territory. These include United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage sites, areas and assets of significant interest that are protected under the Cultural Heritage and Landscape Code, historical centers, areas of major public interest for their historical value, landscape and tourism, and agricultural areas characterized by the presence of quality food productions (i.e., D.O.P., I.G.P., S.T.G., D.O.C., D.O.C.G.). In addition to these, areas protected under Article 142 of Legislative Decree n. 42 of 2004, which includes coastal land (300 m from the shoreline), areas adjacent to lakes (300 m from the shoreline), rivers (150 m from the banks), mountains 1200-1600 m a.s.l., glaciers, national and regional parks, nature reserves, forests, civic use areas, wetlands, volcanoes, and areas of archaeological interest were also considered.

d) Hydrogeological constraints are related to the risks associated with water bodies and rock formations. These areas are classified from low flood risk (P1) to high flood risk (P3), and from temperate landslide risk (P1) to extremely high landslide risk (P4). These constraints are critical for ensuring the stability and safety of renewable energy plants from damage caused by natural disasters in order to guarantee the long-term profitability of the projects.

e) Economic constraints are related to the financial convenience of renewable energy production, and they include the costs of developing renewable energy projects, as well as the availability of subsidies and financial incentives. These economic variables have a significant effect on investment decisions and project performance, and they can make renewable energy companies/enterprises profitable and sustainable.

f) Governance features are related to the presence of public bodies that can facilitate the establishment of RECs (i.e., mountain communities, unions of municipalities, metropolitan cities, territorial integration areas and municipal companies that manage energy, water, and waste).

Table 2 shows the constraints on the installation of RES plants/systems.

Table 2. Constraints on the installation of RES plants/systems

Type	Description
Environmental and landscape	Protected natural areas, Ramsar sites, Natura 2000 sites, IBAs, areas with protected species, areas with poor air quality and noise pollution; UNESCO sites, cultural heritage areas, historical centers, high-value agricultural areas, visual cones and areas near archaeological parks, coastal areas, areas near lakes, rivers, streams, and their banks, mountains above certain altitudes, glaciers and glacial cirques, national and regional parks, forests and woods, areas with civic uses, Ramsar sites, volcanoes, archaeological sites
Hydrogeological	Areas with landslide risks, areas with hydraulic risks
Technical	Resource availability, resource accessibility, availability of space for plants
Economic	Investment cost, access to incentives

2.3 Energy Modeling

The geo-packages that were obtained in the pre-modeling phase were used in the energy modeling phase to define the profiles of the variables from a spatial perspective (at regional, provincial and municipal scales) and a temporal timeframe (at an annual, monthly, daily or hourly-detail scale). Specifically, the electricity consumption profiles were defined by considering the characteristics of different users. The actual and future production profiles were instead defined by considering the characteristics of the different typologies of RES, the performance of the technological solutions, the constraints, and the climatic and environmental features of the territory:

a) Consumption profiles were defined using datasets provided by TERNA and the Regulatory Authority for Energy Networks and Environment (ARERA). Municipal consumption was identified, on the basis of the annual consumption data at the provincial level, using multilinear correlations that allowed the influence of the socio-economic variables of the territory (such as population, building characteristics, employment, number of companies, etc.) on the relative energy consumption to be highlighted. Furthermore, the hourly consumption profiles of different types of users (residential and non-residential) were identified, considering typical weekdays and holidays on a monthly basis.

b) Actual production profiles were defined utilizing the information available on the power of the already existing RES plants and typical utilization hours (of RES technology and geographical area). The hourly profiles identified on a monthly basis were detected from the different types of RES. The hourly profiles of the solar and wind-to-energy technologies were evaluated as a function of the climate conditions, considering the orography of the terrain. The hourly profiles of the hydroelectric plants were constant, and they considered the monthly water flows and the river heads. The hourly profiles of the biomass and geothermal plants were constant, with monthly variations that depended on the considered geographical area.

c) Future production profiles were defined considering the availability of RES throughout the Italian territory. Specifically, three future production models were used to assess the energy potential from solar, wind, and biomass sources. The amount of electricity that could be produced was determined by considering the specific characteristics of the various RES (e.g., the lower calorific value of different categories of crops and waste materials), the technical characteristics of the plants/systems (e.g., conversion efficiencies), and the features of the Italian areas, that is, local climate variables (e.g., wind and solar profiles) and territorial constraints (which can limit access to resources and/or the possibility of installing plants/systems).

The results of the energy modeling were implemented in three geo-packages to simulate different consumption scenarios and those of actual-future productions. Table 3 presents the different types of hourly profiles that resulted from the energy modeling of the user and RES. The hourly electrical consumption profiles were identified for the residential, primary, secondary and third sectors (The primary sector includes agriculture, forestry, livestock farming and mining; the secondary sector includes processing industries; the tertiary sector includes trade, credit, insurance, transport and communications and other activities). The buildings of the different sectors were analyzed for this analysis, considering their characteristics. Instead, the main RES plants/systems were analyzed for the actual production, and the main technologies were identified. Only solar, wind and biomass were analyzed for future production because they are the main resources exploited in the Italian territory.

Table 3. Types of produced profile

Consumption	Actual Production	Future Production
Residential sector	Solar	Solar
Primary sector	Wind	Wind
Secondary sector	Biomass	Biomass
Tertiary sector	Hydraulic	
	Geothermal	

2.4 Indicators and Indexes

Since the main purpose of REC is to obtain energetic, environmental, economic, and social benefits at a local scale, a comprehensive set of indexes and indicators was defined to assess their performances [11]. The indexes and indicators are classified in Table 4 into four main dimensions: energy, economics, environmental, and social. Each dimension includes a different point of view on the impact of RECs on a territory. This methodical approach offers a complete understanding of the energy system, and it allows specific actions to be made, thorough evaluation, and well-informed decision-making to obtain sustainable planning and management of energy.

The energy dimension encompassed several key indicators, which were organized into three main sections: consumption, actual production, and future production. This logical framework provided a comprehensive evaluation of the energy system. The study, which involved examining the electricity consumption patterns, consented the current demand to be identified across various sectors, thereby highlighting opportunities for optimization and efficiency improvements. Assessing the actual production from RES provided information about the actual supply capabilities, which, in turn, aided the integration and stability management of the grid. The actual production was essential to predict the future production capacity in order to plan ahead, and it enabled the renewable potential and various future scenarios to be forecast.

The instantaneous consumption and production pertaining to the "energy" indicators and indexes were calculated on an hourly basis, although these results could also have been aggregated on a daily, monthly, or yearly basis (Table 4). Self-consumption index (SCI) was the most important indicator for the REC scenarios, and it was thus used to quantify the amount of energy production that would be instantaneously consumed by a prosumer. It was also used to calculate the SCI and self-sufficiency index (SSI), which, in turn, were used to evaluate the quota of self-consumption on the total production and consumption, respectively, considering daily, monthly or yearly periods. The over-production and the uncovered demand were also considered. Indeed, a certain amount of over-production can be shared with other members of the REC, and this can be defined as collective self-consumption.

The "economic" dimension was focused on financial measures related to energy production and consumption. Energy prices consider the cost of energy withdrawal and input into the national network. In addition to the cost of energy withdrawal, the revenues from self-produced energy, over-production and the economic incentives from collective self-consumption were also evaluated. The payback time considers the time required to recover the cost of investment in RES technologies [12].

The "social" dimension included those indicators believed to be useful to assess the impact of RECs on the community. One of these impacts is the reduction of energy poverty, that is, the percentage of the population that is unable to keep their homes adequately warm in line with the poverty status. A just community should also include vulnerable users who could benefit more from the sharing of electricity. The social impact can also be assessed from the number of involved members (and the types of users) in an REC to the total population or considering the type of governance that can facilitate the creation and stability of RECs [13].

The "environmental" dimensions address the impact of RECs on air, soil and water eco-systems. Greenhouse gas emissions depend directly on the energy consumption of fossil fuels. Other pollutant analyses could be added, such as that of NOx emissions, to measure the use of thermoelectric power plants and particulate concentrations with PM10 and PM2.5 for the use of heating boilers.

These indicators, when used together, lead to a complete evaluation of various aspects of the performance of RECs and guarantee a reliable assessment of their effectiveness.

