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ENEA's Approach and Technologies for the Development of Smart Energy Communities in Italy

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Abstract: The implementation of certain European Union (EU) directives into Italian national legislation through several legislative decrees has catalyzed the establishment of energy communities in Italy. In this context, Energy and Sustainable Economic Development (ENEA), in its capacity as a public research body, has developed a model of support aimed at facilitating the involvement of national stakeholders in the formation of energy communities. Smart Energy Communities (SECs), representing the evolution of both energy and smart communities, are seen as a convergence of these paradigms and as an enhancement of their proactive components. This study examines several technological solutions proposed by the ENEA model, which are instrumental in supporting the advancement of SECs. It also provides an overview of the key tools—either operational or under development—designed to fulfill the objectives of the model. The ENEA model places particular emphasis on fostering citizen engagement in energy-related matters, as well as on evaluating the progress of energy communities through both energy-specific metrics and broader social and environmental considerations. Through these innovations, the role of SECs as drivers of local energy transitions is reinforced, ensuring that the socio-economic and environmental benefits extend beyond the mere technical infrastructure of energy systems.

Keywords: Energy communities; Renewable resources; Energy; Tools; Management; Blockchain; Local economy; Citizen engagement

1 Introduction

Although the rules of the game are now defined and play a leading role in the new energy scenarios, Renewable Energy Communities (RECs) are still characterized by an alternation of lights and shadows, enthusiasms and perplexities, certainties and fears, as well as a multiplicity of doubts that are not always adequately and/or satisfactorily answered. Several challenges are in place on complex and evolving regulation, technological aspects, community engagement and sustainability.

The RECs extend the audience of players to citizens involved in the energy transition, placing them in an active and central role in the process of leading the country towards decarbonization and radical change in the way energy, goods and services are produced, managed and used. Therefore, representing a great opportunity for the Italian energy system and for citizens, the REC requires the willingness to share energy, data and energy needs, i.e., a cultural leap towards greater sociality and open-mindedness.

The energy community paradigm aims at leading the Italian local context to evolve towards a community capable of managing the resources of its territory by raising awareness and sharing energy sources. Nevertheless, the time is ripe for the spread of RECs in the national territory following the completion of the regulatory framework, i.e., the implementation of EU Directives 2001/2018 [1] and 944/2019 [2] into Italian national legislation through Legislative Decrees 199/2021 [3] and 210/2021 [4], the Integrated Text on Widespread Self-consumption (TIAD) released by the ARERA, which is the regulatory authority for energy networks and the environment [5], and the implementation decree by the Ministry of the Environment and Energy Security (MASE) [6]. Focusing on the community aspect in Italy, it is clear that many citizens and local administrations are not fully aware of the benefits of energy communities. Engaging different stakeholders (private individuals, public entities, companies, and local governments) and balancing different interests can be complex. In addition, resistance to change and unfamiliarity with energy-sharing models can slow adoption.

ENEA's tools and services for the Critical Infrastructures and Renewable Energy Communities (ICER) Division aim to foster the energy communities and examine their implementation and operation by offering specific solutions, analyzing strategic data and developing enabling paths and standards. The Division supports local institutions in defining the technical and technological aspects aimed at promoting and disseminating RECs and promotes activities to facilitate the exchange of experiences and the transfer of good practices. ENEA's vision is to drive a dual transition that redefines the concept of energy communities. This involves evolving from traditional energy communities and focusing on integrating energy and digital tools to move towards the innovative vision of SECs. In this new model, energy systems are not only interconnected with digital technologies but also deeply embedded within the social elements of the community.

The SEC concept [7] emphasizes the active role of citizens as central participants in a comprehensive ecosystem of services. These communities go beyond energy production and consumption to address broader societal needs, fostering collaboration, sustainability, and resilience. By combining energy efficiency, digital innovation, and social inclusivity, ENEA aims to empower individuals to shape their communities, ensuring that energy transitions are not only technological but also human-centric and locally driven. The route starts with RECs as an enabling factor for the development and implementation of SECs on the active participation of citizens and the development of local economies based on the sharing of goods and services (sharing economy) in the logic of a stronger participation and expression of people in the processes of social transformation.

