Power Engineering and Engineering Thermophysics
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Integrated Multi-Objective Modelling and Digital Decision-Support Framework for Renewable Energy Communities: Energy Performance, Self-Consumption, and Territorial Optimization

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Received: 03-16-2026 **Revised:** 05-12-2026 **Accepted:** 05-24-2026

Citation: G. Mutani, G. Massa, S. Romano, D. Martellotti, X. Zhou, L. Blaso, and A. Tundo, "Integrated multi-objective modelling and digital decision-support framework for renewable energy communities: Energy performance, self-consumption, and territorial optimization," *Power Eng. Eng. Thermophys.*, vol. 5, no. 2, pp. 123–139, 2026. https://doi.org/10.56578/peet050204.

Abstract: Renewable Energy Communities (RECs) are increasingly recognized as decentralized energy systems capable of improving renewable energy integration, enhancing local self-consumption, and supporting the transition toward low-carbon energy infrastructures. However, the effective deployment of RECs still faces significant challenges related to the integration of spatial analysis, energy modelling, operational optimization, and socio-economic assessment within a unified framework. This study investigates an integrated multi-objective framework for the design, evaluation, and operational support of RECs through the combination of geospatial analysis, energy performance modelling, and digital decision-support tools developed within the ENEA Smart Energy Communities (SEC) platform. The proposed methodology was developed by integrating spatially explicit territorial datasets, renewable resource assessments, electricity demand profiles, and multidimensional key performance indicators (KPIs) within a coordinated analytical framework. Three complementary tools were implemented and evaluated: the geoCER geoportal for territorial-scale renewable energy planning and REC scenario modelling, the DHOMUS platform for residential load monitoring and self-consumption optimization, and the Local Token Economy (LTE) system for token-based user engagement and energy-aware behavioral incentives. The results showed that the integrated framework effectively supported the assessment of REC configurations under different territorial and operational conditions. In the Anguillara Sabazia case study, the REC configuration increased the Self-Consumption Index (SCI) from 30% to 65% and the Self-Sufficiency Index from 36% to 79%, while reducing the Energy Surplus Index from 70% to 35%. In the Sardinia case study, the scenario-based analysis demonstrated that renewable energy integration and coordinated energy sharing significantly improved territorial self-sufficiency under optimized REC configurations. The geospatial modelling approach also enabled the identification of suitable renewable deployment scenarios while considering environmental and territorial constraints. The results indicate that the integration of energy modelling, digital monitoring systems, and spatially explicit planning tools provides an effective pathway for improving the operational performance, flexibility, and scalability of RECs. The proposed framework offers practical support for decentralized energy planning, distributed renewable energy management, and data-driven decision-making processes in future community-based energy systems.

Keywords: Renewable energy communities; Energy modelling; Distributed energy systems; Performance indicators and indexes; Self-consumption optimization; Energy performance assessment; Territorial energy planning; Demand-supply management; Renewable energy integration; Digital decision-support system

1 Introduction

The energy performance of territory is determined to a great extent by the energy policies adopted at the European level, as well as by the range of human activities that occur within the area, all of which inherently require energy.

Furthermore, access to renewable resources is influenced by the specific characteristics of the territory, including not only the availability of land but also its features, climatic conditions, and any existing constraints. Renewable Energy Communities (RECs) represent an emerging, bottom-up approach to the ongoing energy transition. Their objective is to foster collaboration among local communities, thereby enabling them to achieve greater energy independence by harnessing locally available renewable resources and facilitating the production, distribution, and exchange of clean energy. This sustainable territorial model places community members at its core, and it delivers benefits that extend beyond the energy dimension, such as local clean energy generation and self-sufficiency, to encompass broader economic, environmental, and social well-being. However, the transition to climate-neutral energy systems requires systemic transformations that integrate distributed resources, multi-actor participation, and data-driven decision-making processes. In this context, RECs emerge as operational nodes of decentralization, as they can enable local energy flows to be optimized within distributed systems [1, 2]. RECs are structural components of decentralized energy systems, and they play a key role in simultaneously improving efficiency, resilience, and sustainability [3]. From a technical point of view, RECs support prosumer-based configurations that improve supply-demand balances, increase self-consumption, and enable demand-side management strategies, and they therefore directly contribute to the flexibility and efficiency of the system. This makes them particularly relevant for integration into smart grid architectures [4]. In addition to their environmental benefits, RECs generate quantifiable, socio-economic impacts—cost reductions, local value creation, and the mitigation of energy poverty—which can be assessed through such key performance indicators (KPIs) as self-sufficiency, renewable shares, and avoided emissions [5]. However, their effectiveness depends on the spatial and regulatory variables. The integration of geographic information system (GIS) tools allows territorial constraints, the availability of resources and infrastructural configurations to be incorporated in optimization processes, thereby highlighting the centrality of place-based approaches [6]. In this framework, RECs can be modelled as local energy hubs within multi-objective optimization frameworks are capable of balancing environmental, economic, and technical performances in an integrated way. Despite this, there is still a limited integration of spatial analysis, energy modelling, and the socio-economic dimension. This gap highlights the need for unified frameworks based on multi-dimensional KPIs [7]. In Italy, the transposition of Renewable Energy Directive II (RED II) [8], through Legislative Decree 199/2021, has established an enabling regulatory framework for the development of RECs. However, a gap persists between regulatory maturity and the effective implementation capacity of such RECs. The main challenges to the implementation of this framework include the lack of uniformity in authorization procedures, the saturation of grid infrastructures, which affects more than 40% of the primary substations, and the complexity of the energy data management procedures [9]. Additional constraints are related to the cybersecurity requirements, compliance with the General Data Protection Regulation [10], and to broader issues of digital resilience. Thus, the territorial distribution of RECs remains uneven, with a higher concentration in Northern and Central Italian regions, while Southern regions still exhibit a significant untapped potential [11]. In this context, geospatial tools can play a strategic role in supporting planning processes and in identifying optimal configurations at the local scale. A substantial growth—up to approximately 3,500 RECs and 450 MW of installed capacity—has been projected by 2026, on condition the infrastructure bottlenecks are overcome and both the technical and managerial capacities are strengthened [12]. The 2024–2025 period witnessed a phase of acceleration, with more than 1,800 active configurations and 174.5 MW of installed capacity; however, these figures remain below the targets set by the National Recovery and Resilience Plan [13]. RECs are complex systems that require advanced digital tools for their design and management. Multi-scalar simulation, predictive algorithms, and artificial intelligence enable energy scenarios to be modelled and the production, consumption, and storage to be optimized [14]. The multi-actor structure of RECs and the variability of renewable sources require decision support tools (DSTs) that are capable of integrating technical, economic, environmental, and social parameters. DSTs can be used to support scenario evaluations, system optimizations, and impact assessments by integrating spatial data, demand profiles, and regulatory constraints. They also improve transparency and inclusiveness in decision-making [14]. At the territorial level, the integration of RECs and DSTs enables energy self-sufficiency to be achieved, dependence on centralized systems to be reduced, and local resilience to be enhanced [15]. ENEA has developed the Smart Energy Communities (SEC) platform [16], an integrated and modular ecosystem that supports the full REC lifecycle, that is, from planning to operation. The platform integrates design, simulation, monitoring, and modelling of energy flows. The SEC platform includes modules for territorial planning (geoCER), techno-economic analysis (Recon), user engagement (smart SIM), residential energy optimization (Dhomus), digital twin simulation (Simul), and Local Token Economy (LTE) models [17]. The contribution and novelty of this paper is to present different key aspects in analysing RECs with these three modules: geoCER, which is used for modelling and planning renewable energy systems and RECs at a territorial scale, Dhomus, for load optimization and self-consumption, and LTE, for promoting environmental, economic, and social benefits within RECs.