Table 4. Indicators and indexes

Dimension	Indicator	Description	Unit	Scale
Energy	C	Consumption by sector	kWh	y, m, d, h
	Actual production	Actual production by RES	kWh	y, m, d, h
	Future production	Future production by RES	kWh	y, m, d, h
	SC	Minimum production and consumption	kWh	y, m, d, h
	OP	Produced electricity that exceeds consumption	kWh	y, m, d, h
	UD	Consumed electricity not covered by production	kWh	y, m, d, h
	Shared electricity	Energy shared with other users	kWh	y, m, d, h
	CSC	Shared electricity consumed by other users	kWh	y, m, d, h
	SCI	Self-consumption to total production	%	y, m, d
	SSI	Self-consumption to total consumption	%	y, m, d
	OPI	Overproduced energy to total production	%	y, m, d
Economic	Energy price	Cost of energy per unit of consumption	€/kWh	-
	SC revenues	Economic savings from self-consumption	€	y, m, d, h
	OP revenue	Economic profit from the sale of energy	€	y, m, d, h
	Incentives	Financial contribution with incentives	€	y, m, d, h
	CAPEX	Capital expenditure of RES investment	€	-
	PBT	Time to recover the investment	Years	y
Social	Energy poverty	% of population unable to keep home adequately warm by poverty status	%	-
	% of REC members	% of REC members to population	%	-
	% of REC fairness	% of vulnerable consumers	%	-
Environmental	GHG emissions	mass of $CO_{2,eq}$	kg, t	y, m, d, h
	% of GHG emissions	% reduction of $CO_{2,eq}$ emissions	%	y, m

Note: y indicates year; m indicates month; d indicates day; h indicates hour; C indicates consumption; SC indicates self-consumption; OP indicates over-production; UD indicates uncovered demand; CSC indicates collective self-consumption; OPI indicates over-production index; CAPEX indicates capital expenditures; and PBT indicates payback time.

2.5 Scenarios

The actual and future energy scenarios, with and without RECs and new RES technologies, are presented in this section for Italian municipalities. The scenarios were created on the basis of the consumption, the actual and future RES production. The outcomes of the scenarios were then evaluated from energy, economic, environmental, and social points of view with indicators and indexes.

a) Scenario 0 pertains to the evaluation of the present state of electricity production from RES, that is, utilizing the existing infrastructure. It considers the overall energy consumption across sectors (i.e., residential, primary, secondary, and tertiary sectors), as well as production from solar, wind, biomass, hydroelectric, and geothermal plants. This is the starting scenario that was then used for comparison purposes with other “future” scenarios.

b) Scenario 1 was used to investigate the effects of the use of PV panels with roof-integrated technologies. It was divided into two sub-scenarios:

Scenario 1.1, which excluded buildings in historical centers.

Scenario 1.2, which excluded buildings in historical centers, cultural buildings, and protected landscape areas.

These scenarios were used to estimate the potential increase in electricity produced from PV with two different types of constraints, considering that new panels are less visible.

c) Scenario 2 was used to assess the impact of the use of wind turbines in suitable locations. It was divided into two sub-scenarios:

Scenario 2.1, which evaluated the installation of 850 kW wind turbines.

Scenario 2.2, which considered the installation of 2,000 kW wind turbines.

These scenarios were used to evaluate the potential electricity production that could be achieved using standard wind-to-energy technologies.

d) Scenario 3 was used to evaluate the impact of using forest and agricultural biomass, or waste to produce electricity. It was divided into two sub-scenarios:

Scenario 3.1, which limited the use of biomass plants in municipalities with poor air quality.

Scenario 3.2, which involved installing biomass plants in all the municipalities.

These scenarios were utilized to assess the results of installing biomass plants for electricity production, considering different environmental constraints.

e) Scenario 4 was used to evaluate the impact of RECs with PV energy production. This scenario was utilized to evaluate the exchange of electricity among users from different sectors (residential, primary, secondary, and tertiary), considering the use of roof-integrated technologies on residential buildings (only domestic users were considered prosumers).

f) Scenario 5 was used to evaluate the impact of RECs with PV panels on residential buildings and the exchange between residential prosumers and users. It was assumed that only 25% of the residential users had installed PV panels (i.e., prosumers) and that the energy was shared with the remaining 75% of the members (i.e., users).

These scenarios offer a first overview of the potential for renewable energy production with REC configurations in Italian municipalities, such as the different use of renewables and the potential of the renewable share that could be achieved for the various territories. A problem that arises concerns large cities, which are very critical from an energy point of view. However, RECs might be able to help to better exploit renewable resources in these cities.

3 Case Study of Italy

Italy is working toward improving its energy system, in line with international agreements on climate change, European directives, national plans, and the energy crisis in 2022, with the aim of attaining a better performance of the three components of the energy trilemma: energy security, environmental sustainability and energy equity [14, 15]. Indeed, the diffusion of RECs, together with energy efficiency measures and increased use of renewables and smart grids, could contribute toward attaining energy, economic, environmental and social benefits throughout the Italian territories. However, this process requires the involvement of all the actors in a territory, including its citizens, companies, public bodies, and politicians.

This section is dedicated to exploring the main characteristics of the Italian territory that can influence such an energy strategy. Specifically, this study considered the features of RES, environmental pollution and some territorial disparities across the Italian regions. Self-consumption with renewable plants and a share of energy for vulnerable citizens could enhance the sustainable development of Italian territories. Figure 2 shows the spatial distribution of air pollution throughout Italy, with the average PM2.5 concentrations for the year 2019. Italy has had to face serious air pollution problems in recent years, particularly concerning high concentrations of particulate matter (PM10 and PM2.5) [16]. The Po Valley (or “Padana” plain) is one of the regions in Europe that is affected the most by air pollution caused by a high density of industrial areas, high traffic volumes, and its unfavorable orography, that is, being surrounded by mountains. Moreover, energy poverty (i.e., the inability to keep a home adequately warm, in line with the poverty status) and the level of employment are also represented in the figure to show the regional differences in economic health and social aspects. Southern regions, such as Sicily, Calabria, Puglia and Basilicata, have energy poverty rates of over 12%, while northern regions, such as Lombardy and Veneto, have energy poverty rates below 6%. The Alpine regions, the Aosta Valley and Trentino Alto Adige, show higher energy poverty rates as a result of their colder climates and higher energy costs [17, 18]. The employment rate can be used as a key indicator of economic health and social progress. Northern and central regions generally boast higher employment rates (the highest is Trentino Alto Adige) than the southern ones (the lowest is Campania), and this has led to social inequality and economic imbalances [19].

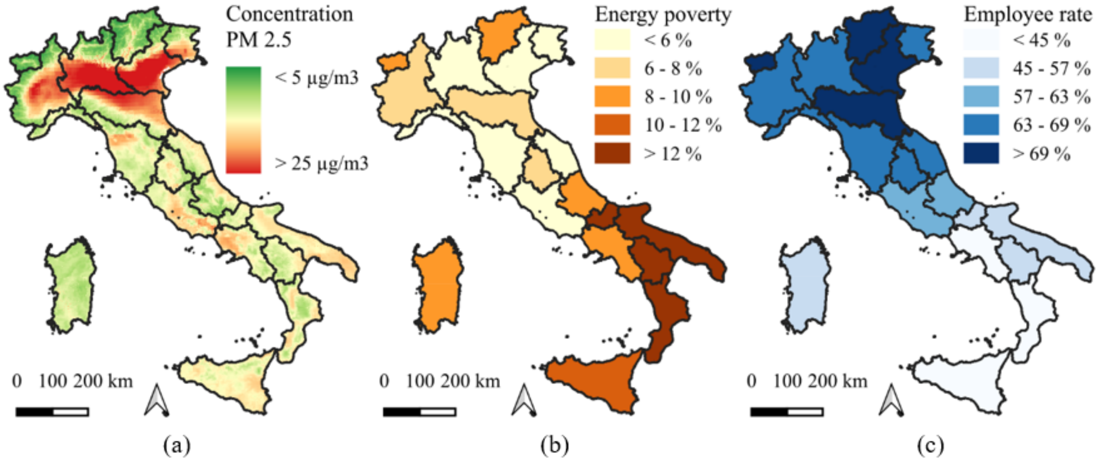


Figure 2. (a) Annual average PM2.5 (2019), (b) Energy poverty (2022), and (c) Employment rates (2023)

Italy's geographical position and economic condition exhibit pronounced regional disparities, which are particularly evident in the distribution of agricultural land and industrial activities. According to the national statistical data from ISTAT [19], the southern regions have the largest agricultural land area (7,238,204 ha), which accounts for nearly half of the national amount. This distribution reflects the crucial role of agricultural activities in the southern regions. The northern regions overwhelmingly dominate the industrial (automotive, chemical, and textile industries) and services sectors, while the agriculture sector is more balanced.

These regional disparities in industrial structure and land use patterns significantly influence the energy consumption patterns and the possibility of renewable energy development. The northern regions, with their advanced manufacturing and service sectors, have high energy demands, which are primarily concentrated in industrial and commercial areas. The concentration of energy-intensive industries in the north necessitates a higher reliability and stability of the energy supply, and also creates a market demand for renewable energy applications.

Conversely, energy consumption in the southern regions is more closely connected to agriculture and residential life, with the energy demands being relatively dispersed and lower in total volume. These characteristics make distributed renewable energy systems (such as small-scale PV and biomass energy) particularly promising for applications in the southern regions.