Within the RECs and the main challenges in place in the Italian scenario, the ICER Division is responsible for:

- Promoting the spread of energy communities;
- Examining the implementation and fostering the operation (by offering specific solutions);
- Analyzing strategic data;
- Developing enabling paths and standards;
- Supporting institutions in defining the technical and technological aspects aimed at promoting and disseminating RECs;
- Promoting activities to facilitate the exchange of experience and the transfer of good practices.

2 The ENEA Model of SECs

ENEA's primary objective is to act as a technical-scientific advisor for the development of concrete REC initiatives in the territories (contextualization of the initiatives in relation to the prerogatives of the local area) and for the evaluation of their implementation process. The ICER Division also contributes to the creation of best practices for RECs in various regions and municipalities, i.e., three main pilot projects under development in North (Garda CER in the Lombardy Region), Central (Anguillara Sabbazia CER in the Lazio Region) and South (Portici CER in the Campania Region) of Italy. It proposes tailored models for public administrations and local stakeholders that integrate energy and digital transitions with territorial development and enhancement. In the context of RECs, the activities are split into three main aspects: digital tools to support RECs (Figure 1), REC pilot cases, and the REC observatory.

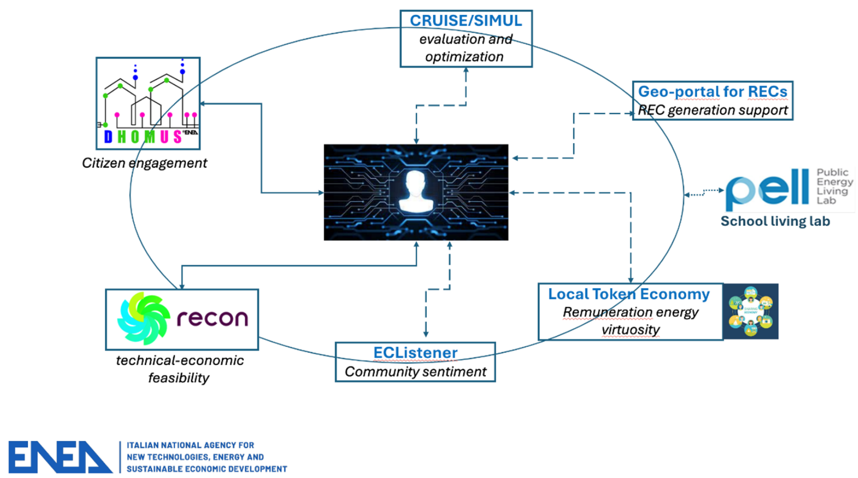


Figure 1. Digital tools supporting RECs

In the development trajectory towards SECs, the strategic positioning is to provide digital tools for the start-up, promotion and evaluation of RECs, leaving the management to market operators. In particular, the applications involve:

- A REC economic simulator (RECON) for technical-economic feasibility analysis and flexible and conscious management of residential users;
- Tools to support the engagement of end users and the energy management of their home, i.e., Smart Sim and data homes and users (DHOMUS);
- A dashboard for the evaluation and optimization of RECs by monitoring energy performance and through a digital twin of energy communities, i.e., CRUISE (a smart energy interactive dashboard) and SIMUL (a simulation tool for modelling the RECs);
- A tool to support and direct the generation of renewable energy for RECs in the national territory, i.e., a geo-portal for RECs;
- Service for SECs for the remuneration of energy virtuosity through tokens, i.e., Local Token Economy (LTE).

2.1 ENEA Digital Tools

In SECs, citizens represent the key element for the success of the initiative and have a positive impact on the quality of the environment. The starting point of the engagement of citizens is the stimulation of their interest and the increase of the awareness about energy issues.

