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Feasibility study of a renewable energy community using stochastic methods: a case-study in Genoa city

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ABSTRACT

Renewable energy communities (RECs) provide a novel approach to organizing the production-consumption of renewable energy, involving multiple stakeholders who generate and utilize electricity from renewable sources (commonly wind turbines or solar panels). The REC's economic feasibility depends on sociotechnical factors that are location-dependent and determine costs and benefits. A significant advantage is the shared energy, which balances the energy production and consumption. Approximate estimations of shared energy can be derived from monthly-based models; a more comprehensive analysis requires an hourly-based model. This study develops a stochastic methodology to assess the feasibility of RECs under uncertainty. The approach combines Monte Carlo simulations with hourly energy balance and economic evaluation. The methodology is applied to a condominium-scale case in Genoa, Italy, as a representative example, but can be generalized to other urban contexts. The proposed case study involves a cluster of private buildings with a PV infrastructure and some apartments (consumers) that participate in the REC. This analysis aims to assess the feasibility of the REC under various scenarios, considering factors such as installed power capacity and the number of apartments comprising the community. The results of this study provide valuable insights into the viability of forming a REC in private buildings, offering a methodology for stakeholders involved in sustainable energy planning. The proposed approach can be extrapolated to other locations by selecting the proper parameters.

1. Introduction

Although the concept of community is not unique and is complex, in the energy context, it can be linked to the objectives that the community pursues, which mainly include environmental, social, economic, energy autonomy, political, and infrastructural aspects [1]. Energy communities often invest in local, renewable energy sources, such as solar panels, wind turbines, or small-scale hydropower, which are referred to as Renewable Energy Communities (RECs). These resources enable them to generate electricity or heat locally, thereby reducing their dependence on centralized, fossil fuel-based power plants. Members of energy communities may have a stake in the energy assets and decision-making processes; the interaction between members has been previously reviewed by Adu-Kankam and Camarinha-Matos [2]. The REC can take a cooperative ownership approach, where members jointly own and manage the energy infrastructure or form partnerships with third-party energy providers. The key point is energy sharing. Excess energy generated by one member can be shared or sold to others within the community, enhancing energy resilience and efficiency. Several dimensions (technological, environmental, sociocultural, and legislative) are involved in activating RECs; an overview can be found in Kyriakopoulos [3].

The formation of a REC has economic benefits derived from the effective use of the energy produced by the renewable installations. Typically, RECs pursue additional non-economic objectives that are linked to achieving renewable targets, participating in energy-related social activities, reducing carbon emissions, and promoting sustainability and energy independence [4]. Challenges affronting the effective adoption of RECs emerge in regulatory, technical, and financial aspects [5]. It can be inferred that the effectiveness of a REC depends on the effective management of consumption and production. Different optimization approaches have been adopted to manage scheduling in RECs,

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particularly from the demand side [32]; uncertainty in certain parameters (e.g., Energy prices, RES production, and demand) has been modeled using stochastic and robust optimization. Smart RECs are based on deploying intelligent tools for managing production and consumption. Smart systems can positively affect economic performance, flexibility, safety, and sustainability [6]. In particular, machine learning algorithms are of interest in addressing the forecast problem that helps establish optimum management strategies [7]. Recent research has highlighted the multifaceted role of RECs in integrating self-consumption with storage, flexibility, and grid connection. For instance Ref. [8], highlighted the potential and economic limits of community-scale batteries for collective self-consumption and energy arbitrage under Italian regulations. Moreover, recent scenario-based studies demonstrate that smart flexibility activation in Energy Communities offers additional benefits, such as reducing peak demand and deferring costly grid reinforcements while enhancing cost efficiency [9].

On the other hand, the installation of a production plant represents an investment; the performance of this investment (e.g., net present value, payback period) depends on multiple factors, such as the power of the installation and the benefits coming from energy saving by self-consumption, energy sold to the grid, and possible incentives for shared energy. An overview of the social arrangements, technical aspects, and impacts of RECs is presented by Gjorgievski et al. [10]. Additionally, this paper reviews how the economic, environmental, technical, and social impacts are quantified. Commonly used indicators include energy bill savings, cost savings, levelized energy cost, internal rate of return, payback period, life cycle cost, and net present value. Other performance measures include energy-related indicators, such as the self-consumption or self-sufficiency rate. Environmental benefits linked to RECs have also been investigated, for example, by studying the CO_2 abatement costs in Belgian micro energy communities, which show how collective electrification strategies can yield both environmental and economic benefits [11].