The REC system in Italy is currently undergoing a progressive transformation, in terms of stakeholder composition, which is characterized by an increasing participation of private companies and Energy Service Companies, alongside the persistent social function of cooperatives and third-sector organizations [15]. In parallel, remote self-consumption schemes enabled by digital platforms, which are commonly referred to as cloud-based models, are expanding, thereby allowing distributed users to be aggregated at the national scale and procedural barriers to REC participation to be reduced [8]. The integration of RECs with decision-support tools (DSTs) represents a critical enabling factor for the achievement of territorial energy self-sufficiency, which is achieved through an improved matching between localized renewable energy generation and demand profiles [12]. However, several limitations, including regulatory fragmentation, limited accessibility, the standardization of energy data, and insufficient interoperability among digital platforms, still constrain the large-scale implementation of such an integration [13]. These constraints highlight the need for the development of standardized, scalable, and user-oriented DST frameworks that are capable of supporting planning and operational decision-making processes. Overall, the coupling of REC configurations with data-driven tools can be considered a strategic pathway toward decentralizing energy systems which contributes to decarbonization targets, system resilience, and equitable energy access [1, 2]. A territorial energy performance is the result of interactions between energy policies, local demand patterns, and the availability of renewable energy resources, which are significantly influenced by the physical and climatic characteristics of the specific context [5]. Within this framework, RECs adopt a bottom-up approach to the energy transition, which enables local resources to be valorized, integrated models of sustainable development to be fostered, and combined energy, economic, and social benefits to be generated [4]. The tools analyzed in this study address the key barriers that currently limit the deployment of REC models in the Italian context. The relevant solutions include those that can be used to simulate energy self-sufficiency scenarios that are based on territorial-specific parameters, but, at the same time, support active user engagement in energy production and consumption management [14]. Such approaches are aligned with a medium- to-long-term perspective oriented towards resource circularity and the optimization of local energy exchanges. Case studies on the Region of Sardinia and the Municipality of Anguillara Sabazia (Lazio), which are presented in the following sections, demonstrate the applicability and effectiveness of these approaches under different territorial conditions and for different types of REC.

2 Indicators and Indexes Used to Measure the Performance of Renewable Energy Communities

Any indicators identified to monitor the performance of RECs should address the shared need to define an integrated monitoring system. This requires the selection of a common core set of indicators, scalable at the territorial level, which are capable of ensuring coherence among different sustainability strategies across different spatial scales. In this framework, territorial strategies (pertaining to areas without any borders) play a key role in assessing any contributions that are made toward the achievement of national sustainability objectives.

Such an approach entails the necessity of aligning with the integrated monitoring system of the National Strategy for Sustainable Development (Strategia Nazionale per lo Sviluppo Sostenibile, SNSvS) [18], which evaluates, through a common and territorially scalable set of indicators, the contribution of local contexts to the implementation of the SNSvS. Indeed, pursuant to Article 34 of Legislative Decree 152/2006, which was subsequently amended and supplemented, SNSvS constitutes the national reference framework for environmental programming and evaluation processes at a territorial scale.

The current SNSvS includes a shared core of context indicators, which are structured in two levels [19]: first-level indicators [20]—comprising 55 indicators associated with National Strategic Choices (Scelte Strategiche Nazionali, SSN)—and second-level indicators—comprising 190 indicators that are used to monitor National Strategic Objectives (Obiettivi Strategici Nazionali, OSN). These indicators are embedded in an integrated monitoring system that is based on a common territorially scalable set, and they are closely linked to Equitable and Sustainable Well-being (Benessere Equo e Sostenibile, BES) indicators [21], whose aim is to assess societal progress, not only from an economic perspective, but also in social and environmental terms, and with the ISTAT SDG indicators (identified to play and with the ISTAT SDG indicators (identified to play an active role in the production of statistical measures for monitoring progress towards the Sustainable Development Goals, as required by the United Nations Statistical Commission).

A comparative table is proposed in the Appendix of this work to consider the key categories that are necessary to assess the performance of RECs and to select the indicators from SNSvS (highlighting the energy-related ones), as well as the synergies with the selected SNSvS objectives and strategic choices that are aligned with the SDGs. The main drivers of SNSvS for the sustainable development of the Italian territory are highlighted in the second column: People, Prosperity, Planet, and Partnership; "Peace" is also included in SNSvS, but no peace indicators have been identified for RECs. The data source is also indicated in the fourth column for each indicator. From this table the main categories of KPI for the REC are identified.

The KPIs for RECs can be used to assess the feasibility across the energy, economic, environmental, and social dimensions, while also ensuring their sustainability over the short, medium, and long term within a given territory [22, 23]. These KPIs typically vary according to which stakeholders are involved, and they can include such REC members as citizens, private companies, public entities, policymakers, service providers, and local or national authorities. Furthermore, REC participants may assume different roles, that is, as consumers, producers, or prosumers, that is, members that both consume and generate energy. Energy-related KPIs play a central role in guiding the assessment process. The core metrics primarily encompass such indicators as self-consumption, self-sufficiency, energy savings, and reductions in greenhouse gas (GHG) emissions. At the same time, these energy indicators are closely interconnected with economic, environmental, and social impacts, all of which should be systematically evaluated. The most relevant KPIs for RECs are summarized in Table 1. Formulas are provided for each indicator/index to enable the measurement of the energy, economic, environmental, and social performance of RECs.

Table 1. KPIs and indexes used to evaluate the energy, economic, environmental, social and governance performances of RECs

Category	Key Performance Indicators and Indexes	Formulas
Energy Performance	Self-consumption, SC (kWh): the amount of clean energy production (P) that is instantaneously consumed (C) by a prosumer.	$SCprosumer = \min(C, P)$
	Collective self-consumption, cSC (kWh): the amount of clean energy that is surplus-produced (SP) by the single members and shared with other members to meet any uncovered demand (UD) of the REC.	$cSC_{REC} = \min(UD, SP)$
	Self-Consumption Index, SCI (-): the quota of self-consumed energy to total production (P).	$SCprosumer = \frac{SC}{P}$
	Collective Self-Consumption Index, $cSCI$ (-)	$cSCI_{REC} = \frac{SC+cSC_{REC}}{P}$
	Self-Sufficiency Index, SSI (-): the quota of self-consumed energy to total consumption (C).	$SCprosumer = \frac{SC}{C}$ $SSI_{REC} = \frac{SC+cSC_{REC}}{C}$
	Energy saving, ES, by REC members (kWh).	$ES = SC + cSC_{REC}$
	Surplus production, SP (kWh): the excess of energy produced.	
	Energy Surplus Index, $ESurplus$ (-): the quota of excess energy produced.	$ESurplus = \frac{SP}{P}$
	RES Capacity, Cap_{RES} (-): the amount of actual RES production to the maximum RES production scenario.	$Cap_{RES} = \frac{P_{\text{actual}}}{P_{\max}}$
	Operational time, t_{op} (h): the amount of time the REC is operational in self-consuming/sharing energy mode.	$t_{op} = \frac{t_{SC,cSC}}{t_{\text{total}}}$
Economics Feasibility	Expenditure, Exp (€): the amount of expenditure on RES or energy efficiency investments.	
	Net Present Value, NPV (€): is the difference between the present value of cash inflows and outflows over a period of time t (i is the discount rate).	$NPV = \sum_t \frac{\text{Net Cash Flow}_t}{(1+i)^t} - CapEx$
	Payback Time, PBT (year): the number of years necessary to recover the expenditure in RES or energy efficiency measures.	$PBT = \frac{Exp}{\text{Annual Net Cash Flow}}$
	Cost of Electricity withdrawn (€/kWh): the cost of energy withdrawn from the grid.	
	Price of Electricity produced by RES and sold to the grid (€/kWh): the price of energy produced by RES.	
	Economic Benefit: reduced energy costs (or reduction in energy bills) for REC members.	
Environmental Impact	Carbon Emission Reduction (tons $CO2_2$): GHG emissions saved.	$UHI = T_{\text{urban}} - T_{\text{rural}}$
	Renewable Energy Penetration: reduction in fossil fuel dependency.	$SUHI = LST_{\text{urban}} - LST_{\text{rural}}$
	Reduction in UHI effects (-): reduction in UHI–$SUHI$ and/or $UHII$–$SUHII$.	$UHII = \frac{T-T_{\text{mean}}}{T_{\text{stdev}}}$; $SUHII = \frac{LST-LST_{\text{mean}}}{LST_{\text{stdev}}}$ where, T is the outdoor air temperature (°C), measured at local weather station; LST is the Land Surface Temperature (°C), from remote sensing satellite images.