2.1.1 ENEA DHOMUS

Whit this objective of citizen engagement, ENEA has developed two tools, Smart Sim and DHOMUS, targeted at improving energy awareness, promoting the virtuous consumption of available resources and fostering the energy transition process. These tools are dedicated to citizens with different purposes. Smart Sim is a freely accessible web tool intended for anyone, while DHOMUS platform is reserved for users equipped with smart devices for the energy management of their house. Although there are different levels of detail in both cases, the user has visibility into his consumption and can receive personalized feedback and advice for increasing energy efficiency and lowering bill costs. These services are enabling tools for citizens to become an active part of the stability of the national electricity grid. That is, users are no longer simple "consumers" or "prosumers", but can increasingly play a key role in the geographical contexts in which their homes are located.

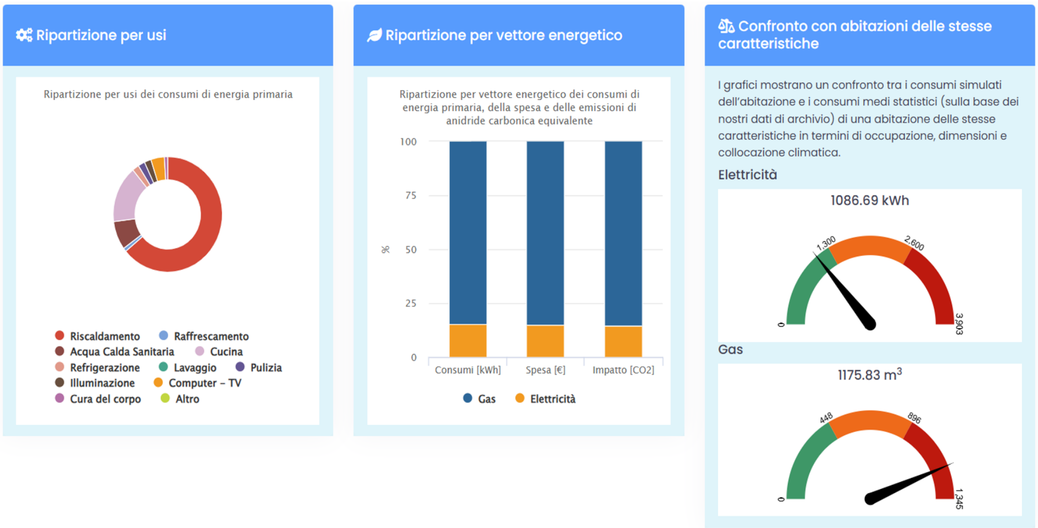
As shown in Figure 2, Smart Sim is a service freely available on the web, designed to provide suggestions on how to improve the use of energy in the house and, therefore, save on bill costs. It is the result of a collaboration between ENEA and the Research Center for Territory, Construction, Restoration and Environment (CITERA) and the Sapienza University of Rome. The user provides information by filling out an online questionnaire, including data about the house, the systems and appliances installed, energy behavior and the figures of the electricity and gas bills for the last year. The request for technical information is very limited in order to facilitate even not skilled people. During the filling procedure of the questionnaire, the user is supported by explanatory notes and pre-filled answers.

Once the questionnaire is completed, the user is able to carry out a self-assessment and obtain advice aimed at improving his energy performance. All this is made possible by the execution of a simulation in a simplified dynamic regime, which allows the estimation of annual consumption, both from electrical and thermal points of view based on the characteristics of the house. The comparison of the expected consumption with real consumption one deriving from bills generates a set of feedbacks available to the user through graphs and suggestions.

As shown in Figure 3, DHOMUS is a platform that collects data related to the homes of users who share their smart home data through smart devices enabled to communicate with the platform. The platform, therefore, collects this data, processes it and gives it a graphic display, aimed at providing educational feedback to the user himself, encouraging efficient and conscious energy management. In the future, this technology will enable the end user to participate in demand management programs so that he can optimize his energy demand according to the real needs of the grid, for example, by contributing to the reduction of peaks and providing flexibility services.

The added value of the DHOMUS platform, compared to other solutions available on the market, is to provide added services and personalized feedback to the citizen because of the processing of data from similar users, as well as algorithms developed by ENEA for the disaggregation of consumption, the benchmark and the analysis of consumption profiles.