3.1 REC Development

The origins of energy communities can be traced back to the early 20th century and stem from the traditional European energy cooperation model, which was used to develop the first local electricity production and consumption projects. The first Italian energy cooperative was created in the Funes Valley in Alto Adige in 1921, and it was named "Società Elettrica Santa Maddalena." Today, this cooperative continues to produce energy from renewable sources using hydroelectric, PV, and biomass plants. Citizen cooperatives began to appear in Europe in the 1970s, initially in Denmark, and then in Germany and Belgium, with the aim of promoting and sharing renewable energy.

Italy formally introduced the new REC and energy sharing policy in March 2020 through the "Milleproroghe Law." Multiple REC pilot projects were simultaneously launched. The emergence and development of the first generation of RECs in Italy was an important energy transformation and social innovation event. Magliano Alpi has been hailed as "the first new energy community in northern Italy" (the Piedmont Region). The community is based on a 20 kW solar PV system, which is located on the Town Hall roof, and five households have become members of this community.

The development of RECs has made significant progress in recent years. According to GSE data [20], 67 REC configurations were operative in Italy in 2022; of these, 25 had a power rating of between 0 and 10 kW, 24 between 10 and 20 kW, 12 between 20 and 50 kW, and 6 between 50 and 100 kW. A total of 501 end users are now connected to REC configurations, of which 70% are engaged in collective self-consumption. Figure 3 provides an overview of the RECs in Italy and shows there is a higher presence in the northern regions.

The Italian REC configuration demonstrates a good potential, and the introduction of incentive measures in 2024 has encouraged further developments. Italy plans to add 12 GW of renewable energy capacity through REC projects by 2030, thereby contributing to the country's energy transition.

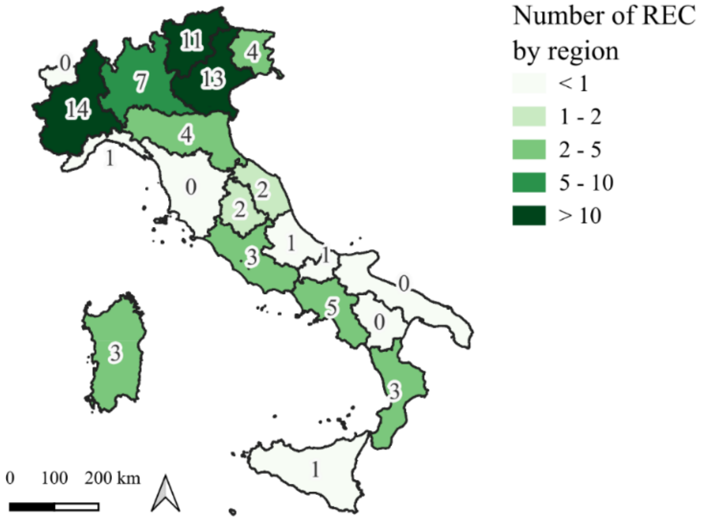


Figure 3. RECs in Italy by region (2022)

4 Results and Discussion

This section describes the potential for renewable energy systems and the implementation of energy communities regarding the electricity system, focusing on electrical consumption, RES availability, energy technologies on the market, the actual production by RES and the future production by RES, considering different possible scenarios.

4.1 Consumption

The first analysis was conducted on electricity consumption at the municipal level by type of user. Italian electricity consumption amounted to approximately 290-295 TWh [21] in the 2021-2022 period. The most significant consumption came from the secondary sector (industries), which alone accounted for 45% of the total consumption in that period, followed by the tertiary (commercial, 29%), residential (24%), and, finally, primary (agricultural, 2%) sectors.

It can be observed, in Figure 4, that northern regions are the most energy-intensive ones, and Lombardia is the highest consumer, with 64.3 TWh (22.1% of the total electricity), which is primarily driven by the secondary sector (53.1%). On the other hand, the regions with the lowest consumptions are Valle d'Aosta and Molise, with total consumptions of 0.9 and 1.3 TWh, respectively. Energy consumption generally depends to a great extent on the specific characteristics of each region, including factors such as population density, land use, climate, and socio-economic features. Statistical top-down modeling with multilinear regressions was used to identify the municipal consumption of the four economic sectors. Hourly profiles were then estimated considering the typical monthly days for residential and non-residential users [22, 23].

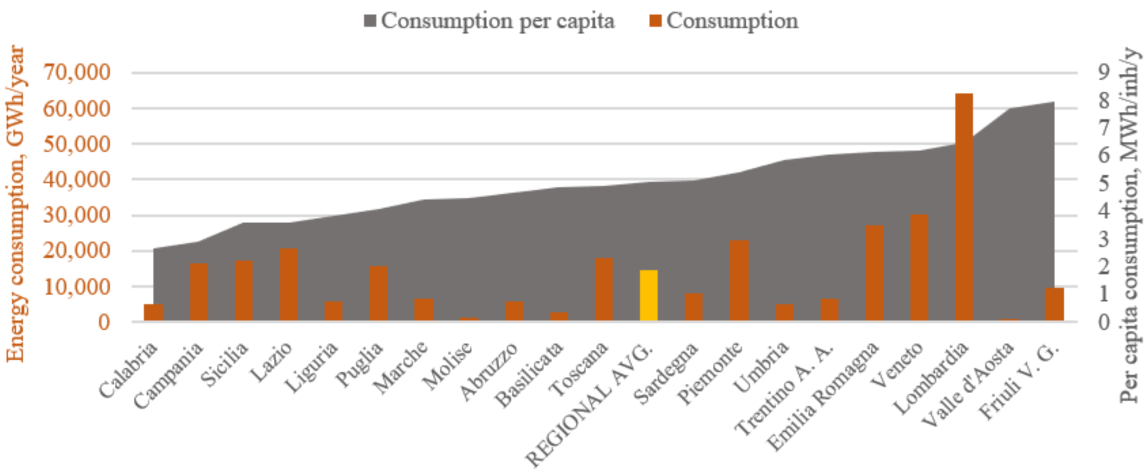


Figure 4. Electricity consumption by region and national average (year 2022)

4.2 RES and Related Technologies

4.2.1 RES

The second analysis was conducted on the availability of RES that would be suitable for electricity generation; the data source references are reported in Table 1. This is a fundamental step that allowed the potential energy production in different areas to be identified on the basis of their specific characteristics. Specifically, solar, wind and biomass were investigated.

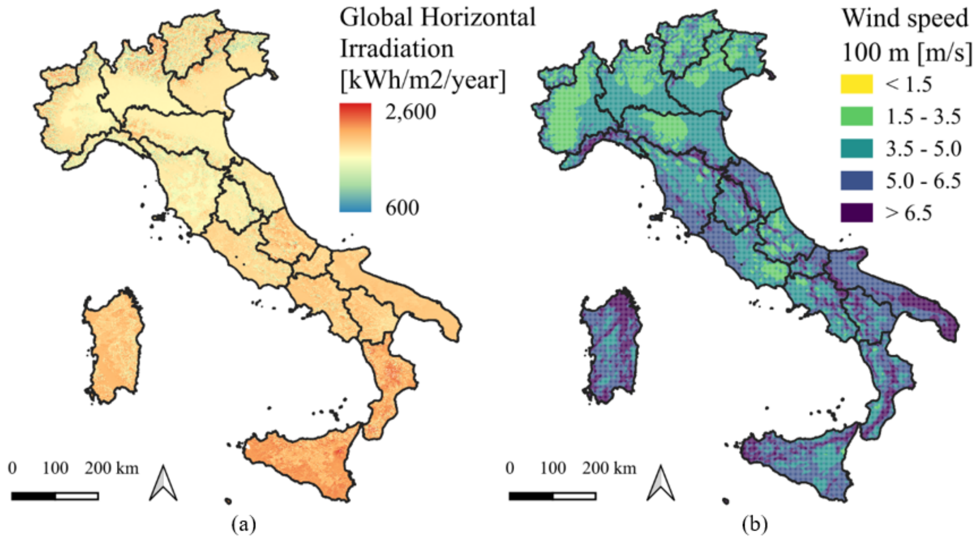


Figure 5. (a) Annual global horizontal irradiation (GHI), and (b) Mean wind speed at 100 m.a.s.l.