Category	Key Performance Indicators and Indexes	Formulas
Social Impact	Community Engagement, Eng_{REC}: quota of families in the REC on the total number of families in the primary cabin area.	$Eng_{REC} = \frac{fam_{REC}}{fam_{\text{total}}}$
	Vulnerable Engagement, Eng_{vul}: quota of vulnerable families to the total number of families participating in the REC.	$Eng_{vul} = \frac{fam_{vul}}{fam_{REC}}$
	Energy-fuel poverty, $LIHC$ reduction: reduction (%) of families under energy-fuel poverty conditions.	$LIHC = \begin{cases} 1, & \text{if } (I_i - E_i) < PL_i \\ \text{and } E_i > \text{median}(E) & \\ 0, & \text{otherwise} \end{cases}$ where, I_i is the annual disposable household income, €; E_i is the household expenditure on energy services, €; PL_i is the relative poverty line, which is equal to 60% of the median national household income, €.
Governance Framework	Public Engagement, Eng_{pub}: quota of public members (Municipalities, Mountain Unions and/or public entities) in the REC.	$Eng_{pub} = \frac{\text{m}_{pub}}{\text{m}_{REC}}$
	REC Initiatives: number of educational initiatives about REC in a year.	

Note: KPI = key performance indicator; REC = renewable energy community; RES = renewable energy source; GHG = greenhouse gas; UHI = urban heat island; SUHI = surface urban heat island; LIHC = low-income-high-cost.

3 Tools for Renewable Energy Communities

This paragraph presents three tools that were developed within ENEA research activities to support the development of RECs through targeted digital solutions. These tools include DHOMUS [24], which was designed not only for energy monitoring and informed household energy management, but also to enhance user engagement and raise the awareness of energy consumption behavior, the LTE [25], which was designed to promote and reward energy-efficient behavior, and the geoCER geo-portal, which was designed for the planning of RECs at a territorial scale (CER is the acronym for RECs in Italian "Comunità Energetiche Rinnovabili"). Together with other tools developed by ENEA, these solutions provide an operational foundation for the fostering of the growth of RECs and the support of their evolution toward more advanced community-based energy models (Figure 1). The following sections describe the tools and present the selected application cases.

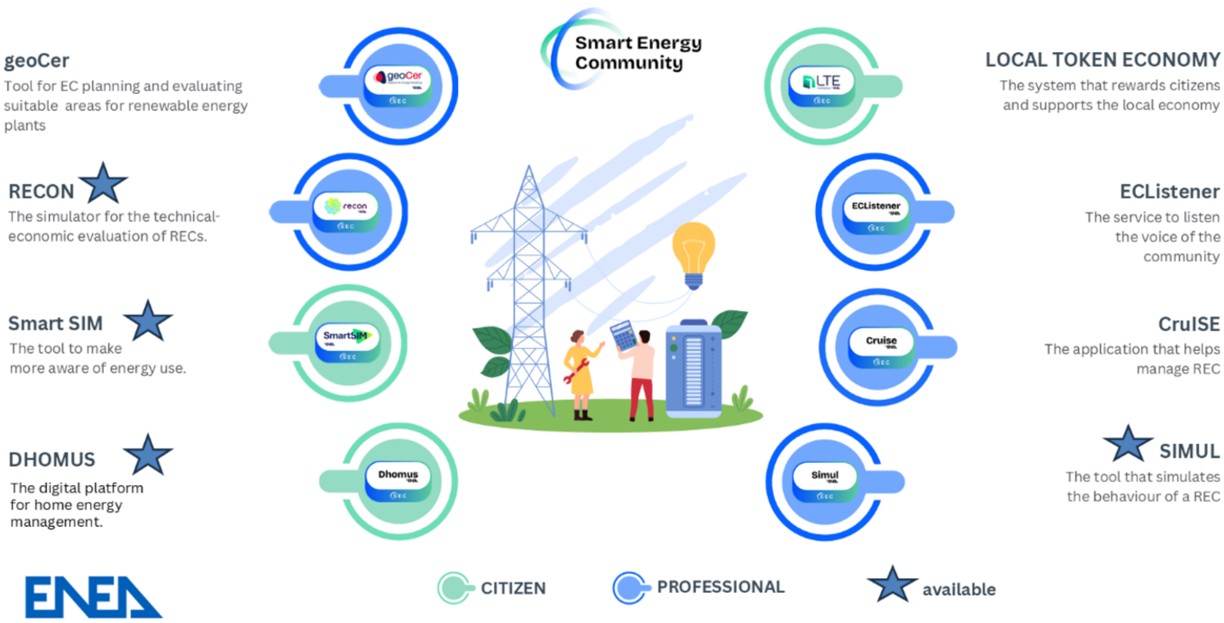


Figure 1. Digital tools on the Smart Energy Community (SEC) platform set up by ENEA, including DHOMUS, Local Token Economy (LTE), and geoCER

The description of these three tools for REC evaluation allows us to analyze how different users might be interested in performing different analyses, for local-territorial scales and based on economic, environmental or social benefits. This is the main contribution of this work and, at the same time, a limitation, as they are not the only tools for REC analyses.

3.1 DHOMUS

The DHOMUS platform is a digital infrastructure that was developed by ENEA to monitor and analyze residential electricity consumption [24]. The platform targets households equipped with devices and sensors that measure energy consumption and, where available, households with renewable energy generation and energy storage systems, and thus with the capability of transmitting data to a centralized platform.

Several connectivity solutions were tested during the development phase. Chain 2 devices are currently adopted, in particular for users that participate in energy communities. These devices acquire data directly from next-generation smart meters (Open Meter 2G), through power line communication, over the domestic electrical network, and they then transmit the data to the DHOMUS platform. The platform collects, synchronizes, and processes data from the connected households to provide informative feedback aimed at improving energy efficiency, awareness, and flexibility. It was designed to support advanced services for the flexible management and Demand Response of future developments. Access to the platform is provided through a dedicated web interface, which is compatible with desktop and mobile devices.

Users receive feedback that is calculated by algorithms that were developed by ENEA for load disaggregation, benchmarking, and energy profile analysis purposes. The objective is to make energy-related concepts and usage patterns visible and comprehensible, even to non-expert users. The user interface is structured in three main sections: D-ati, HOM-e, and US-er. The D-ati section allows real-time and historical energy data to be visualized, with different levels of temporal aggregation, depending on the household equipment. For prosumers, energy production data is presented across different time scales, providing an immediate and detailed overview of their energy behaviors. A real-time area chart displays consumption, production, self-consumption and grid withdrawals, highlighting daily variations and the dynamics between these components. Additional bar charts and real-time KPIs illustrate the relationship between self-consumed energy and energy fed into the grid. For consumption, the system indicates the proportion covered by self-consumption compared to grid purchases. This information enables users to assess their energy efficiency and encourages practices that increase direct self-consumption (SC) and overall self-sufficiency.

The HOM-e section enables installed devices and sensors to be visualized and interacted with. This section also includes a disaggregation of general consumption into end-uses and a calendar plot that highlights the peak consumption hours. Users can identify their highest consumption periods and the hours when load shifting might be required, in the context of demand response programs, by referring to color-coded cells.

The US-er section allows comparisons to be made with users that exhibit similar consumption profiles, thereby providing personalized feedback and encouraging energy-efficient behaviors through benchmarking mechanisms.

The DHOMUS platform, by integrating datasets from multiple users, operates as a monitoring and analysis tool for residential clusters, including collective self-consumers and RECs. As shown in Figure 2, the platform enables produced, self-consumed, and shared energy flows, the latter of which is incentivized under Legislative Decree 199/2021, as well as the hourly contributions of individual users, to be analyzed. These functionalities support demand optimization strategies and the promotion of consumption shifts toward periods with a higher renewable energy availability.