Over the years, various experiments have been carried out using different commercial sensor solutions tested and integrated together through a gateway, the Energy Box, capable of communicating with the DHOMUS platform and transmitting all the data collected in houses or acquired directly from third-party clouds. The DHOMUS platform can be used via a web interface from any device that has internet access (e.g., a computer, smartphone, etc.): private data are available only for the user that generates them, but aggregated ones are used for creating knowledge and comparing different habits.



(a) (b) (c)

Figure 2. Smart Sim: (a) User feedback with the breakdown of their primary energy consumption in final uses (heating, household appliances, etc.); (b) Breakdown of consumption by type of energy vector, cost and relative environmental impact; (c) Comparison between their electricity and gas consumption with those of similar families

Figure 3. DHOMUS user interface: Real-time monitoring: Breakdown of energy into consumed, produced, withdrawn and fed into the grid, and self-consumed with different time references

A monitoring experiment of a fresh energy community is currently underway in the municipality of Anguillara Sabazia. In this experiment, the data are monitored in homes through a user device, which communicates directly with the new-generation electricity meters via conveyed waves (PLC-C) and provides the collected data in a precise and reliable manner.

2.1.2 ENEA RECON

Moreover, ENEA has developed RECON to support local authorities, stakeholders and citizens towards conscious and informed choices aimed at creating RECs and jointly acting renewable self-consumers (CSS) and to promote the active participation of citizens in the energy market. It is a detailed but also easy-to-use and free tool, which is available online. RECON is currently available in Italian. The first version of the simulator (RECON 1.0) was released in May 2021, obtaining very positive results, with more than 4,000 registered users and over 7,000 evaluation sheets created. RECON 1.0 was able to simulate RECs and CSS in the residential sector based on the transitional provisions defined by Art. 42 bis of Italian Decree-Law nr. 162/2019 [8] and subsequent implementing measures, namely Resolution 318/2020/R/EEL issued by ARERA [6], the Ministerial Decree Sept. 16, 2020 [9] and the Technical Rules released by GSE, which is the Energy Service Managing Authority [10].

In April 2024, the new version (2.0) of the simulator was released, updated to the legislative and regulatory framework in force in Italy, namely Legislative Decree 199/2021 [3] which implemented the RED II Directive [1] and its implementing measures: the ARERA's TIAD [5–11], the Ministerial Decree nr. 414/2023 [12] and the GSE Operating Rules updated to April 2024 [13]. RECON calculates all relevant energy quantities, i.e., the onsite self-consumption and shared energy in the configuration, energy self-sufficiency, the environmental benefits in terms of reduction of carbon dioxide (CO_2) emissions, savings related to onsite self-consumption, revenues from energy sales, the public Italian incentive granted to these configurations in the form of a premium tariff, the drawback of network charges according to the ARERA regulation, operating and management costs, discounted cash flows and the main financial indicators, i.e., Net Present Value (NPV), Internal Rate of Return (IRR), Weighted Average Cost of Capital (WACC), and payback time.

Among the most important upgrades of RECON 2.0, it can analyze RECs and CSS composed of an indefinite number of consumers, prosumers and producers, and simulate different consumption profiles other than residential ones, i.e., condominium, office, school, commercial, and industrial profiles. Electricity withdrawn from the public grid can be provided on a monthly or annual basis, depending on data availability, and prosumers' consumption is automatically calculated based on the contribution of onsite self-consumption. As regards renewable energy production technologies, RECON 2.0 can evaluate photovoltaic plants, while the next release will include modules for the calculation of the yield of mini-wind and mini-hydroelectric systems. The economic and financial analyses are carried out for each Renewable Energy System (RES) power plant by considering different financing options, i.e., operating rental, leasing, purchase with equity and/or debt capital, and capital contributions, including the next-generation EU subsidy (EU RRF) dedicated to RES power plants installed in small municipalities with less than 5,000 inhabitants and tax deductions if applicable.

RECON includes four input sections, and the first is related to the general data of the configuration, i.e., type and date of the constitution, location, and details of the users and RES power plants. The second section collects information on the power plants. Figure 4 shows a screenshot of this section, at the bottom of which there are two gauges that represent the percentage of new plants (i.e., operative from 12/16/2021 according to Legislative Decree 199/2021) and the incentivized power (according to Decree 414/2023). The requested inputs include technical data (size, position of the modules, etc.), the date of entry into operation, the sales method of the energy fed into the grid, the type of investment and its main characteristics.