The formation and operation of energy communities are subject to regulations and policies that vary by region and country. The emergence of RECs is impacted by factors such as policy schemes and support for the stakeholders [12]; in this respect, the common directives and accords of the European Union (EU) will push forward the adoption of RES, and the RECs activation in the coming years as a strategy in agreement with the just transition mechanism expected to reach the 2030 and 2050 sustainable development goals [13,14]. Single European countries are expected to establish specific rules to implement a REC. The role of RECs is highlighted in the Renewable Energy Directive of the European Parliament, which promotes the use of energy from renewable sources [15]. To better understand the European context regarding RECs adoption, some recent works provide valuable insights. For example, Ahmed et al. [16] synthesize the evolution, challenges, and policy gaps of RECs, concluding that coherent national transpositions of EU directives remain the most decisive factor for long-term scalability. Taromboli et al. [17] perform a systematic review across EU Member States, highlighting that heterogeneous regulatory schemes cause divergent financial outcomes and that social aspects—particularly energy poverty mitigation—are still underrepresented in REC policy frameworks.

For now, in Italy, some rules consider the kind of association and incentives for sharing clean energy produced by RES installations have been approved recently [18,19]. In Italy, the REC concept has rapidly evolved under a complex regulatory and territorial framework. The emerging trends in Italy, as well as the normative framework, are extensively presented [20]. Brunoro et al. [21] define a methodological pathway for multi-stakeholder REC formation, concluding that institutional coordination and definition of regional key performance indicators are essential to replicate successful cases across the country. Blečić et al. [22] examine the first REC in Cagliari (Italy), where an integrated decision-support tool revealed that public-private partnerships in social housing can simultaneously reduce energy poverty and enhance local engagement. Belloni et al. [23] employ a thermal-electric co-simulation framework for Italian RECs, finding that optimized aggregation of prosumers and consumers yields up to 18 % cost reduction and 34 % CO_2 abatement compared to baseline scenarios. Finally, Magni et al. [24] analyze national Decree 414/2024, showing that incentive schemes introduce regional disparities—particularly between northern and southern municipalities—necessitating adaptive tariff mechanisms for equitable REC growth.

Recent literature has significantly deepened the understanding of RECs through stochastic and optimization-based frameworks. Volpato et al. [25] developed a stochastic programming model for REC design, and proposed a “best-scenario” selection method that limits the deviation between stochastic and perfect forecasts of life-cycle costs, thus validating stochastic optimization as a reliable design tool. Budin and Delimar [26] extend a similar approach through a two-stage stochastic optimization combined with clustering, demonstrating that optimal PV-battery storage sizing under demand uncertainty improves both self-consumption and fairness in profit allocation among members. Collectively, these works reinforce the methodological relevance of stochastic modeling for RECs, supporting the approach adopted in this study to assess community feasibility under uncertainty.

Building on these advancements, this work develops a stochastic methodology for assessing REC feasibility under uncertainty, providing a generalizable tool that integrates energy, economic, and social dimensions. The methodology is exemplified through a condominium-scale case study in Genoa, Italy, but its structure is transferable to other contexts. Genoa is a port city in northern Italy; its strategic location on the Ligurian Sea has facilitated trade routes connecting the Mediterranean with the rest of Europe. This city is the sixth-largest in Italy, with a population of more than 500,000, which requires access to green energy at affordable prices. The city’s green transition is an open problem, and ongoing research and projects are considering three main axes: climate, demographic, and digital [27]. The city’s location has potential for photovoltaic panels installation as a renewable energy source (RES) [28]. The city could benefit from implementing RES and strategies that support citizens as active actors in the energy sector. By installing a RES, a new active role in the energy market is assumed, as an energy consumer and producer (prosumer), and the possibility of interacting with others to share excess energy and enhance efficient use of the installation emerges. If the performance of a RES is optimized by sharing the excess energy produced, additional benefits (e.g., reducing the risk of energy poverty) could occur. One strategy to optimize RES is the formation of a Renewable Energy Community (REC), an association of energy consumers and at least one producer or prosumer that shares the energy produced from a renewable source.