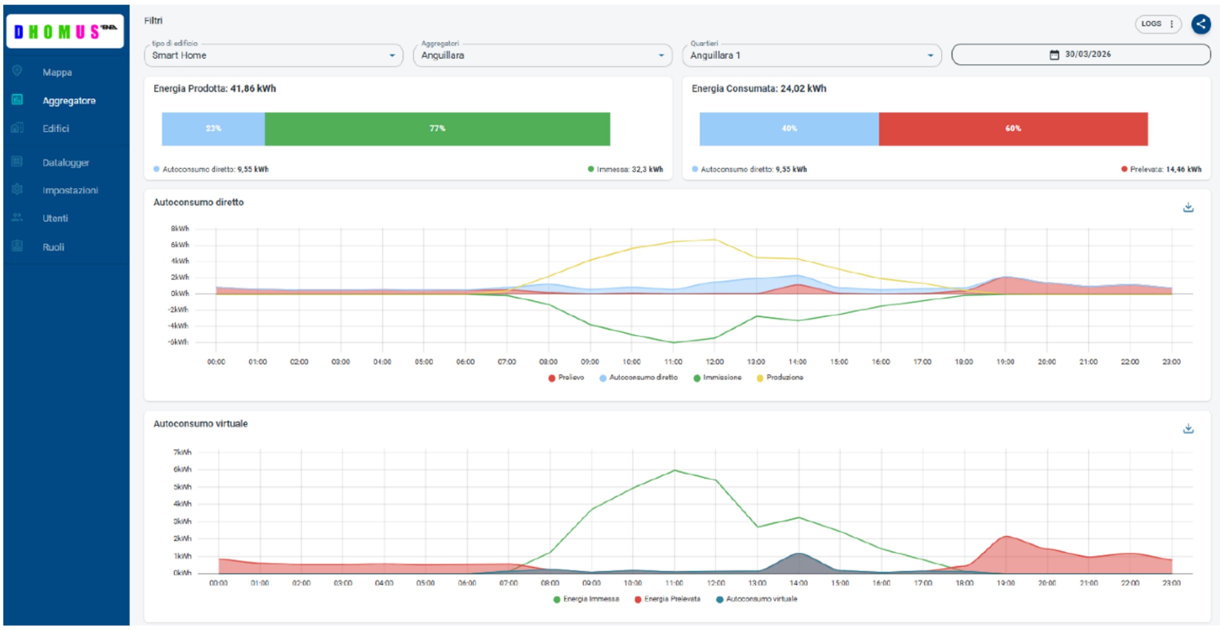


Figure 2. The interface is designed to aggregate Renewable Energy Community (REC) data and display the produced and consumed energy

3.2 Local Token Economy

LTE [25], which was developed by ENEA, is an innovative socio-technical platform that was designed to support SECs through the integration of blockchain technology, token-based incentives, and local digital marketplaces. LTE reframes energy from a purely physical commodity into a multi-layered driver of value creation, while operating simultaneously as a measurable resource, a digitalized asset, and a socio-economic coordination mechanism [26].

Energy is monitored, at the physical level, through distributed sensing infrastructures that enable the real-time tracking of production and consumption patterns and support demand-side management and self-consumption optimization via the Dhomus tool. At the digital level, the optimization algorithm transforms the energy data into tokens, and these tokens are added to a wallet that is based on blockchain technology and transformed into verifiable and exchangeable assets within a decentralized system. At the socio-economic level, LTE leverages tokenization to translate energy-related behaviors, such as renewable energy sharing, consumption reduction, and load shifting into economic rewards, thereby embedding energy performance within local value creation processes (Figure 3).

Thus, through this integrated approach, energy becomes the core coordination variable of the system, and it enables decentralized governance, peer-to-peer market interactions, and active user participation. Tokens function as a complementary local currency [27], and they foster circular economy dynamics [28], while reinforcing the link between energy efficiency and economic engagement.

The Smart Community pilot scheme conducted in Anguillara Sabazia, one of the first Italian cases of a blockchain-enabled energy community based on token economics, is an example of a practical implementation of LTE. In this context, users operate as prosumers, thereby actively participating in energy production, consumption, and exchange. The LTE platform links individual energy performance to economic incentives, in this way promoting efficient energy use, enhancing local energy sharing, and also offering the possibility of addressing energy poverty while strengthening social cohesion.

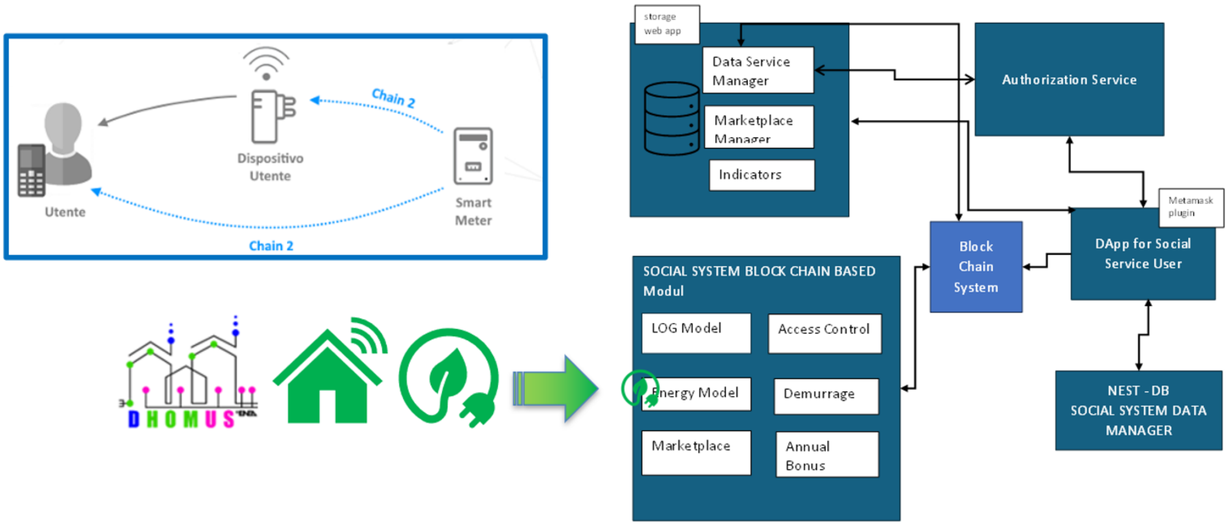


Figure 3. Diagram of the interaction between the Local Token Economy (LTE) tool modules and the user device utilized in DHOMUS

The Anguillara Sabazia pilot scheme implements an energy reward algorithm that has the aim of incentivizing a reduction of the peak demand. Eq. (1), through processes user-level data on energy injection and withdrawal, via API integration, and it evaluates the rewards considering the mitigation of the peak electricity demand from the grid.

$$Tcp = MT - \sum_{i=1}^{n}(kWci - kWpi - SC) \cdot t \cdot TkWp \tag{1}$$

where:

- Tcp is the number of tokens assigned for peak load control, token;
- MT is the maximum number of possible tokens, token;
- $kWci$ is the power engaged at a given moment i, kW;
- $kWpi$ is the power produced at a given moment i, kW;
- SC is the maximum allowable load threshold—A value that is set by the System or by an administrator, kW;
- $TkWp$ is a conversion factor that is used to transform the kWh that exceeds the peak into the number of tokens, token/kWh;
- t is the considered time interval, h; and
- n is the number of points (moments or measurements) of the production/consumption curves, -.

3.3 The geoCER Platform

A geoportal is currently under development, as part of the Program Agreement between the Ministry of the Environment and Energy Security and ENEA, related to Electricity System Research—Three-Year Implementation Plan 2025–2027, which was drawn up in collaboration with the Politecnico di Torino, to support the modelling and planning of RECs. This work is based on a previous research project [29].

The geoCER platform was conceived as an integrated platform to systematize the physical and environmental characteristics of a territory, as well as the energy needs and the potential for exploiting renewable sources at a territorial level. The adopted methodological approach combines a place-based perspective with multi-objective models to integrate energy, economic, environmental, and social dimensions within a single analytical framework.