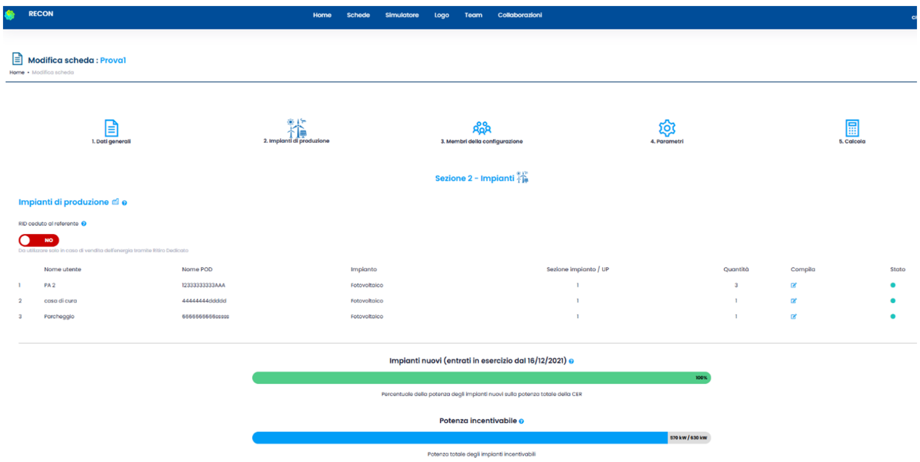
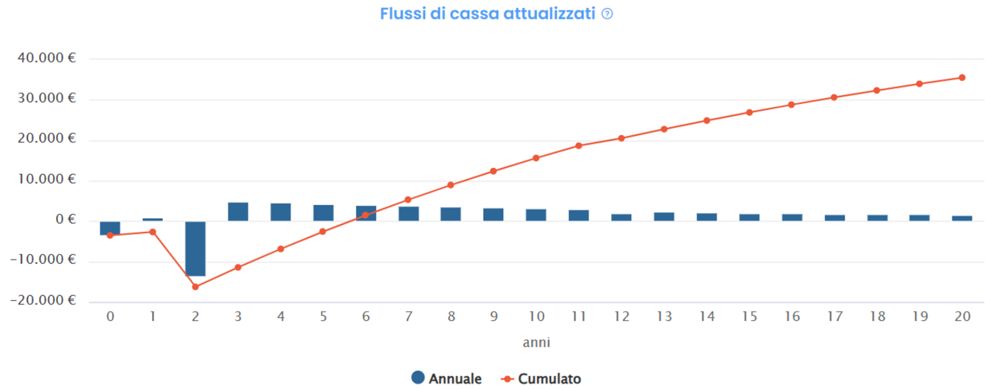


Figure 4. RECON "plant" general section where is possible to list and detail data related to each renewable energy production plan installed in the energy community

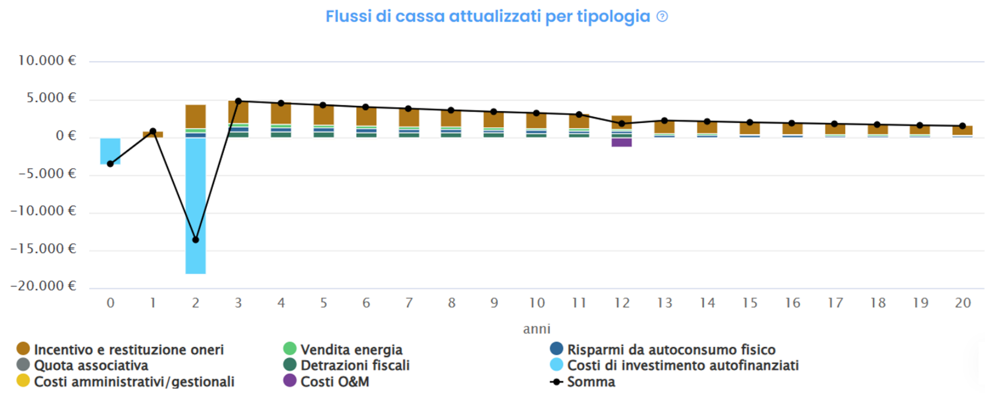
Note: The bottom gauges are related to the quota of new plants (i.e., operative from Dec. 16th, 2021 according to Italian Legislative Decree 199/2021) and RES power that can access the national feed-in tariff for diffuse self-consumption.