This work develops a stochastic methodology to assess the feasibility of Renewable Energy Communities (RECs) under uncertainty, by combining hourly energy balance with a Monte Carlo-based economic evaluation. The proposed framework is broadly applicable to different urban contexts; here, it is applied to a representative case study in Genoa, Italy, to illustrate its potential and practical implications. It is considered a case of a condominium (a cluster of residential buildings) that decides to install a solar panel on the property and evaluate the economic performance of the investment over time, considering the establishment of a Renewable Energy Community. Rather than focusing exclusively on a location-specific analysis, the novelty of this work lies in providing a generalizable modeling approach for REC feasibility that incorporates uncertainty in production, consumption, and economic parameters. This computational approach enables the evaluation of multiple possible scenarios and the identification of critical factors that could impact the project’s feasibility.

2. Methods

Two main steps were followed to evaluate the feasibility of forming a REC: first, an energy balance, and second, an economic analysis. In the proposed numerical model, the input parameter space is populated using real-world data and a Monte Carlo method, generating numerous possible cases (e.g., 10,000), which accounts for uncertainties and helps explore the impact of these input parameters on energy-related and economic performance. The proposed approach is exemplified by considering a hypothetical case study involving a simple and general REC configuration of a private condominium that establishes a REC following a PV installation.

2.1. General methodology

In this section, the general methodology is described, divided into energy balance and economic analysis.

2.1.1. Energy balance in a REC

A REC is a self-consumption association that comprises several members who act as energy consumers, producers, or prosumers. The energy produced by the renewable installation is shared among members, and from this sharing, benefits are obtained. The possible REC configurations in Italy are based on the concept of virtual shared energy, the excess energy, $E_{pa} = E_p - E_{sc\ real}$ (remaining from the net production, E_p, after the real self-consumption $E_{sc\ real}$) is injected into the grid, and at the *same time* (hourly based), the consumers take energy from the grid, E_c, this energy constitutes a virtual self-consumption, $E_{sc\ virtual}$, see Eq. (1).

$$E_{sc\ virtual} = \min\left(E_{pa}, E_c\right) = \min\left(E_p - E_{sc\ real}, E_c\right) \tag{1}$$

The real self-consumption corresponds to the energy consumed in situ, that is, in the POD where the renewable installation is installed. Virtual self-consumption, $E_{sc\ virtual}$, is the quantity that determines the received economic incentive in addition to common energy transactions related to energy withdrawal from the grid and energy injected into the grid. Thus, to perform the energy-related balance, it is necessary to have information on the energy produced by the renewable installation and the energy consumption of each REC member hour by hour.

The indicator to quantify the energy-related performance of the REC is the self-consumption factor, a, that represents the ratio between the self-consumed energy, E_{sc}, by the REC and the energy produced by the installation, E_p, considering the two parts of the self-consumption, E_{sc}, i. e., the real, $E_{sc\ real}$, and the virtual, $E_{sc\ virtual}$, self-consumption as expressed by Eq. (2)

$$a = \frac{\sum E_{sc}}{\sum E_p} = \frac{\sum E_{sc\ real} + \sum E_{sc\ virtual}}{\sum E_p} \tag{2}$$

This study focused on the feasibility of REC under current Italian incentive schemes, excluding batteries and explicit flexibility mechanisms. However, future extensions of the stochastic framework can integrate additional smart energy strategies. Battery energy storage can be included through a dynamic state-of-charge equation for the stored energy $E_s(t+1) = E_s(t) + \eta_{ch} P_{ch}(t)\Delta t - 1/\eta_{dis} P_{dis}(t)\Delta t$, subject to $0 \leq Es(t) \leq E_{s,max}$, in which way the charge, η_{ch}, and discharge ,η_{dis}, efficiencies and storage capacity are considered $E_{s,max}$. Likewise, demand-side flexibility may be represented by shifting a portion of the load profile, formulated as scheduled demand $L_{sched}(t) = L(t) + \Delta L(t)$, where $\sum_t \Delta L(t) = 0$. Such formulations, in line with recent contributions on community batteries and flexibility activation in energy communities, would allow the framework to capture the impact of coordinated storage operation and demand scheduling on REC performance.