From an operational point of view, the geoportal is based on the use of open-source Quantum Geographic Information Systems (QGIS) for the construction of spatially explicit databases and models at different scales (national, regional, provincial, municipal, and primary cabins). Figure 4 describes the main structure of the geoportal. The data collection mainly includes: the electricity consumption profiles, according to the types of users (domestic, primary, secondary, tertiary sectors); characterization of the available renewable energy resources; integration of the territorial and environmental variables (orography, climate), the building stock and the socio-economic conditions (demographic structure, vulnerability, and energy poverty). A qualifying element of the system is the construction of geo-databases (with geo-datasets and geo-packages) that refer to the conventional areas underlying the primary substations of the national electricity grid. This geoportal implements information on the territorial areas related to: electricity consumption, existing plants, current and potential productions from renewable sources, availability of energy resources, as well as technical, environmental, economic, and regulatory constraints and limitations in force. In addition, the analyses include the identification of the main renewable technologies that can be applied in the actual context. The technical specifications of the geoportal are being developed, in accordance with the standards in force pertaining to the interoperability of data, services and information, to ensure its integration with other platforms and operational scalability. The main output of the tool is the simulation of REC development scenarios, which are evaluated through an integrated set of energy, economic, environmental, and social indicators.

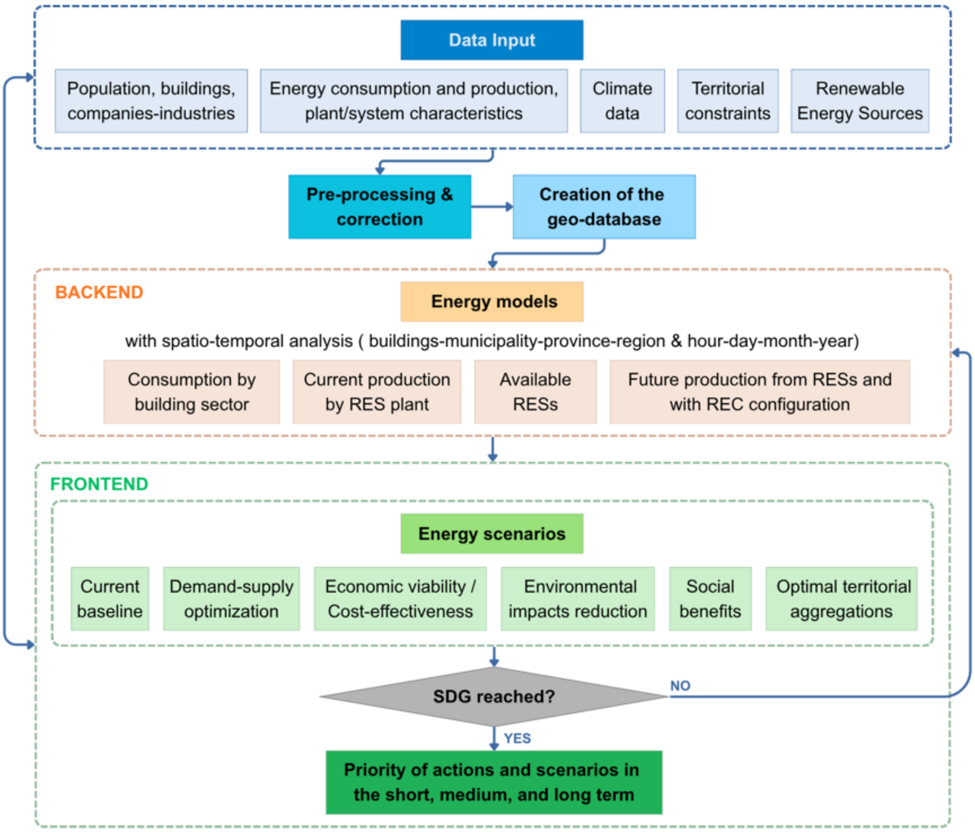


Figure 4. The main structure of the geoportal geoCER

4 Case Studies

Two case studies have been selected to describe the main features of ENEA tools for evaluating RECs. For DHOMUS and LTE a pilot REC has been selected in Anguillara. The same case study could not be used for the geoportal geoCER that performs analysis on a much larger territorial scale. For geoCER, that identifies the more suitable territories to host RECs, the Sardinia Region was selected. The reason for this choice is linked to the fact that Sardinia is a sparsely populated region with abundant renewable resources, making it a perfect location for RECs. However, care must be taken to preserve its landscape and environmental integrity.

4.1 The Anguillara Case Study for DHOMUS and Local Token Economy

The DHOMUS platform was used to monitor and analyze the energy flows of the Renewable and Solidarity Energy Community of Anguillara in real time [16]. This REC, which arose from a collaboration between local stakeholders, can be considered as a useful demonstration project to validate innovative models of shared energy management, and it has addressed social, environmental and ethical aspects. Table 2 summarizes the characteristics of the users that were initially involved in the trial.

The monitoring of the electrical data of the users' dwellings was carried out employing devices based on Chain 2 technology, in accordance with the relevant technical standards [30, 31]. This architecture enables parameters to be acquired and transmitted to the DHOMUS platform in a standard data format that was designed to ensure interoperability between the various monitoring tools and platforms. The monitored parameters are: Active Energy Withdraw, Active Energy Fed-in, and Active Energy Produced.

Table 2. Characteristics of users who participated in the trial

ID User	Number of Occupants	Photovoltaic System Power (kWp)	Storage Battery Capacity (kWh)
1	2	6.00	-
2	2	3.20	5
3	3	4.80	-
4	2	6.00	-
5	2	-	-
6	1	-	-
7	2	3.45	-
8	3	-	-
9	1	3.00	-
10	3	-	-

The data collected by the platform were processed to calculate the total energy consumption of the community users. Figure 5 shows the energy balance of the Anguillara REC for 2025, on a month-by-month basis, and highlights the energy that was fed into the grid, which is shown as a negative value on the y-axis, and the energy that was consumed, with the positive values being broken down into energy consumed directly, shared virtually, and purchased from the grid.

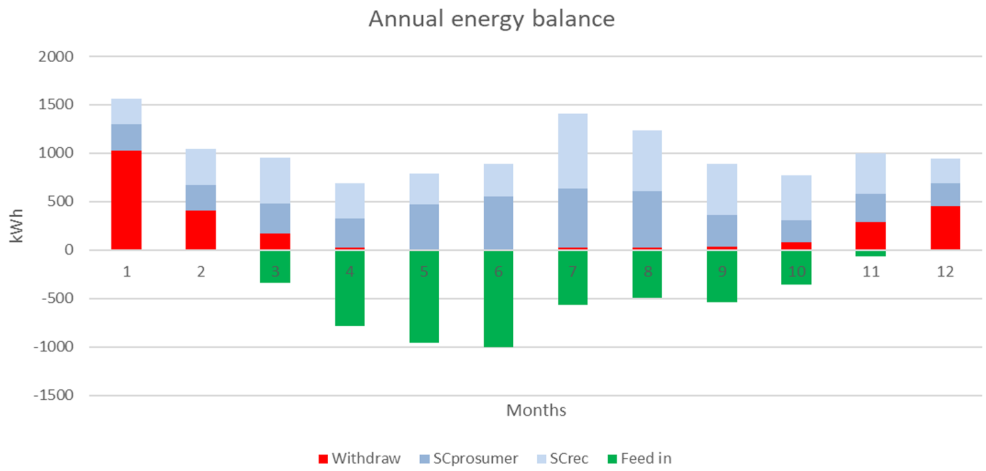


Figure 5. Energy balance of the Anguillara Renewable Energy Community (REC) for 2025

Table 3. Key performance indicators (KPIs) calculated for the Anguillara Renewable Energy Community (REC)

KPIs	Prosumer	REC
Self-Consumption Index, SCI	30%	65%
Self-Sufficiency Index, SSI	36%	79%
Energy Surplus Index	70%	35%

Moreover, the KPIs were compared to analyzing the energy behaviors of the individual users and to assess their evolution within the REC. The first considered indicator was direct SC, which represents the share of energy immediately used by the prosumer at the time of production and provides a direct economic benefit by avoiding grid charges, excise duties, and system fees. The second indicator, that is, collective self-consumption (cSC), was then introduced to account for the energy shared among community members. According to the current regulations, this shared quota entitles participants to GSE incentives and to the reimbursement of part of the grid charges [32].