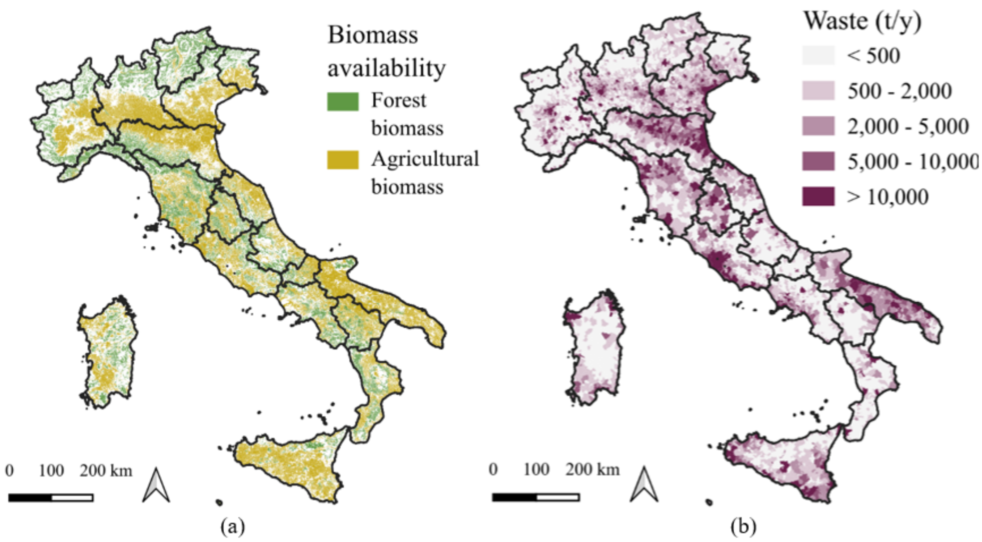


Figure 6. (a) Spatial distribution of the forest and agricultural biomass (2018), and (b) the annual availability of waste by municipality (2022)

Considering the latitude of each region and within each region, on the basis of the altitude, the Italian territory was divided to distinguish plain, hilly, and mountain areas in order to determine the solar irradiation values. On the basis of the results of this classification, the hourly solar irradiation data was simulated with QGIS by considering the orography of the territory with DTM 20, the shape of the buildings, and the specific monthly values of solar components, with diffuse-to-global radiation, and the type of atmosphere, with its Linke turbidity factor and transmissivity. The hourly solar irradiation values were simulated using the "Area solar radiation" and "r.sun insoltime" QGIS tools for twelve typical days of the month. These results are shown in subgraph (a) of Figure 5, together with the annual solar irradiation of the Italian territory on a 20 m × 20 m grid.

The data for the wind speed profiles were obtained from the Italian Wind Atlas (AEOLIAN), developed for RSE, which provides the wind data at a resolution of 1.4 km. A thirty-year hourly historical series (1990 - 2019) of wind speed (m/s) and direction (since 2015) over onshore and offshore domains was used for the analysis. Subgraph (b) of Figure 5 shows the average annual wind speed over the Italian territory at 100 m.a.s.l.; the highest values can be observed over the islands and, more generally, along the coasts and in the southern regions (Puglia, Campania, and Basilicata). Moreover, the wind results were also collected for the coastal, plain, hilly, and mountain areas of each region, and the hourly trends of the typical monthly days were identified.

Finally, three different typologies of biomass were considered for the analysis on its availability for electricity generation: forest, agricultural and waste. Information regarding the forest categories and agricultural crops was obtained for the forest and agricultural biomass by considering the land cover and through the use of the most recent CORINE Land Cover released in 2018 [24]. The quantity of forest and agricultural biomass was evaluated by means of QGIS, which calculated the areas and, with the "Merge" tool, joined those areas that used the same type of biomass.

The information regarding the availability of waste was collected from the National Waste Register of ISPRA, which contains the quantities of waste collected at a municipal level for 2022 [25]. The waste categories that were eligible for energy production were identified considering their reuse and renewable fraction [26, 27]. Figure 6 illustrates the spatial distribution of the forest and agricultural biomass, as well as the annual waste that could be used for electricity generation. Agricultural areas are mainly concentrated in the plain portions of the territory, while forested areas are located in the mountainous parts. The production of waste is closely related to the size of the urban centers, the number of inhabitants, and the activities present in the area.

4.2.2 RES technologies

The most frequently used technology was identified for each RES, with the aim of evaluating the production of clean energy throughout the Italian territory. The information on the existing system/plant by type of RES was obtained from the "Atlaimpianti" geographic atlas [28]. The installed power and the utilization hours were identified for each municipality, altitude, and region.

The energy conversion efficiency of the different types of systems/plants was used to estimate the electricity generation from renewable sources for future RES productions.

Monocrystalline PV panels, with an installed power of 3-6 kW (power installed for 76.5% of the PV systems), were considered for the use of solar resources. Monocrystalline panels allow the maximum efficiency to be obtained, and the SunPower Maxeon 6 AC PV panel was used as a reference, as it is ideal for diffuse and residential applications. The performance ratio was calculated monthly for the typical municipalities of each region, considering the altitude to evaluate plain, hilly and mountain areas. The main technical data of the panel are summarized in Table 5.

Table 5. PV panel specifications

Model	Nominal Power, W	Power Tolerance, %	Module Efficiency, %
SunPower Maxeon 6 AC	445	+ 5/0	23

The most commonly used wind turbines are produced by the Vestas company, and they have nominal powers of 2,000 kW (power installed by 25.6% of the systems) and 850 kW (power installed by 25.1% of the systems) [29]. Consequently, two models of wind turbines were selected: Vestas V52, with a nominal power of 850 kW, and Vestas V90, with a power output of 2,000 kW. Vestas V52 wind turbines have 52 m diameter blades, a swept area of 2,124 m^2, and a maximum hub height of 86 m. Vestas V90 wind turbines have 90 m diameter blades, a swept area of 6,362 m^2, and a maximum hub height of 105 m. Both models have a cut-in wind speed set at 4 m/s and a cut-out speed set at 25 m/s. The main technical data of the two wind turbines are summarized in Table 6. The conversion coefficient is not a constant value, and it mainly varies according to the tip speed ratio, wind speed, and blade-turbine design. It can reach a maximum efficiency of about 0.5, within a specific wind speed range, and then gradually decreases.

Table 6. Wind generator specifications

Model	Nominal Power, kW	Rotor Diameter, m	Hub Max Height, m	Cut-in Wind Speed, m/s	Cut-out Wind Speed, m/s
Vestas V52	850	52	86	4	25
Vestas V90	2000	90	105	4	25

As far as the use of agricultural, forest and waste biomass are concerned, Combined Heat and Power (CHP) plants were considered as a reference due to their high overall energy efficiency (higher than 75%) [30], which is obtained by producing both electrical (with an efficiency of about 20%) and thermal energy for district heating. About 400 (14%) biomass plants use solid biomass in Italy. These plants are located, in particular, in northern Italy and have a median installed power of 200 kW. The main technical data of the reference biomass plants are summarized in Table 7, and the conversion efficiencies for electricity production are 11% and 21-25% [31, 32].

Table 7. Technical data of the biomass power plants

Model	Power, kW	Power Plant Size, m^2	Electric Net Power, kWel	Conversion Efficiency (el), %	Hours of Use, h
PowerSkid 200 +	200	40	200	11	7200
Turboden 7 CHP	5000	1000-1600*	702	21-25	7000

Note: The plants have a storage facility

4.3 Actual Production Achieved by RES

In order to provide a comprehensive overview of the diffusion and use of RES for electricity generation, the actual production (kWh) was calculated from data provided by the GSE on the installed nominal power (kW) and the utilization hours (h) of each RES (solar, wind, biomass, hydraulic, and geothermal) in the various Italian regions [28, 33, 34].

More than 92,000 GWh of electricity is produced each year at the national level from plants powered by RES. Most of this energy comes from hydropower plants, which generate 28.9% of electricity. This is followed by biomass plants (23.1%), PV systems (21.8%), wind plants (20.3%), and, finally, by geothermal plants (5.8%).

It can be observed, in subgraph (a) of Figure 7, that the most productive regions are Trentino-Alto Adige, with an annual production of about 12,000 GWh (around 94% from hydropower plants) and Puglia, with a production of about 9,500 GWh per year (about 50% from wind-to-energy plants). Conversely, the least productive regions are Molise and Liguria.

Subgraph (b) of Figure 7 illustrates the reference locations used to analyze the hourly profiles of the solar and wind-to-energy technologies in each region. These locations were identified for each region according to their altitude in order to group the various areas into coastal, plain, hilly, and mountainous areas.