2.1.2. Monte-Carlo economic analysis

The investment model is based on the calculation of the cash flow C_t in each period t given by the addition of the i applicable benefits b and j costs c during the given annual period t as denoted in Eq. (3).

$$C_t = \sum_i b_{i,t} - \sum_j c_{j,t} \tag{3}$$

The three main benefits $b_{i,t}$ comes from: b_1 is the direct energy savings, proportional to real self-consumption $E_{sc\ real}$; b_2 is the incentive received by virtual shared energy, proportional to $E_{sc\ virtual}$; b_3 is the energy sold to the grid, is proportional to the surplus E_{pa}. The main costs included in the model are the installation cost c_1 and operational and maintenance (O&M) cost c_2, both proportional to installed power.

The financial outputs considered are the net present value (NPV) and the discounted payback period (DPBP), as shown in Eqs. (4) and (5), respectively.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + DR_c)^t} - C_0 \tag{4}$$

In Eq. (4), the variable C_0 represents the initial cash flow, containing the initial cost of the solar installation. The variable, t, is used to refer to each annual period, and the associated cash flow is designed by C_t. The total simulation period, T, was fixed to 20 years. The real discount rate, DR_c, is calculated from the nominal discount rate, DR, and the inflation rate, IR.

$$DPBP = t_{C_t<0} + |B|/C \tag{5}$$

The *DPBP*, Eq. (5), represents the time required to recover the investment, including the time value of money. It is calculated based on the last period with a negative cash flow $t_{C_t<0}$. Additionally, the formula uses the cumulative discounted cash flow at the end of this last negative period, B, and the total discounted cash flow after the last negative period, C.

2.2. Case study

The hypothetical case study involves a condominium comprising five residential buildings in Genoa, which constitutes an energy community with n members who freely decide to participate in the REC and install a new renewable power plant based on PV panels on the common property. Each building has 20 apartments, totaling 100 apartments (potential consumers), and one solar panel (producer). To constitute the REC, all apartments must have their own Point of Delivery (POD); additionally, an extra POD is used for condominium consumption to connect the PV installation to the grid. The condominium consumption corresponds to the shared services of common spaces, such as lighting, elevators, doors, and security systems. Then, part of the condominium consumption is considered real energy self-consumption, and part of the aggregated consumption of the n REC members is regarded as virtual energy self-consumption.

At least two members form each self-consumption community in one of three configurations: a renewable energy community (REC), a collective self-consumption group (CSCg), or a remote individual self-consumption (rISC). See Table 1 for a reference to the self-consumption configurations for renewable energy sharing in Italy that receive incentives for sharing energy [19].

In particular, the CSCg is a special form of REC integrated by consumers and producers/prosumers located in the same building. This configuration applies to our case study. The adhesion (or retirement) to such REC is voluntary; individual members can choose their energy provider freely. The shared electricity gives access to an economic incentive received by the representative of the self-consumption com-

Table 1
Self-consumption configurations for renewable energy sharing in Italy.

Configuration	Location	Members	Power
Renewable Energy Communities (REC)	Same primary cabinet	Min 2	<1 MW
Self-consumption group (CSCg)	Same buildings	Min 2	<1 MW
Remote individual self-consumer (rISC)	Same primary cabinet	Max 2	<1 MW

munity; the distribution of this incentive must be accorded in the REC statutes. This paper evaluates the energy-related and economic performance of the association dependent on the number of apartments that adhere to the community, *n*.

2.2.1. Energy production estimation

In Italy, diverse RES (such as solar, wind, geothermal, or hydro) can participate in the self-consumption configurations for renewable energy sharing presented in Table 1. There are some restrictions on the installation; for example, the maximum nominal power must be $P < 1\ \mathrm{MW}_p$, and the installation must be installed after the REC constitution. It was considered that those conditions are satisfied in the case study. Two possible configurations of solar PV panels, varying the nominal peak power P_A or P_B.were simulated.