The values reported in Table 3 show a clear improvement in performance within the RECs configuration. The SCI increases from 30%, for the individual prosumer, to 65% in the community, while Self-Sufficiency rises from 36% to 79%, thus indicating a substantially higher ability to meet the energy demand through internal production. Moreover, the Energy Surplus Index decreases from 70% to 35%, thereby reflecting a more efficient use of the energy produced within the community. This reduction indicates that a small share of energy remains unused, but it also highlights the presence of an operational margin that allows new users to be integrated, thereby supporting the internal absorption of the entire renewable energy production. As such, the indicator becomes a key KPI for strategic decision-making related to resource planning and the potential integration of new members, thereby ensuring that any future expansion will not compromise the community energy balance. Overall, the synthesized KPIs demonstrate that participation in the energy community significantly enhances both SC and self-sufficiency, thereby improving the valorization of locally produced renewable energy and the associated economic benefits.

Interoperability with the LTE platform is ensured through an exchange of data at a 15-minute temporal resolution. Such operability is a prerequisite for the activation of value-added services and participation in flexibility markets.

The Anguillara Sabazia pilot scheme represents an early-stage implementation of the LTE framework within a relatively small and localized community. The system currently primarily supports the exchange of services among participants through tokens generated for virtuous energy behaviors, such as the optimization of self-consumption and the reduction of the peak demand. This configuration highlights the role of LTE as an enabling infrastructure for local energy-driven economies, where value circulation is directly linked to energy performance.

To date, the community has issued approximately 4400 tokens, thereby reflecting a still limited but operational level of economic activity (Figure 6). The scale of token circulation is constrained by the size of the user base, and by the relatively narrow range of available goods and services. As a result, the system currently functions more as a complementary exchange mechanism than as a fully developed local market.

Anguillara Member Wallet details:	4417 Token			
Block number	**Sender Wallet**	**Token**	**Data Transaction**	**Activity**
163	xxxxx	10	20/01/2026 15:21	Community Service Payment
150	xxxxx	2	30/10/2025 12:22	Environmental Bonus
150	xxxxx	1	30/10/2025 12:22	Community fee
143	xxxxx	2	10/10/2025 12:58	Community fee
143	xxxxx	3	10/10/2025 12:58	Environmental Bonus

Figure 6. Community Manager Dashboard showing the community wallet and some transactions

Several critical challenges have emerged during the pilot phase. First, user engagement and continuity of participation have proved to be key factors that influence the vitality of the token economy, particularly in a small community where network effects are inherently limited. Second, the diversification of services and use cases remains a constraint, as a restricted offer reduces the attractiveness and utility of the tokens. Third, the cognitive and technological complexity associated with understanding both the energy-related metrics and token mechanisms has introduced barriers to adoption for some users. Finally, the alignment between energy performance indicators and perceived economic value is still evolving, and careful calibration of the reward algorithms is therefore required to ensure fairness, transparency, and sustained motivation.

Despite these limitations, the Anguillara Sabazia case provides valuable insights into the practical deployment of LTE, and it demonstrates the potential of activating localized value loops rooted in energy behaviors. At the same time, it underscores the importance of scaling strategies, user-centric design, and ecosystem diversification to enhance the robustness and long-term viability of token-based energy communities.

4.2 The Sardinia Region Case-Study for geoCER

This section presents an example of a pre-feasibility analysis on RECs for the Sardinia Region, which is a territory that is rich in energy resources and has a low population density, which makes RECs particularly attractive.

Sardinia is the second largest island in the Mediterranean, after Sicily, and it covers an area of approximately 24,100 km^2. It is located to the west of the Italian peninsula, between French Corsica and the Tunisian coast. Its capital is Cagliari, and its territory is divided into 4 provinces and the Metropolitan City of Cagliari, and it has 377 municipalities. Sardinia's climate can be classified as dry-mediterranean with sunny and windy peaks. Its coast extends for a total of about 1900 km, but more than 80% of the territory is mountainous, while 68% is made up of hills and rocky plateaus.

The Sardinia Region was divided into 83 primary cabins for the pre-feasibility analysis of RECs [33], but this work has considered the spatial detail of the municipalities as it is more precise. At the end of 2025, there were 52 RECs in Sardinia [33] (Table 4), that is, about 6% of the total number of Italian ones, and they were mainly concentrated in the Southern territories; these involved 422 members and 71 renewable systems, with an installed power of about 3700 kW.

The buildings were classified according to their type of use for the spatial analysis of energy consumption, as shown in Table 5; these data were obtained from the Sardinia Region geoportal [34]. The same classification of the buildings was used for the distribution of energy consumption as is used for all the Italian regions.

Electricity consumption was evaluated:

• For residential buildings: considering the number of dwellings/families, the building volumes in each census section [35], and the hourly profiles of the consumption of families by province [36].

• For non-residential buildings: considering the regional consumption [37], the volume of the buildings, and the number of employees per type of user.

The typology of buildings is represented in Figure 7 for the city of Olbia, as an example. It is possible to observe the presence of residential buildings (RL), schools (TS), industrial buildings (SP), and commercial (TC) buildings in the North-East areas. The hourly profiles of the typical monthly days were evaluated, considering the types of users and the dimensions of the buildings, and were then used for the calculation of energy indicators and indexes. Buildings were considered as territorial units for the analysis of the performance of the RECs with geoCER, while hours were considered as the temporal units.

Table 4. Number of Renewable Energy Communities (RECs) in the Sardinian provinces

Province	Number of RECs
Sassari	10
Nuoro	9
Oristano	5
South Sardinia	17
Cagliari	11

Note: The data refers to December 31st , 2025.

Table 5. Number and volume of the buildings in Sardinia

Classification	Number of Buildings	Total Building Volume (m^3)
R (Residential)	351,710	568,746,503
PA (Primary–Agriculture & Extraction)	80,532	52,832,060
SP (Secondary–Production & Industry)	12,825	56,949,457
TH (Tertiary–Healthcare)	8,467	20,954,020
TC (Tertiary–Commercial & Public Services)	7,883	29,609,651
TS (Tertiary–School)	1,873	12,922,359
TI (Tertiary–Intermittent Use)	1,101	5,014,146
Others	32,668	18,698,393

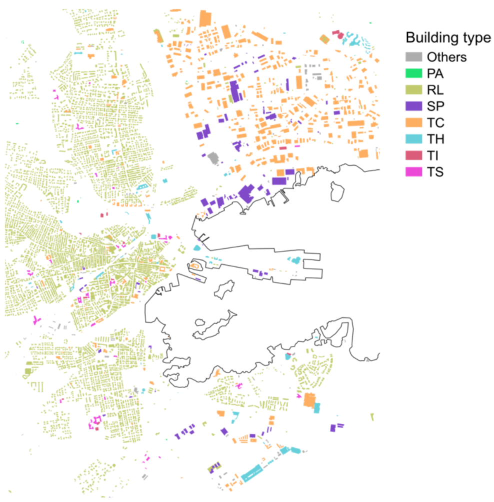


Figure 7. Representation of the building users in the city of Olbia

The results of the pre-feasibility analysis of the RECs were first organized considering the actual scenario with reference to the electrical consumption and production from renewable systems and plants. In a second step, the potential production for future plants was analyzed considering different scenarios. The aim was to produce and share clean energy where there was an energy demand. Indeed, RECs can be a way of increasing self-consumption and self-sufficiency, especially in high-density urban areas.

Figure 8 shows that the energy consumption of Sardinia is concentrated in the cities of Cagliari (with 972 GWh), Sassari (with 522 GWh), and Olbia (with 233 GWh). These cities are also the most heavily populated areas in Sardinia, even when considering summer tourism; the internal mountain areas consume much less energy.

Figure 9 shows the actual renewable energy production by province and by type of renewable: solar, wind, biomass, and hydroelectric. These data refer to July 2021 [38], and they were calculated once the installed power and the utilization hours of the existing renewables plants in Sardinia were known [39]. As it is possible to observe, the energy production from hydroelectric plants is very low, wind and solar resources are used in all the provinces, and the biomass production is also low, except for the city of Oristano, which has three biomass plants.

The territorial constraints were then considered to evaluate future scenarios in which the availability of renewable sources could be boosted. The main constraints (i.e., historical, cultural, agricultural, environmental, and landscape) are provided by Legislative Decree 175/2025 (Law 4/2026), together with areas that are not suitable for hosting renewable energy plants.