The third section is dedicated to electrical consumption profiles and end uses, which are related to the user type. RECON relies on a set of algorithms that calculate hourly consumption based on monthly or annual withdrawals from the public grid (these data are available from the bills) and the consumption profile. For prosumers with RES power plants already in operation, it is possible to indicate if electricity withdrawn data provided are affected by onsite self-consumption. RECON calculates hourly self-consumption and, therefore, the hourly consumption profile as the sum of withdrawals and onsite self-consumption. The fourth section requires a series of parameters, i.e., technical data related to the selected RES technology, economic data related to the start-up and management of the configuration (REC constitution costs, annual costs for any outsourced services and personnel costs), data of measuring devices if present, membership fees, and financial data, e.g., cost of capital and inflation.

Before performing simulation, RECON carries out a series of checks related to the minimum number of components in the configuration and the correct data entry. The energy and economic-financial simulation are carried out for the configuration and for each component. Simulation results are divided into energy and economic results. As an example, Figure 5 shows the annual discounted cash flows, cumulative and by type. In order to support users in their projects, RECON provides tooltips for all Input/Output (I/O), and only applicable fields to the specific situation are active in the Graphical User Interface (GUI). Moreover, some fields have default values that can be freely modified. Moreover, RECON allows registered users to save incomplete projects and to finish and run them later, e.g., when missing information in the initial stages is available. In this way, it is possible to modify the project and duplicate it to perform sensitivity analyses and, therefore, to identify the optimal configuration. Figure 4 shows the RECON "plant" section with the list of RES power plants and their main characteristics (name, technology, section, and quantity), the compile button and the status (i.e., data provided or not). Figure 5 shows an example of discounted cash flow charts reported in RECON financial results, i.e., total cash flows, cash flows by typology highlighting incentive, revenues for electricity sold to the grid, savings for onsite self-consumption (for prosumers), membership fee (if present), tax deduction, REC's equity, administrative costs, Operation and Maintenance (O&M) costs and their sum.



(a)



(b)

Figure 5. Example of discounted cash flow charts reported in RECON financial results: (a) total cash flows, (b) cash flow analysis categorized by type over a 20-year period

Note: The chart uses colored bars to show different cash flow components, including: **Gold**: Incentives and refund of charges, **Green**: Energy sales, **Blue (light)**: Savings from physical self-consumption, **Brown**: Membership fees, **Teal**: Tax deductions, **Purple**: Operation and maintenance (O&M) costs, **Cyan**: Self-financed investment costs. The black line represents the net cash flow (sum) across the years.