Solar energy production is inherently intermittent; throughout the year, solar irradiance fluctuates, affecting the energy generated. We consider historical data for the city to calculate the hourly energy production during a typical year. The hourly production of the installation was computed using the photovoltaic-geographical-information-system tool PVGIS [29]. The solar radiation database, PVGIS SARAH2, for 2020, was used to obtain data. The PV technology considered is crystalline-Si PV panels with a fixed orientation and nominal peak power $P_A = 50\ KW_p$, or $P_B = 100\ KW_p$. Estimated system losses were selected as 14 %. Using this data as a typical production year, hourly production data were generated for 20 years by adding a random variation within a 10 % band.

2.2.2. Demand estimation

Statistical data on energy consumption by the neighboring population can be gathered from energy utility records. Typical values for one apartment are calculated using statistics from the analysis of domestic consumption by each Italian province, as provided by the authority ARERA [30]. The statistics provide the average hourly consumption value for three types of days (Monday to Friday, Saturday, and Sunday) for each month of a selected year. The hourly consumption for each one of the 100 apartments was estimated using statistical information about the typical consumption and a random generator within a 10 % band. An example of consumption during a typical winter day (100 random patterns within a 10 % variation band and the statistical data from the ARERA database) is shown in Fig. 1.

The aggregation of all the random patterns generated for the condominium and its members is necessary to calculate the annual energy consumption and the shared electricity. An example of a typical year comparing production and REC consumption is presented in Fig. 2.

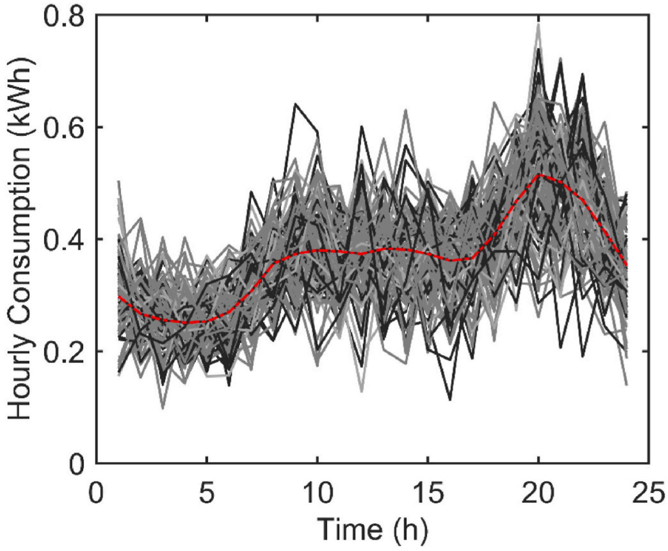

Fig. 1. Hourly consumption in a typical winter day of a Genoa apartment (red line). One hundred random consumption profiles were generated to simulate each consumer in the REC.

A detail of the shared consumption calculation that is $E_{sc\ virtual}$ using Eq. (1), which is presented in Fig. 3. It can be observed that in the nine sample days included in this graph, only part of the energy produced by the installation is used during peak production, except for two days (5 and 6) when the production was below the consumption all the time.

2.2.3. Other assumptions

All the distributions used to populate the parameter space were uniform. Solar production variability was modeled using a normal distribution centered on PVGIS hourly data. Household consumption profiles were perturbed using a uniform distribution with a ±20 % band, for the different REC members, and 10 % reflecting the range of intra-household annual variability. To represent year-to-year uncertainty in PV production, we apply a multiplicative stochastic factor of 10 % to the hourly PV time series of each simulated year. The ±10 % range reflects (i) interannual variability of the solar resource in Europe—typically 3–6 %; (ii) residual uncertainty of satellite-derived irradiance at monthly/annual scales; and (iii) operational effects that vary stochastically between years. Considering these components jointly yields an overall annual uncertainty; the ±10 % envelope is conservative yet realistic. This stochastic variability is treated independently of long-term module degradation, which is not considered in the case study, representing a simplification.