Six main solutions were proposed for future scenarios, whereby all the renewables from solar (with only roof-integrated systems), wind, and biomass (i.e., forest, agricultural and waste) sources were considered, as well as the sharing of energy within RECs. Table 6 shows the energy production that was considered for future scenarios. It can be observed that exploiting wind with onshore and offshore technologies is certainly one of the most promising solutions, when the landscape constraints are not included.

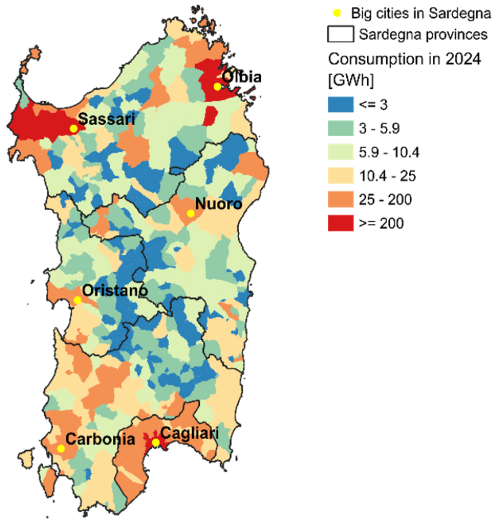


Figure 8. Actual energy consumption in the Sardinian municipalities

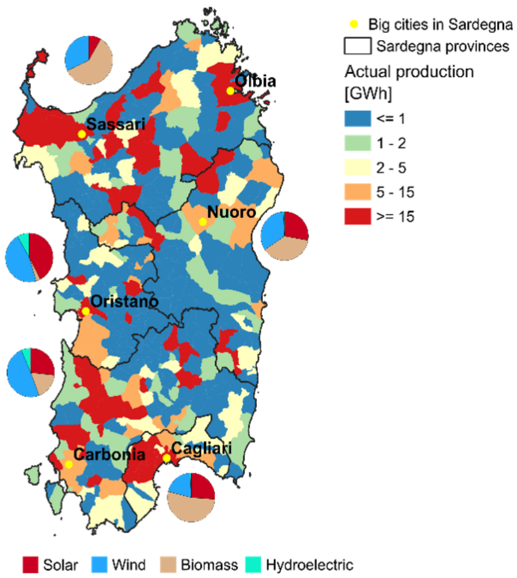


Figure 9. Actual energy production from renewables: Solar, wind, biomass, and hydroelectric in Sardinia

Table 6. Future energy production considering the constraints in Sardinia

Province	Solar Potential (GWh)	Wind Potential (GWh)	Biomass Potential (GWh)
Sassari	1891.23	35,773.29	106.54
Nuoro	1184.57	22,060.94	46.21
Oristano	1479.84	10,148.81	74.17
South Sardinia	3521.68	30,001.93	106.07
Cagliari	1834.17	2586.39	24.38

Starting from the baseline scenario, S0, the future scenarios are [40, 41]:

• Scenarios S1.1 and S1.2, consider the maximum electricity output to come from PV systems, but with a different level of constraint in historical city centers.

• Scenarios S2.1 and S2.2, consider the maximum electricity output to come from two different wind turbines.

• Scenarios S3.1 and S3.2, consider the maximum electricity output to come from biomass plants, with and without air quality limits.

• Scenario S4 includes RECs that consider the maximum PV production on residential buildings and the share of energy with the other types of buildings.

• Scenario S5 includes RECs that consider a maximum PV production of 25% for residential buildings and the share of energy with the other 75% of residential buildings.

• Scenario S6, considers the maximum electricity output to come from all the renewable plants and systems.

Table 7 shows the median results, in terms of self-consumption and self-sufficiency, of the scenarios analyzed. This data refers to the municipalities and pertains to the hourly production and consumption profiles of typical monthly days. As it is possible to observe, all the renewable production in the actual scenario is used for self-consumption (with SCI = 1), and self-sufficiency is lower than 0.1. Figure 10a shows the self-sufficiency of scenario S0, which has lower values than 0.1, especially in large cities where energy consumption is very high and renewable production is low. Only in Sassari is self-sufficiency higher than 0.8, because the city has powerful biomass, wind, and solar plants.

Table 8 shows the self-consumption and self-sufficiency indexes for the city of Cagliari. The actual self-sufficiency is 0.01, but 0.25-0.28 could be reached by considering the S4 and S5 REC configurations and by boosting all the renewables, as in scenario S6. Figure 10b shows self-sufficiency with PV for scenario S1.2, in which the median values reach 0.53 and 0.15 for the city of Cagliari. This can be explained by considering Figure 11a and Figure 11b, where the energy production with PV systems is totally consumed in winter and partially consumed in summer, and the self-sufficiency is 0.11 and 0.48, respectively, with an annual average value of 0.15.

Finally, Figure 10c shows self-sufficiency for scenario S6, where all the available renewables are boosted and 0.8 and higher values are reached; only the city of Cagliari, with its high energy consumption and low availability of renewables, remains below 0.3.

When the potential future production is boosted with renewables, only a quota of energy can meet the demand, while self-consumption decreases and self-sufficiency increases. The aim of the platform is to produce exactly what is needed, with higher self-consumption and self-sufficiency values, and the best solution could then be reached for REC with a good mix of renewables and different types of users with various profiles.

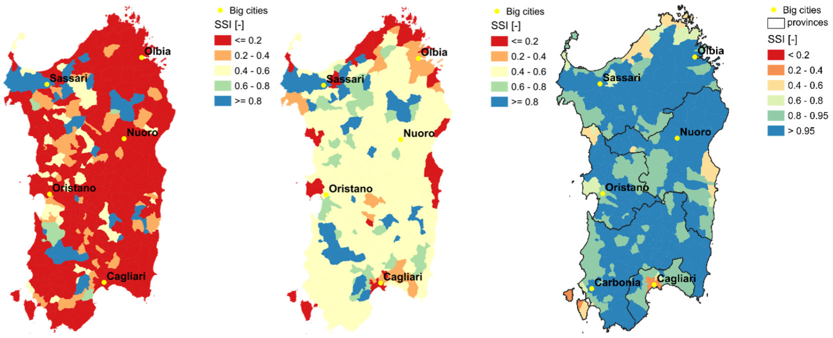
The problem in critical areas, such as large cities, can be solved through the sharing of energy between territories. The surrounding territories can share renewable energy with the city, and the city can share services, such as hospitals, high schools, and universities, as well as offering support for the governance of small municipalities. In this case, energy is exchanged between territories, which are no longer RECs and instead become renewable energy territories (RETs).

Table 7. Median Self-Consumption Index (SCI) and Self-Sufficiency Index (SSI) in the Sardinian municipalities

Scenario	SCI	SSI
S0	1.00	0.10
S1.1	0.20	0.53
S1.2	0.20	0.53
S2.1	0.05	0.88
S2.2	0.03	0.88
S3.1	1.00	0.28
S3.2	1.00	0.28
S4	0.20	0.52
S5	0.27	0.41
S6	0.03	0.96

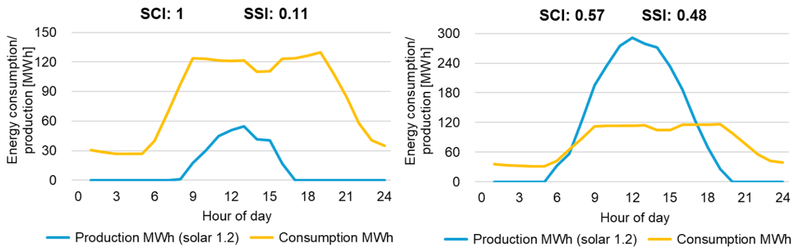
Table 8. Self-Consumption Index (SCI) and Self-Sufficiency Index, SSI in the city of Cagliari

Scenario	SCI	SSI
S0	1.00	0.01
S1.1	0.97	0.16
S1.2	0.98	0.15
S2.1	1.00	0.03
S2.2	1.00	0.04
S3.1	1.00	0.02
S3.2	1.00	0.02
S4	0.91	0.25
S5	0.80	0.28
S6	0.90	0.28