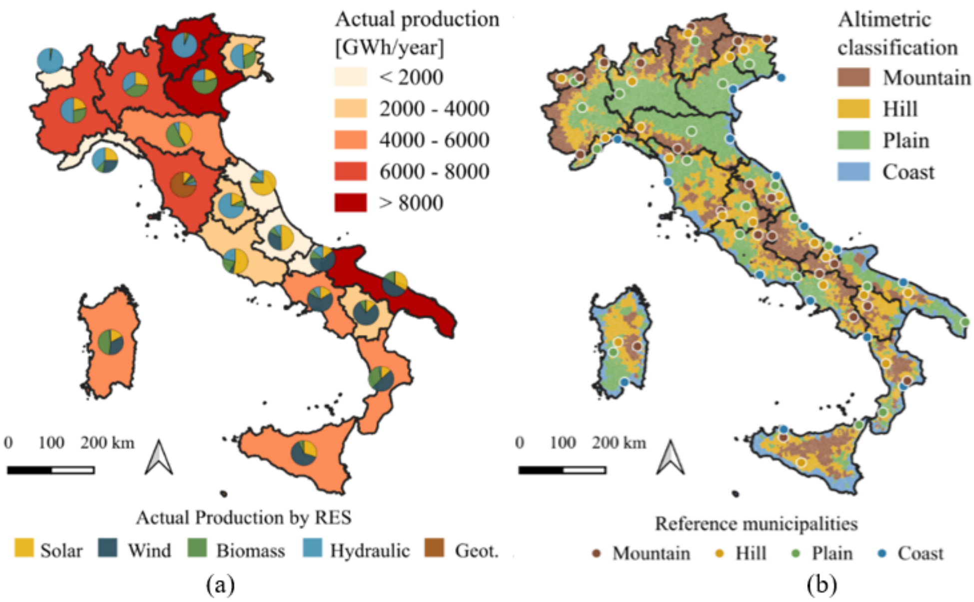


Figure 7. Actual electrical energy production (a) by region, and (b) referent locations by altitude class

4.4 Future Production by RES

The future production was estimated on the basis of the availability of RES and the characteristics of the technologies, the typology of the territory, and all the territorial constraints. This analysis only considered the total potential future production from solar (Scenario 1), wind (Scenario 2), and biomass sources (Scenario 3).

The electricity production from solar sources was calculated by assuming the installation of roof-integrated PV panels on existing buildings, considering the different users [35]. Two scenarios were analyzed:

Solar 1.1, where buildings within the historic centers were excluded, as they fall under landscape constraints;

Solar 1.2, in which the landscape restriction area was extended to sites identified by means of the Cultural Heritage and Landscape Code.

Under this hypothesis, it is possible to produce between 220 and 254 TWh/year at the national level and as the maximum, depending on the type of constraints that are applied. It can be noted, in Figure 8, that the regions with the highest potential are Lombardy and Sicily, while the lowest potential production is indicated for the Aosta Valley and Molise. This is because the estimation of solar production is influenced by not only the annual solar irradiation (which is higher in the southern regions) but also the extent of the surface area that is available for installing the panels (which also depends on the number of buildings and the percentage of available area free from constraints, as shown in subgraph (b) of Figure 8. About 50% of the roof area available for the installation of PV panels is in northern regions (15% in Lombardy). Only 31% is in southern regions (13% in Sicily and Sardinia).

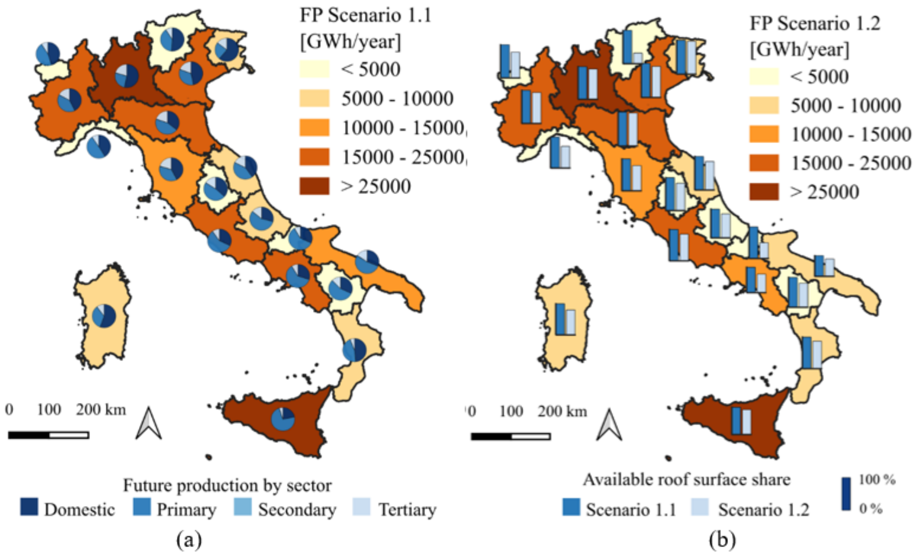


Figure 8. Future electricity production with PV technologies: (a) Scenario 1.1 with the production by sectors, and (b) Scenario 1.2 with the available roof surfaces and different constraints

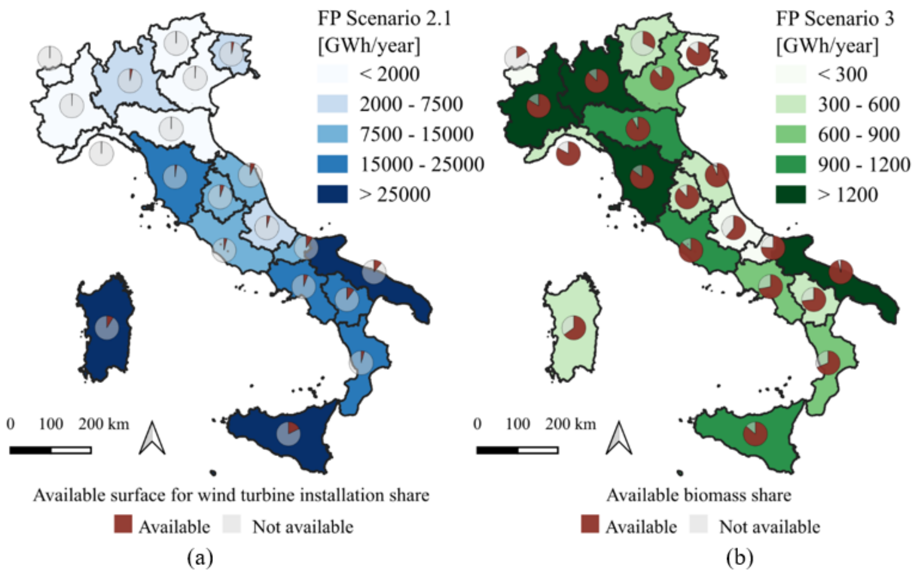


Figure 9. Future potential electricity production considering the constraint limits for (a) Scenario 2.1 for the wind-to-energy technology, and (b) Scenario 3 for biomass plants

The introduction of territorial constraints related to the Code of the Cultural and Landscape Heritage (Scenario 1.2) impacts the various regions to different extents. In some regions, the reduction in productivity, when comparing the first and second scenarios, is considerable: in Trentino-Alto Adige (-68%) and Molise (-50%). In other regions, the impact is much more limited, such as in Friuli Venezia Giulia, Emilia Romagna, Piedmont and Lombardy, where this reduction is less than 7%.

The PV potential was also assessed according to the type of users in each sector. The pie charts in subgraph (a) of Figure 8 show the share of production attributed to the domestic, primary, secondary and tertiary sectors.

The use of two wind turbines was analyzed: Vestas V52, with a nominal power of 850 kW (Wind 2.1), and Vestas V90, with a nominal power of 2,000 kW (Wind 2.2), regarding the wind-to-energy potential. By observing the data reported in subgraph (a) of Figure 9, it is possible to note a significant variation in the wind potential across different Italian regions. It is evident that the potential is predominantly concentrated in the southern regions of Italy (Sicily, Puglia, and Sardinia), and this suggests that these areas are strategic for the development of wind energy. Moreover, wind energy can be considered complementary to solar energy, as it works better in winter and during the night. The analysis showed that it is generally possible to generate between 366 and 532 TWh of electricity each year from wind sources, depending on the type of used wind turbine. The difference in production between the first and second scenarios is influenced by both the different degrees of power of the two wind turbines and the space occupied by each of them. In Italy, there are important constraints to the installation of wind technologies, mainly pertaining to their dimensions and environmental-landscape impact. Overall, only 5% of the territory has been deemed suitable for wind-to-energy technologies, with higher values in the Southern regions and islands.

Finally, the amount of electricity that can be produced through biomass plants was estimated by analyzing the quantity of dry biomass and the relative lower heating value (LHV) available from agriculture, forestry, and municipal waste disposal. The analysis revealed that, at a national scale, it would be possible to produce about 13,500 GWh of electricity using these types of biomasses. More than half of the producible energy would come from agricultural biomass (55%), followed by forestry biomass (30%) and waste (15%). It can be observed, in subgraph (b) of Figure 9, that the most productive regions are Tuscany and Lombardy. On the other hand, the least productive regions are the Aosta Valley (19 GWh/year) and Molise (147 GWh/year), because of their limited areas and mountainous orography (they are located in the Alps and Apennines, respectively). The estimation of electricity production from biomass considered the limits on resource collection, as well as the restrictions concerning plant installation. The average accessibility to biomass is 82% in Italy, with lower values in the mountainous areas of the Aosta Valley (16%) and Trentino Alto Adige (32%).