The economic analysis relies on cost assumptions derived from reports and recent literature to represent the Genoa case study, see Table 2. Benchmark data from Ref. [31] show that PV system cost in Europe typically lies in the range of 574–1312 €/kWp (5th to 95th percentile) for utility-scale systems (including soft costs, installation, panels, etc.), and that annual O&M costs tend to run between 1 and 3 % of capital cost depending on size, maintenance regime, and contract structure. Our assumptions about installation costs and O&M thus fall within or slightly below these ranges, reflecting optimistic but plausible values for condominium-scale installations with efficient management. Economic parameters were sampled stochastically: The discount rate was varied between 6 % and 8 %, consistent with the range between the weighted average cost of capital (WACC) reported by ARERA for regulated electricity activities (~5–6 %) and the higher values typically applied to community-scale projects reflecting increased financial risk. Inflation was set between 1 % and 3 %, in line with the European Central

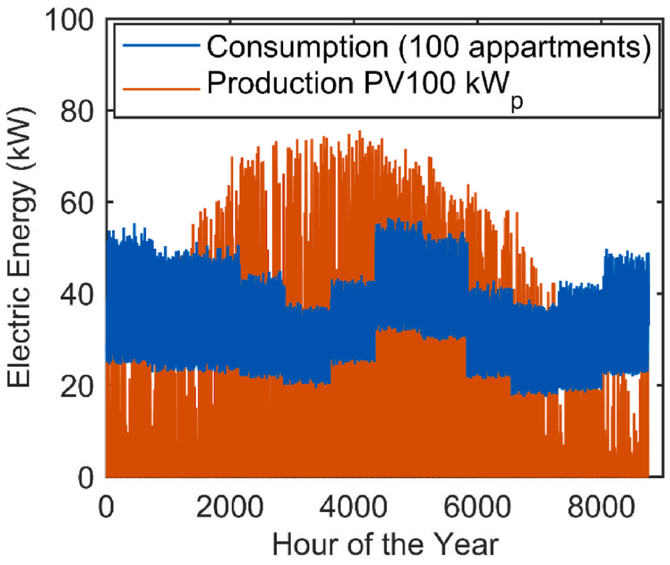

Fig. 2. Typical hourly consumption and production profile of the Energy Community during a typical year in Genoa, Italy.

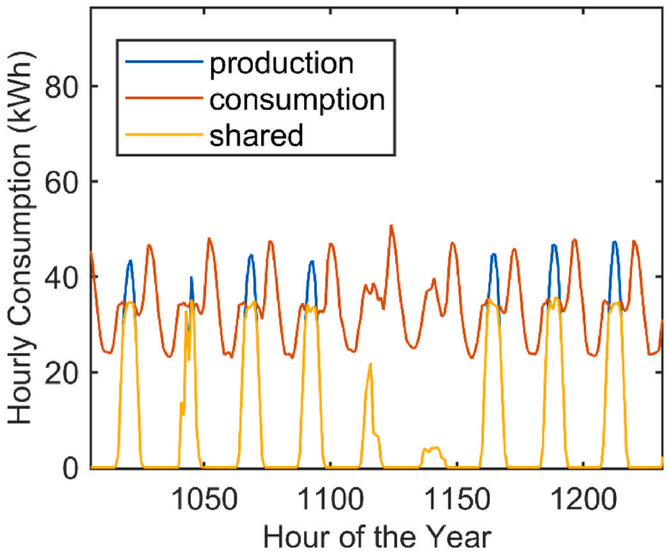

Fig. 3. Details on the shared electricity calculation for nine days in February.

Table 2
Economic parameter intervals set used for the case study.

Parameter	min	max	Unit
Installation cost, c_1	900	1200	€/kWp; applies only one time
Operational and maintenance cost, c_2	0.5 %	2 %	€; Percentage of installation cost
Direct selfconsumption saving b_1	0.2	0.39	€/kWh, proportional to electricity price
REC incentive b_2	0.113	0.113	€/kWh, defined by MASE
Energy sold to the grid b_3	0.13	0.15	€/kWh, typical price

Bank's long-term inflation target (2 %) and historical pre-crisis averages. While higher short-term peaks were observed in 2022–2023, these are regarded as exceptional shocks rather than baseline assumptions for long-term REC investments. This approach allowed for robust uncertainty exploration, although it does not capture time-dependent volatility in energy markets. Incentive levels for virtual self-consumption were set according to the Italian regulatory framework [19], with a tariff of 113 €/MWh for shared renewable electricity, accessible to communities with PV installations below 1 MWp.