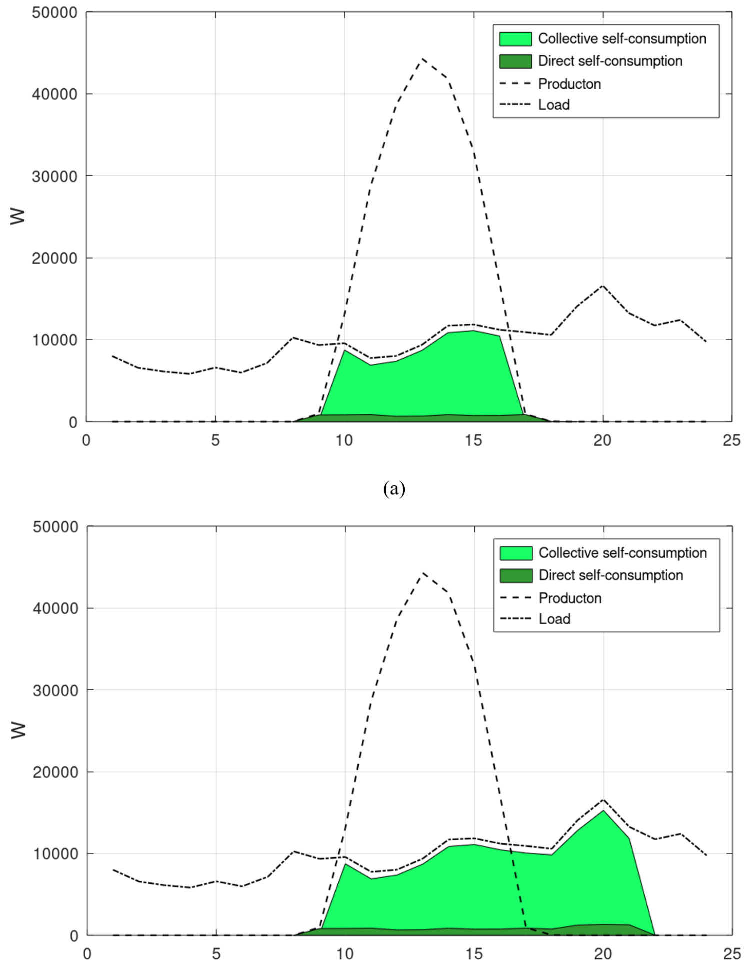
2.1.3 ENEA SIMUL and CRUISE

The SIMUL and CRUISE tools, developed by ENEA, have been designed to experiment with the simulation and management of RECs. The SIMUL tool allows to model the RECs through the definition of a digital twin able to reproduce the behaviour of the energy community starting from the consumption curves of the members from the characteristics of the renewable energy production plants and the electricity storage plants in the residential, tertiary and industrial sectors. The tool provides the impact of RECs in terms of key performance indicators (energy injected and withdrawn from the grid, direct self-consumption, shared energy, self-sufficiency, etc.), which are useful in the planning and management phase of the community, making it possible to evaluate different scenarios for the energy improvement. The aim is to predict with a suitable degree of approximation the trends of the community indicators when some parameters change, such as the number of participants or the installed production power.

The CRUISE tool is instead an interactive energy dashboard able to exchange data with simulation stages for the optimal management of the energy community. It is a web application that can be configured not only to show different community indicators, deal with multiple communities and respond to those monitoring needs but also to interact with users, which are necessary to stimulate participants and create interest and consensus towards virtuous energy actions. Figure 6 shows the numerical simulation of direct and collective self-consumption (shared energy) for a single day in an energy community.

In both tools, the hourly electricity production of the photovoltaic plants can be simulated, when necessary, using an implementation of the CNR Energy+ model [14] and actual irradiation data, external temperature and wind speed extracted from weather station available nearby of the energy community.

Electrical storage, if included within the REC configuration, was instead simulated using a simplified model, adapting the one proposed by the study [15].



(a)

(b)

Figure 6. Numerical simulation of direct and collective self-consumption (shared energy) for a single day in an energy community (a) without a storage system and (b) with a storage system

2.1.4 ENEA LTE

LTE refers to a decentralized system designed to empower local communities through the use of blockchain-based tokens. This economic tool aims to support sustainable development by integrating local resources, services, and stakeholders in a tokenized model. The LTE tool is based on the digitization of the collaborative economy [16, 17], and the technological levers and secure traceability of blockchain technology are exploited to promote the economic development of the territory even towards subjects in energy poverty [18] and with social fragility. The LTE introduces a transformative layer of economic empowerment for energy communities by leveraging blockchain technology to incentivize and streamline sustainable energy practices [19]. Blockchain, with its decentralized and transparent nature, enables the creation of digital tokens that can be used as rewards for individuals or organizations adopting energy-efficient behaviors. These tokens act as a form of digital currency within the community [20], allowing members to earn, trade, or redeem them based on their contributions to local sharing economy of goods and services based on social and environmental actions.