(a) (b) (c)

Figure 10. Self-sufficiency of the Sardinian municipalities: (a) scenario S0; (b) scenario S1.2; and (c) scenario S6



(a) (b)

Figure 11. Scenario S1.2 for the city of Cagliari: Comparison of photovoltaic (PV) production and consumption profiles for typical: (a) winter days; (b) summer days

5 Conclusions

This study provides an integrated and scalable framework that can be used for the design and evaluation of RECs. This framework demonstrates that the combined use of geospatial analysis, energy modelling, and digital platforms significantly improves the effectiveness of decentralized energy systems. The proposed methodology, which goes beyond fragmented approaches, allows a systemic representation of REC dynamics to be created, and the interactions between technical performance, spatial constraints, and user behavior to be captured. The results confirm that REC setups can substantially improve the alignment between local renewable energy generation and demand. The case of Anguillara highlights the crucial role of effective demand-side management and user involvement in increasing self-consumption and self-sufficiency, while the analysis of Sardinia shows that spatially explicit modelling is essential to identify feasible and optimized energy scenarios under heterogeneous territorial conditions. A key contribution of this work is the integration of digital tools as enabling infrastructures for the deployment of RECs. The combined use of monitoring platforms, GIS-based planning systems, and token-based incentive mechanisms supports not only technical optimizations but also the activation of socio-economic processes, thereby strengthening participation and local value creation. This dual technical-social perspective is essential to ensure the long-term sustainability of REC systems and their effective contribution to sustainability objectives. The case studies also highlight the centrality of scalability through the use of standardized and interoperable data frameworks, digital solutions, adequate infrastructures, and facilitative regulatory conditions. These factors highlight the need for the coordinated development of technical standards and governance models. Future research should focus on the integration of real-time data, predictive analytics, and artificial intelligence techniques to improve system adaptability and enable participation in flexibility markets. Further validation is also needed by considering larger and more diverse case studies. However, the proposed approach contributes to the advancement of REC modelling and offers a robust pathway toward resilient, decentralized, and sustainable energy systems.

Author Contributions

All authors contribute to the conceptualization, writing—original draft preparation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This work has been funded by Project 1.7 "Technologies for the efficient penetration of the electric vector in final uses" as part of "Electrical System Research" PTR 25-27.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

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Nomenclature

C	consumption, kWh
Cap	capacity, -
cSC	collective self-consumption, kWh
$cSCI$	collective self-consumption index, -
DST	decision support tool
Eng	engagement
ES	energy saving, kWh
$ESurplus$	index for surplus of production, -
Exp	expenditure, €
fam	families
GIS	geographic information system
i	discount rate, -
KPI	key performance indicator
$LIHC$	low income high cost, -
LST	land surface temperature, °C
m	number of members in a REC, -
NPV	net present value, €
P	production, kWh
PBT	payback time, year
PE	public engagement, -
PL	relative poverty line, €
REC	renewable energy community
RES	renewable energy source
SC	self-consumption, kWh
SCI	self-consumption index, -
$SUHI$	surface urban heat island effect, °C
$SUHII$	surface urban heat island intensity, -
SP	surplus of energy production, kWh
SSI	self-sufficiency index, -
t	time period, hour-year
Δt	time interval, h
T	air temperature, °C
T_{cp}	number of tokens, -
UD	uncovered demand, kWh
UHI	urban heat island effect, °C
$UHII$	urban heat island intensity, -

Subscripts

pub	public
vul	vulnerable

Appendix

Table A1. Main relations between the SDGs, strategic choices and objectives of the National Strategy for Sustainable Development (SNSvS), and a selection of indicators/indexes to evaluate the performance of RECs

SDG AGENDA 2030	National Strategic Choices	National Strategic Objectives	Categories of indicators for RECs
1 NO POVERTY 16 PEACE, JUSTICE AND STRONG INSTITUTIONS	**People** I. To combat Poverty and Social Exclusion by Reducing Territorial Disparities	I.1 To reduce the intensity of poverty, and of economic and social disparities I.3 To reduce housing deprivation	Social Aspects
8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	**Prosperity** I. To promote Sustainable Economic Well-being	I.1 To ensure the vitality of the productive system I.2 To ensure economic well-being and an equitable distribution of income	Economic Feasibility and Social Impact
7 AFFORDABLE AND CLEAN ENERGY 13 CLIMATE ACTION 11 SUSTAINABLE CITIES AND COMMUNITIES	**Prosperity** VI. To reduce GHG Emissions and Decarbonize the Economy **Planet** II. Ensure sustainable management of natural resources III. To create resilient communities and territories, and to protect landscapes and cultural heritage	VI.1 To reduce energy consumption and improve energy efficiency VI.2 To increase renewable energy production, while avoiding or limiting impacts on cultural heritage and landscape VI.3 To reduce GHG emissions II.2 Achieve net land-use neutrality and combat land degradation and desertification II.4 Implement integrated water resources management at all planning levels III.1 To promote territorial stewardship and maintenance, and to strengthen the resilience capacities of communities and territories, including those pertaining to the impacts of climate change III.2 To regenerate cities and ensure accessibility	Energy Performance and Environmental Impact
12 RESPONSIBLE CONSUMPTION AND PRODUCTION 16 PEACE, JUSTICE AND STRONG INSTITUTIONS	**Prosperity** IV. To promote Sustainable Production and Consumption Patterns and **Partnership**	IV.3 To promote social, environmental, and human rights responsibility within public administrations and enterprises, including those pertaining to sustainable finance.	Energy Performance and Governance Framework

Table A1 (continued)

SDG AGENDA 2030	Integrated Monitoring Indicators for the National Sustainable Development Strategy SNSvS (with data source)
1, 16	1.2.1 Incidence of absolute individual poverty (% of people living in households in absolute poverty compared to the total residents) –source: ISTAT 10.2.1 Percentage of people living in households with an equivalized disposable income below 60% of the median income –source: ISTAT 7.1.1 People unable to afford adequate home heating – NSO indicator –source: ISTAT
8, 9	8.1.1 Annual growth rate of the real GDP per capita –source: ISTAT 10.1.1 Net income inequality (S80/S20 ratio) –source: ISTAT 10.1.1 Adjusted gross disposable income per capita –source: ISTAT
7, 13, 11	7.3.1 Energy intensity –source: ENEA; Total energy consumption by primary source – NSO indicator –sources: ISPRA; National Energy Balance; Gross final energy consumption –NSO indicator –source: GSE 7.3.1 Energy intensity in the residential (NSO indicator –source: Eurostat), services, and industrial (NSO indicator –source: ENEA) sectors 7.2.1 Share of energy from renewable sources in the final gross energy consumption –source: GSE 7.2.1 Renewable energy consumption in the thermal sector – NSO indicator –source: GSE 7.2.1 Electricity generated from renewable sources –source: Terna S.p.A. 7.b.1 Installed net renewable energy generation capacity – NSO indicator –source: ISTAT 7.2.1 Share of energy from renewable sources in the final gross energy consumption – NSO indicator –source: GSE 13.2.2 CO_2 and other GHG emissions –source: ISPRA 13.2.2 Total GHG emissions, according to the national atmospheric emission accounts (tons CO_2 equivalent) – NSO indicator –source: ISTAT 15.3.1 Soil sealing by artificial cover –OSN indicator – ISPRA data source 11.3.1 Soil sealing and land consumption per capita – OSN indicator –ISPRA data source Land degradation – OSN indicator –ISPRA data source 11.7.1 Share of urban green areas over the built-up surface of a city –source: ISTAT Primary expenditure on environmental protection and for the use and management of natural resources, with reference to biodiversity –source: ISPRA 11.3.1 Illegal building activities –source: CRESME 13.1.1 Global mean temperature anomalies – NSO indicator –source: ISPRA Urban Heat Island and Surface Urban Heat Island effects –source: EEA SDI - geospatial data catalogue
12, 16	12.5.1 Separate collection of urban waste –source: ISPRA 17.2.1 Official Development Assistance as a share of the gross national income –source: ISTAT

Note: Threshold values of REC indicators and indexes can be found in the study [42].