While no formal benchmark simulation tool validation was performed, results were cross-checked against deterministic averages from PVGIS (generation) and ARERA (consumption), ensuring consistency with widely used reference profiles. Moreover, the feasibility indicators align in magnitude with those reported by Pasqui et al. [8] for community PV-battery configurations, supporting the credibility of the approach.

3. Results and discussion

3.1. Energy study

It is necessary to obtain the energy production and consumption values on an hourly basis to calculate the shared energy. The hourly results were integrated over time to get the annual values.

The number of members conforming to the REC affects the energy balance between the energy produced, E_p, and self-consumption, E_{sc}. Note that self-consumption has two parts: the real part (direct self-consumption), $E_{sc\ real}$, and the virtual part, $E_{sc\ virtual}$, corresponding to the shared energy within the REC. The amount of energy that is not self-consumed is called surplus. Results for a typical year, varying the number of REC members, are presented in Fig. 4.

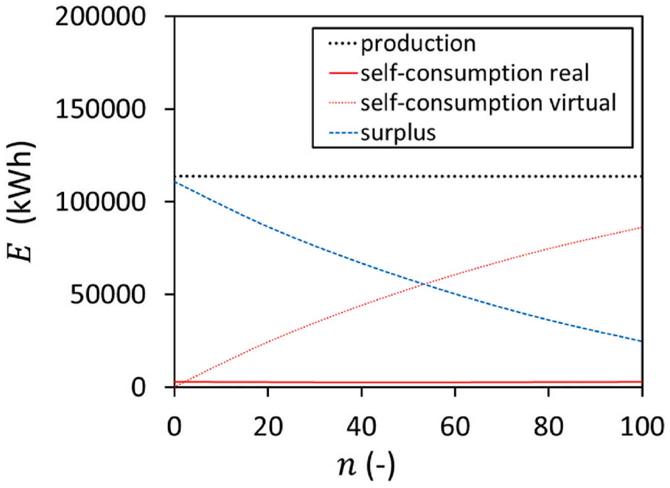

Fig. 4. Energy balance as a function of the REC members in the case of a 100 kWp solar installation, during a typical year.

In Fig. 5 is represented the self-consumption factor, a, considering the two parts of the self-consumption ($E_{sc\ real}$ and $E_{sc\ virtual}$), as expressed by Eq. (2). In the case of an installation with 50 kWp, to obtain a self-consumption factor of $a = 0.7$ around 40 apartments must take part of the REC, note that to get the same self-consumption factor in the case of a bigger PV installation more REC members are needed (almost 80, but relation is not linear).

3.2. Feasibility study

Economic benefits are linked to the direct self-consumption, $E_{sc\ real}$ (by saving on the electricity bill of the prosumer), the virtual self-consumption, $E_{sc\ virtual}$ (that receives an incentive from the National Energy Services Manager GSE). Moreover, the energy sold to the grid represents another income. Analyzing various conditions using the Monte Carlo model, it can be observed that constituting a REC impacts the project's feasibility, reducing the payback period and increasing the probability of obtaining a higher NPV.

Fig. 6 presents the cumulative cash flow (CCF) for the installation of a $P = 100\ \text{kW}_\text{p}$ installation, two cases are included: the single prosumer (no REC) and a REC with $n = 100$ *members*. These two extreme cases help illustrate the positive effects of sharing electricity. In the second

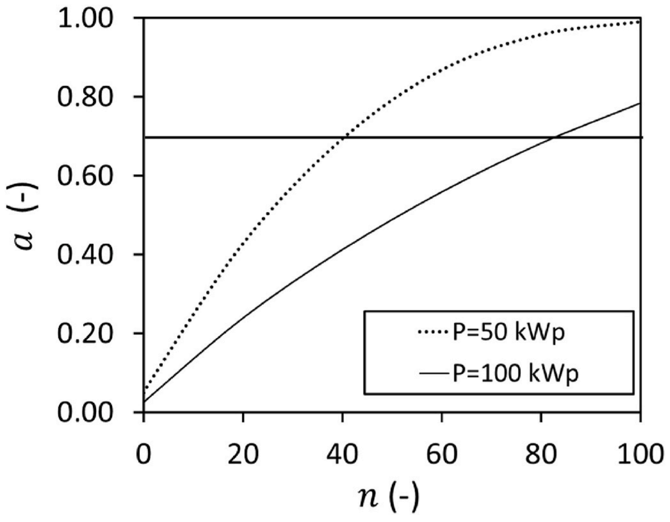

Fig. 5. Self-consumption factor as a function of the number of REC members. The two cases represent installations with different nominal peak powers.