By incorporating blockchain, the LTE system ensures that all transactions—in a marketplace web based—are securely recorded in an immutable ledger. This not only guarantees transparency and trust but also minimizes the risk of fraud or manipulation. Smart contracts, a key feature of blockchain technology, can automatically execute predefined agreements (e.g., rewarding energy-saving actions or distributing energy credits) without the need for intermediaries, further lowering administrative costs and improving efficiency. It is clear that a token-based economy deals with a large number of processes more efficiently, but it is necessary to guarantee the ”asset-token” combination at the origin, both in terms of value and attribution.

When this guarantee is met, the benefit of using tokens in exchange transactions is certainly undeniable and, therefore, basing a sharing economy on blockchain technology is a logical consequence of this condition. The origin of the token is also caused by a rule played by the members in the energy efficiency: the more a member is active in energy efficiency and flexibility, the more tokens are automatically transferred in the wallet. Blockchain technology plays a pivotal role in maintaining the integrity of the energy-token combination. Figure 7 shows the synthesis of LTE platform topics.

Figure 7. Synthesis of LTE platform topics

The intrinsic nature of blockchains has some interesting advantages applicable to the context of a community that starts from energy to create a social, environmental and economic flywheel according to the paradigm of the LTE. Some of the main features of blockchain technologies are the immutability of the ledger, transparency, traceability of transactions and security based on cryptographic techniques. Starting from these principles, blockchain has become the declination of a new concept of trust that can also be applied in contexts of social and environmental value. In this case, the blockchain is seen as a platform that allows the development and concretization of a new form of social relationship. The participation based on blockchain is able to guarantee the possibility of verifying, controlling, and having total transparency on acts and decisions, which are recorded in archives (being unalterable, unchangeable and, therefore, immune from corruption). Smart contracts facilitate automated and trustless transactions between participants, ensuring that all agreements are enforced without the need for intermediaries. Participants in the LTE can be rewarded with tokens for contributing to the local economy, such as by providing services, producing goods, or engaging in sustainable activities. Individuals and businesses within the community can trade goods and services directly using the tokens without relying on traditional fiat currency or centralized institutions. Therefore, at the end, the community can improve its social and environmental role connected with a more efficient energy use.

3 Conclusions

The development of SECs represents a crucial step towards the decarbonization and sustainable management of local energy resources. Through the engagement of citizens, the integration of renewable energy technologies, and the application of innovative digital tools such as RECON, Smart Sim, and DHOMUS, ENEA's approach provides a comprehensive framework for fostering the active participation of citizens and local stakeholders in the energy transition. These tools enable individuals to monitor and optimize their energy consumption while contributing to the broader goal of energy self-sufficiency and environmental sustainability. Approaching these tools, ENEA helps to reduce cultural resistance, address the lack of awareness, and improve the interest and coordination among local actors. Engaging different stakeholders (private individuals, public entities, companies, and local governments) and balancing different interests is becoming less complex. The ENEA tools act as accelerators for achieving the estimated national energy targets. The regulatory and implementation framework envisions 5 GW of installed capacity by 2026, a figure considered reliable through 2027. By 2027, it is expected to result in an additional annual production of 6,250 GWh of renewable electricity. This assumes corresponding savings of 1,500 GWh from direct self-consumption, translating into €600 million in avoided electricity bill costs (calculated using the current end-user tariff). The shared energy within the energy community, estimated at 45% of total production, when extrapolating the RECON data, would amount to 2,800 GWh. This shared energy could generate incentives estimated in the range of €225 million to €337 million.

Additionally, the LTE introduces a new layer of economic empowerment for communities by utilizing blockchain technology to incentivize sustainable energy practices. The use of tokens encourages energy efficiency, further enhancing the overall resilience and autonomy of energy communities. By advancing the integration of smart technologies and promoting social collaboration, ENEA's model addresses both the energy and digital transitions necessary for the success of SECs. This model not only promotes local economic growth but also contributes to the global fight against climate change by reducing CO_2 emissions and enhancing energy efficiency at the community level. As the tools and technologies continue to evolve, the potential for scaling this approach to larger, more diverse communities becomes increasingly promising.

ENEA's innovative approach is not only reshaping local energy landscapes but also empowering communities to take control of their energy future, driving hopefully both environmental sustainability and economic growth and laying the foundation for a greener, more resilient world.

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Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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