4.5 Evaluation of the Scenarios with Indexes

The data regarding consumption, the actual production, and the future production of electricity were analyzed to assess the national, regional, and municipal energy potential and the challenges. SCI, SSI and over-production index (OPI) were evaluated for a daily, monthly and annual period, considering the hourly consumptions and productions over a typical year.

The current scenario was analyzed considering data related to the actual energy consumption and production by RES (Scenario 0). Future scenarios were then considered to assess the potential energy production of PV panels (Scenarios 1.1 and 1.2), wind turbines (Scenarios 2.1 and 2.2), and biomass power plants (Scenario 3). Finally, the potential of two REC configurations was evaluated at a municipal scale, considering the electricity generated by PV panels being shared among the members of a community. Scenario 4 considered the sharing of energy between sectors, and Scenario 5 evaluated the sharing of energy between residential prosumers (25%) and residential users (75%).

It can be observed, for Scenario 0, in Figure 10, that the annual values of SCI are close to 1, while they are about 0.09 for SSI, thus suggesting that the small amount of actual RES production is used completely, and only a minimal part of the energy demand is satisfied. The indexes are quite uniform across the peninsula, with a few exceptions in the Alps and the Apennines between Puglia and Basilicata, the center of Tuscany, and Nord West Sardinia, where the current production is able to satisfy the electricity demand because of the presence of large RES plants and/or a low energy demand.

Figure 11 shows the annual SCI and SSI for Scenario 1.1, which exploits the use of PV panels and roof-integrated technologies, although historical centers are excluded to preserve the typical landscape. On average, abundant electricity production allows up to 50% of the energy demand to be satisfied with high self-sufficiency values. However, the SCI remains quite low, that is, at 30-31%. This is because the hourly peaks in electricity production do not always coincide with consumption, and this results in about 70% of the produced electricity not being directly usable. However, from a comparison of Figures 10 and 11, it emerges that Scenario 1.1 has a very interesting potential and could be further improved with energy sharing and storage. It is possible to see, observing in subgraph (a) of Figure 11, that SCI is low in all the municipalities. However, there are some exceptions in the Po Valley (where the SCI is between 40 and 60%) and in Puglia (where the values rise to 80%). Subgraph (b) of Figure 11 shows high SSI values of about 50%; this value is very good, considering the seasonality of solar radiation (higher values could be achieved, albeit with an over-production in summer). It is possible to note that self-sufficiency is lower than the national values in the municipalities in Lombardy. Lower SSI values are also clearly visible for many large-to medium-sized cities (in red and orange), such as Milan, Rome, Naples, Turin, Aosta, Trento, Genoa, Bologna, Florence, Campobasso, Bari, Taranto, Palermo, Siracusa, and Cagliari, all of which have higher consumptions.

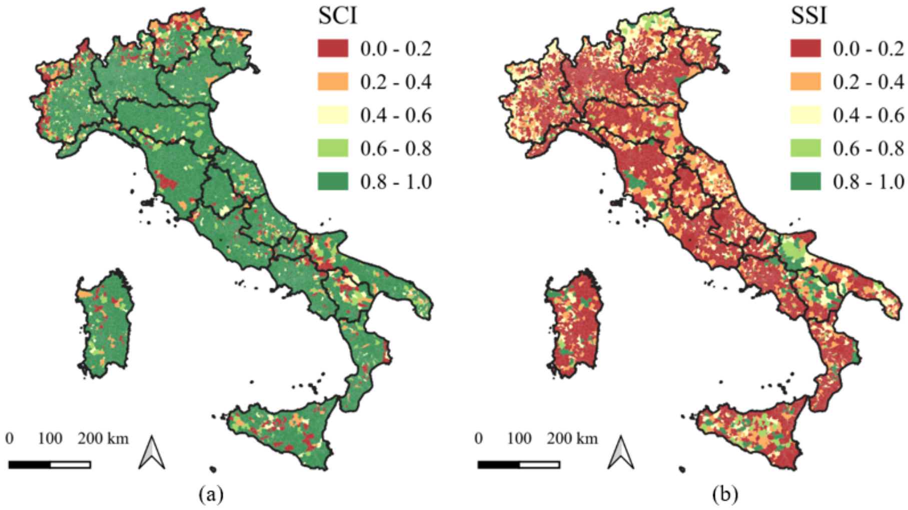


Figure 10. (a) SCI, and (b) SSI for Scenario 0 (actual)

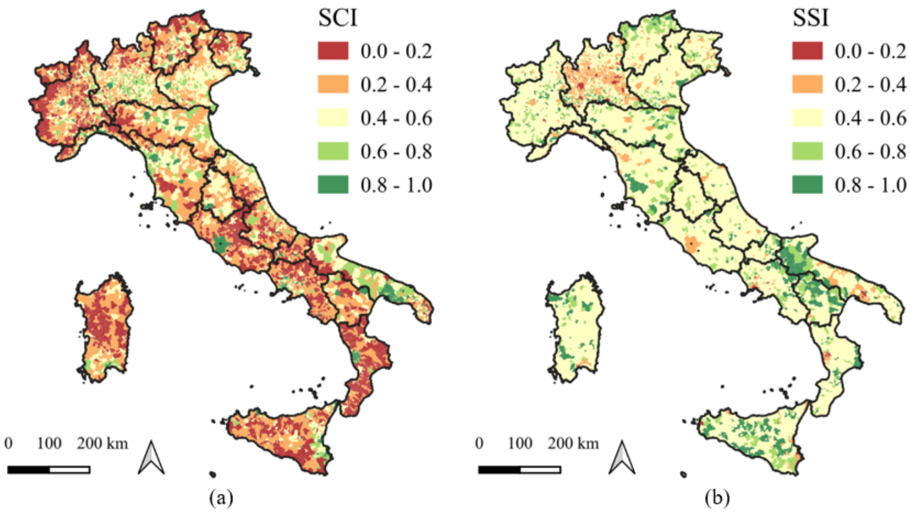


Figure 11. (a) SCI and (b) SSI for Scenario 1.1

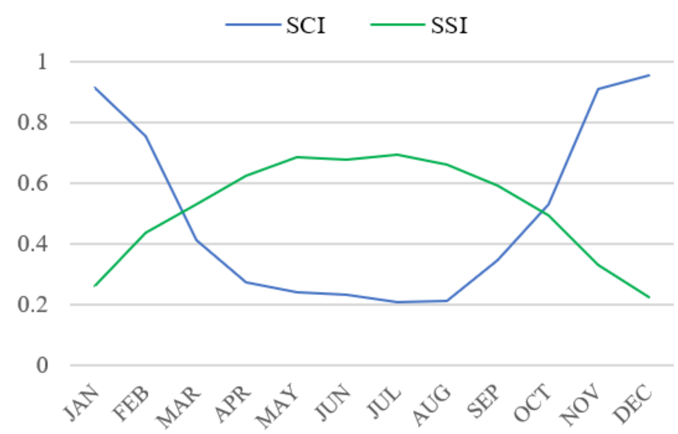


Figure 12. Monthly median values of SCI and SSI for Scenario 1.1 on a national scale

Figure 12 shows the monthly variation of SCI and the SSI. The production of electricity from PV is influenced to a great extent by seasonality. High self-consumption values and low self-sufficiency values can be observed in the winter months, when production is lower. The situation is reversed in the summer months, due to the increase in electricity production. The optimal scenario should have high values for both indexes and low overproduction to reduce the cost of investments.

The exploitation of wind energy in Scenario 2.1 allows even more non-homogeneous results to be obtained between the northern and southern regions. Energy production with wind technologies could meet the users' consumption needs without any excess production, which instead would occur for PV technologies. It is possible to clearly distinguish the areas where the wind potential is high in Figure 13. High values of self-sufficiency and low values of self-consumption are observed only in the southern regions (due to abundant over-production). Instead, high self-consumption and low self-sufficiency values can be observed in the northern regions. On average, Scenario 2.1 and Scenario 2.2 show the SCI of 90% and 80%, respectively, while the SSI is 34% and 39%, respectively.

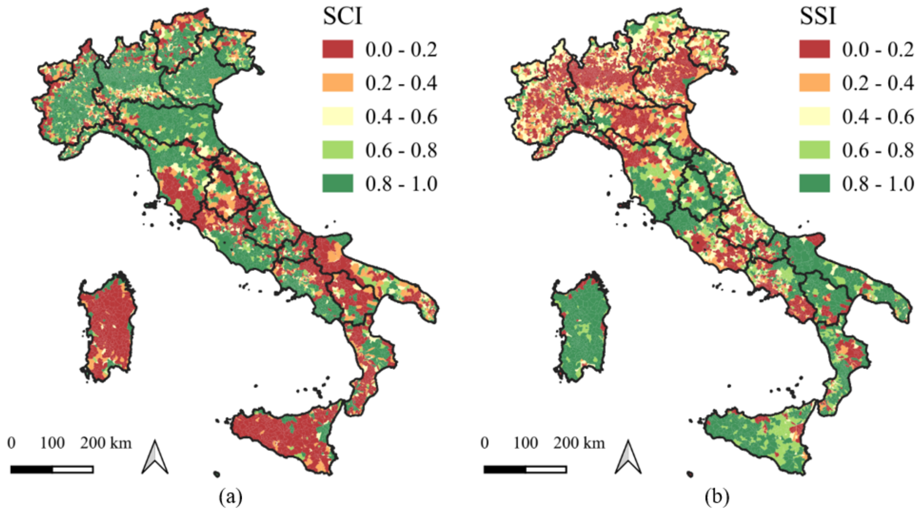


Figure 13. (a) SCI, and (b) SSI for Scenario 2.1

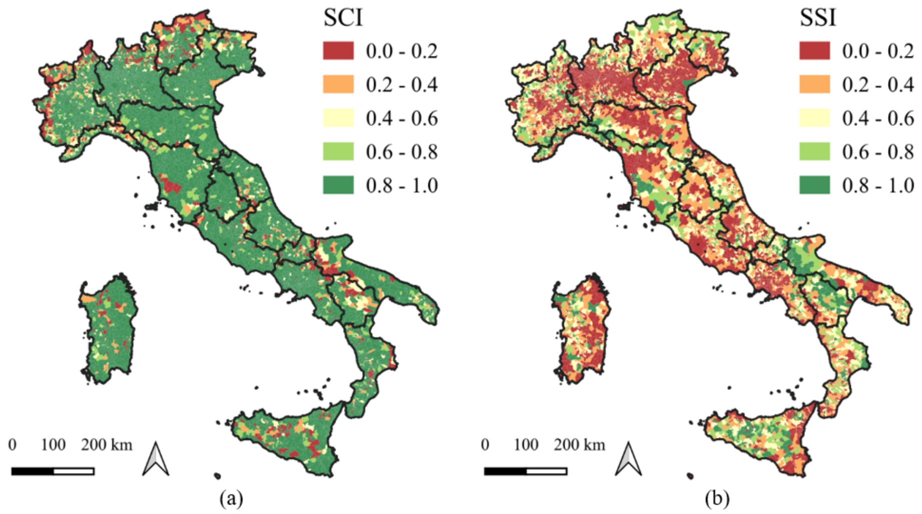


Figure 14. (a) SCI, and (b) SSI for Scenario 3

Considering all the territorial constraints, the results obtained for biomass (Scenario 3) show that this resource has a limited impact on the energy system. All the produced energy is used to meet the energy needs. Figure 14 shows the amount of electricity produced from forest, agricultural and waste biomass that is completely consumed, and high SCI and low SSI values can be observed. The resulting SSI values suggest that, on average, only 22% of the energy demand can be satisfied.

Finally, the results obtained for Scenario 4 (Figure 15) and Scenario 5 (Figure 16) highlight the possibility of sharing energy within an REC. Both scenarios show a low electricity production, due to the decrease in installed

PV power and the possibility of exchanging the over-production with the community members. When comparing Scenarios 1.1 and 1.2, it emerges that the results of Scenarios 4 and 5 show a significant increase in self-consumption (and collective self-consumption), that is, from 30-31% to 56-45%. SSI decreases slightly due to the reduction in PV production; however, the median value remains at around 44-35%.

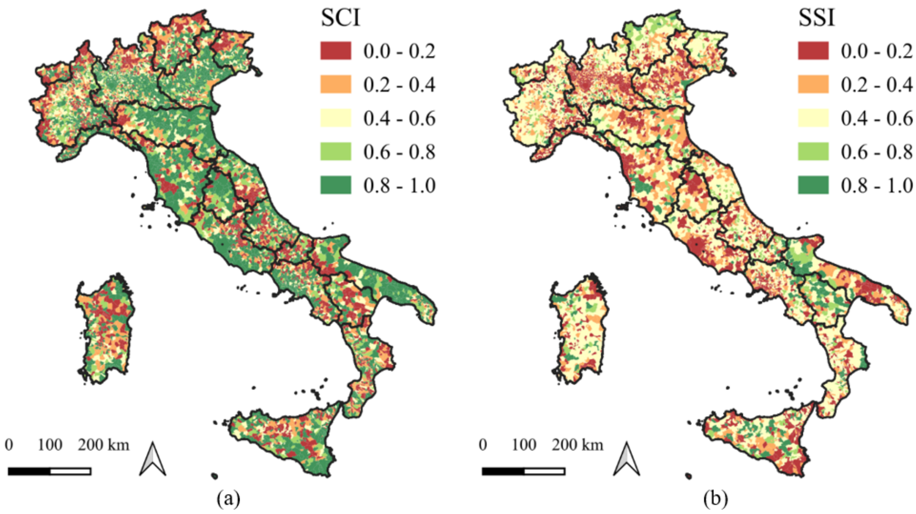


Figure 15. (a) SCI, and (b) SSI for Scenario 4

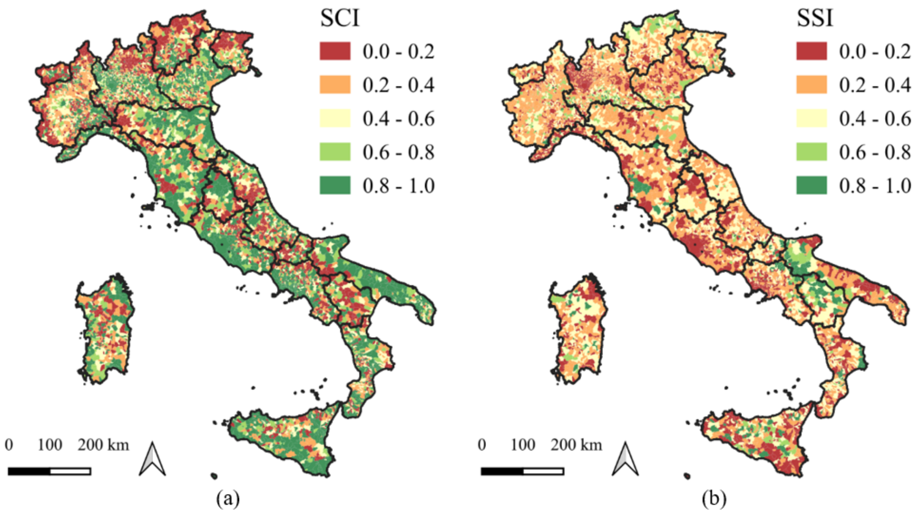
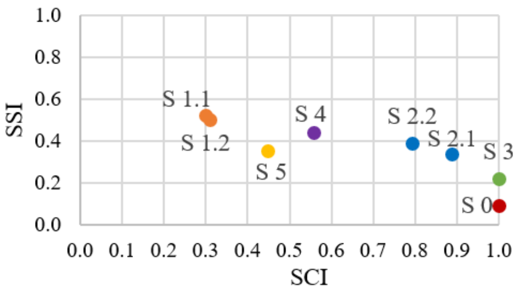


Figure 16. (a) SCI, and (b) SSI for Scenario 5



	SCI	SSI	OPI
S0	1.00	0.09	0.00
S 1.1	0.30	0.52	0.70
S 1.2	0.31	0.50	0.69
S 2.1	0.89	0.34	0.11
S 2.2	0.79	0.39	0.21
S 3	1.00	0.22	0.00
S 4	0.56	0.44	0.44
S 5	0.45	0.35	0.55

Figure 17. Comparison of the median values of SCI, SSI, and OPI for different scenarios on a national scale

Figure 17 presents the median values of SCI, SSI and OPI for the five considered scenarios (for the Italian municipalities). The objective of this scenario is to self-produce the energy needs locally, with a high self-consumption, and in achieving high self-sufficiency in order to guarantee energy independence through RES production. Moreover, a slight over-production guarantees low investment costs. The solar resource in Italy is the most effective solution, even when only a roof-integrated solution is used for landscape protection purposes. Solar Scenarios 1.1. and 1.2 have not only higher SSI values but also high OPI values. Wind Scenarios 2.1 and 2.2 show better results, but this solution can only be adopted in the southern regions. The use of solid biomass, which is distributed throughout all the regions, shows a good result, especially because it is influenced less by climatic conditions and seasonality.

REC Scenarios 4 and 5, which combine solar production and energy sharing within an REC, show good SSI results, with a lower OPI and low costs [36]. When only the solar technologies are considered, the best solution is that of sharing between sectors with different consumption profiles, as shown in Scenario 4. The share between residential prosumers and users, as in Scenario 5, results in lower SCI and SSI values and a higher OPI.

5 Conclusions

This study describes the different stages of designing an Italian geoportal for RECs, that is, from the data sources to the construction of geo-packages and to the modeling of the energy consumption and the place-based production. The indicators, which were used to evaluate the convenience of territories hosting RECs, were also described. This tool was used to support decisions, and it could be used by not only all the stakeholders in a territory, that is, citizens, but also companies, public bodies and policymakers. The goal of this study is to create as many self-sufficient RECs on the Italian territory as possible so that they are able to exploit the locally available resources. This can eventually lead to the overall Italian territory becoming self-sufficient. These first results show that the estimated future share of energy can increase self-consumption and self-sufficiency, and that a mix of renewable sources and a mix of consumers is the optimal choice.

The future developments of this geoportal could involve investigating different aggregations of territories. The presented solution could be adopted by large cities. With their high energy consumption density and low availability of renewables, large cities will need to aggregate with their nearby territories to increase their self-sufficiency. The new TEC concept could be analyzed considering all the benefits that can be obtained with energy, economic, environmental and social indicators.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] United Nation General Assembly, "Transforming our world: The 2030 agenda for sustainable development," A/RES/70/1, 2015. https://documents.un.org/doc/undoc/gen/n15/291/89/pdf/n1529189.pdf

[2] European Union, "Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable energy sources," Official Journal of the European Union, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001

[3] European Union, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/65," Official Journal of the European Union, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413

[4] Istituto Poligrafico e Zecca dello Stato Società per Azioni, "Attuazione della direttiva (UE) 2018/2001 del Parlamento europeo e del Consiglio, dell'11 dicembre 2018, sulla promozione dell'uso dell'energia da fonti rinnovabili," 2021. https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2021-11-30&atto.codiceRedazionale=21G00214

[5] European Union, "Comunità Energetiche Rinnovabili - CER," 2023. https://www.mase.gov.it/sites/default/files/Decreto%20CER.pdf

[6] Governo Italiano, "PNRR - Piano Nazionale di Ripresa e Resilienza (National Recovery and Resilience Plan)," 2021. https://www.mimit.gov.it/it/pnrr/piano

[7] F. D. Minuto, A. Lanzini, L. Giannuzzo, and R. Borchiellini, "Digital platforms for Renewable Energy Communities projects: An overview," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1106, p. 012007, 2024. https://doi.org/10.1088/1755-1315/1106/1/012007

[8] S. Ahmed and A. M. Măgurean, "Renewable energy communities: Towards a new sustainable model of energy production and sharing," *Energy Strategy Rev.*, vol. 55, p. 101522, 2024. https://doi.org/10.1016/j.esr.2024.101522

[9] R. Caferra, A. Colasante, I. D'Adamo, G. Yilan, and D. Lancialonga, "A strategic analysis of renewable energy communities in achieving sustainable development," *Util. Policy*, vol. 90, p. 101810, 2024. https://doi.org/10.1016/j.jup.2024.101810

[10] L'Istituto Poligrafico e Zecca dello Stato Società per Azioni, "Disciplina per l'individuazione di superfici e aree idonee per l'installazione di impianti a fonti rinnovabili," 2024. https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2024-07-02&atto.codiceRedazionale=24A03360

[11] F. Vecchi, R. Stasi, and U. Berardi, "Modelling tools for the assessment of Renewable Energy Communities," *Energy Rep.*, vol. 11, pp. 3941–3962, 2024. https://doi.org/10.1016/j.egyr.2024.03.048

[12] E. Belloni, D. Fioriti, and D. Poli, "Optimal design of renewable energy communities (RECs) in Italy: Influence of composition, market signals, buildings, location, and incentives," *Electr. Power Syst. Res.*, vol. 235, p. 110895, 2024. https://doi.org/10.1016/j.epsr.2024.110895

[13] V. Todeschi, G. Mutani, L. Baima, M. Nigra, and M. Robiglio, "Smart solutions for sustainable cities—The re-coding experience for harnessing the potential of urban rooftops," *Appl. Sci.*, vol. 10, no. 20, p. 7112, 2020. https://doi.org/10.3390/app10207112

[14] World Energy Council, "World energy trilemma framework," 2024. https://www.worldenergy.org/transition-toolkit/world-energy-trilemma-framework

[15] L. Marti and R. Puertas, "Sustainable energy development analysis: Energy trilemma," *Sustain. Technol. Entrep.*, vol. 1, no. 1, p. 100007, 2022. https://doi.org/10.1016/j.stae.2022.100007

[16] Sistema Nazionale per la Protezione dell'Ambiente (SNPA), "La qualità dell'aria in Italia Edizione 2023," 2023. https://www.snpambiente.it/snpa/

[17] Osservatorio Italiano sulla Povertà Energetica (OIPE), "Terzo rapporto sullo stato della povertà energetica in Italia," 2023. https://oipeosservatorio.it/wp-content/uploads/2024/03/rapporto_2023_IT.pdf

[18] I. Faiella and L. Lavecchia, "Energy poverty. How can you fight it, if you can't measure it?" *Energy Build.*, vol. 233, p. 110692, 2021. https://doi.org/10.1016/j.enbuild.2020.110692

[19] IstatData, "The database of the National Institute of Statistics," 2024. https://esploradati.istat.it/databrowser/#/it/dw

[20] Legambiente, "Comunità Energetiche Rinnovabili, il punto della situazione in Italia," 2024. https://www.legambiente.it/rapporti-e-osservatori/

[21] Terna, "Statistical Publications," 2023. https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche

[22] ARERA, "Analisi dei consumi dei clienti domestici," 2023. https://www.arera.it/dati-e-statistiche/dettaglio/analisi-dei-consumi-dei-clienti-domestici

[23] GSE, "Methods of profiling measurement data and related methods of use pursuant to Article 9 of Annex A to Resolution 318/2020/R/eel - Groups of self-consumers of renewable energy acting collectively and renewable energy communities," 2022. https://www.nextville.it/normativa/47866/modalit-di-profilazione-dei-dati-di-misura-e-relative-modali/

[24] Copernicus Land Monitoring Service, "CORINE Land Cover," 2018. https://land.copernicus.eu/en/products/corine-land-cover

[25] ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, "Urban waste databases," 2022. https://www.catasto-rifiuti.isprambiente.it/index.php?pg=ru

[26] A. Tundo, P. Capezzuto, L. Blaso, P. Marinucci, and G. Mutani, "Holistic approach for sustainable cities and communities: Best practices in living labs," in *Innovation in Urban and Regional Planning. Lecture Notes in Civil Engineering Innovation in Urban and Regional Planning*, 2024, pp. 301–312. https://doi.org/10.1007/978-3-031-54118-6_28

[27] ENAMA - Ente NAzionale per la Meccanizzazione Agricola, "Progetto Biomasse Enama - Parte 1 Biomasse ed energia," 2011. https://www.progettobiomasse.it/it/pdf/studio/p1c1.pdf

[28] GSE - Gestore Servizi Energetici, "Atlaimpianti - L'atlante geografico delle rinnovabili," 2021. https://www.gse.it/dati-e-scenari/atlaimpianti

[29] ANEV, "Vent'anni di vento," *Associazione Nazionale Energia del Vento*, 2022. https://www.anev.org/

[30] Gestore Servizi Energetici-GSE, "Teleriscaldamento e Teleraffrescamento. Diffusione delle reti ed energia fornata in Italia," 2022. https://www.gse.it/documenti

[31] C. Delmastro, G. Mutani, and L. Schranz, "Advantages of coupling a woody biomass cogeneration plant with

a district heating network for a sustainable built environment: A case study in Luserna San Giovanni (Torino, Italy)," *Energy Procedia*, vol. 78, pp. 794–799, 2015. https://doi.org/10.1016/j.egypro.2015.11.102

[32] RSE - Ricerca Sistema Energetico, "Costo di generazione dell'energia elettrica da biomassa solida per la definizione dei prezzi minimi garantiti," 2024. https://www.arera.it/fileadmin/allegati/docs/24/132-24RapportoTecnico_Biomassa_SolidaN.pdf

[33] GSE - Gestore Servizi Energetici, "Rapporto Statistico 2021. Energia da fonti rinnovabili in Italia," 2023. https://www.gse.it/documenti

[34] GSE - Gestore Servizi Energetici, "Rapporto Statistico 2023. Solare fotovoltaico," 2024. https://www.gse.it/documenti

[35] G. Mutani, M. Alehasin, Y. Usta, F. Fiermonte, and A. Mariano, "Statistical building energy model from data collection, place-based assessment to sustainable scenarios for the city of Milan," *Sustainability*, vol. 15, no. 20, p. 14921, 2023. https://doi.org/10.3390/su152014921

[36] G. Mutani and V. Todeschi, "Optimization of costs and self-sufficiency for roof integrated photovoltaic technologies on residential buildings," *Energies*, vol. 14, no. 13, p. 4018, 2021. https://doi.org/10.3390/en14134018