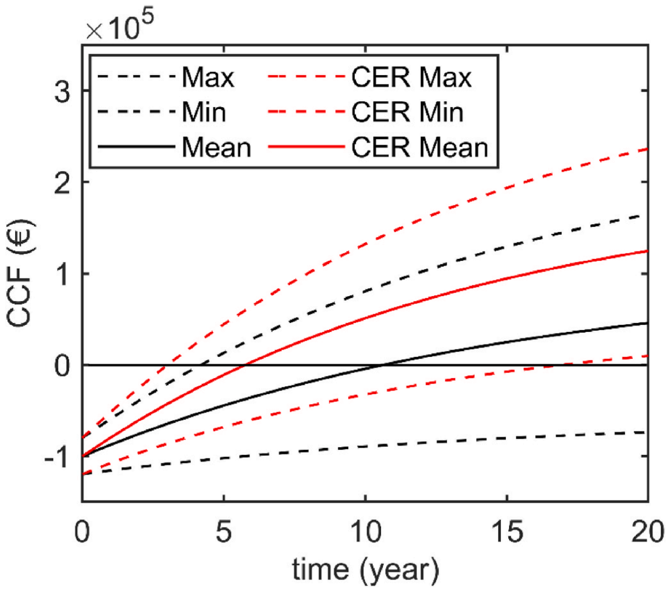

Fig. 6. Cumulative cash flow after 10000 Monte-Carlo simulations. The maximum, minimum, and mean values of all the simulations are presented. Two cases are included: no REC (black lines) and 100 members REC (red lines). $P = 100$ kW$_p$.

case, it is supposed that all the perceived benefits from the community members are accounted for in the cash flow.

Various factors, including the initial cost, maintenance cost, energy sale prices, and the discount rate, affect the feasibility of the considered renewable project. However, it is also noted that implementing an economic incentive for the energy virtually shared within the REC members helps to recover the high initial cost of the installation early (reduce the payback period). Moreover, it is possible to obtain a net economic benefit that could be in an amount proportional to the range of the initial inversion, see Fig. 7. The adhesion of enough members is necessary to ensure a balanced system and maximize the collective self-consumption. Although, it must be considered that incrementing the number of REC members could reduce the perceived individual benefit of each member, depending on the accorded repartition of the incentives and other incomes perceived by the REC. More details on percentiles are presented on Table 3.

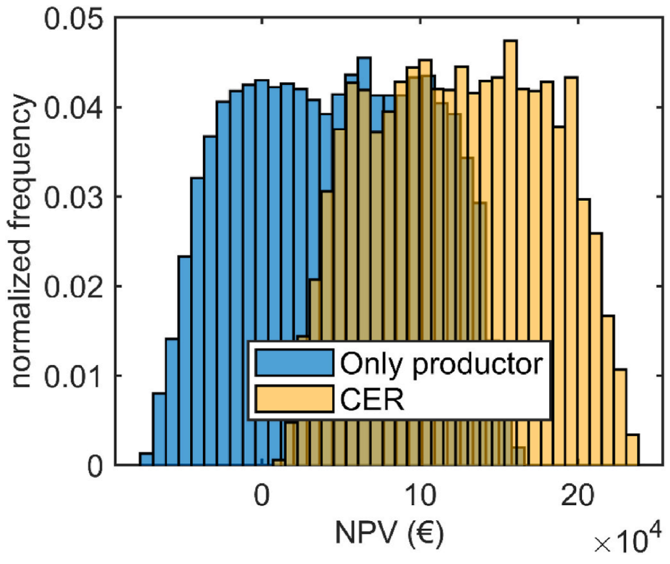

Fig. 7. NPV value after 10000 Monte-Carlo simulations comparing a single prosumer that installs a PV installation vs. the same installation forming a 100 members REC. $P = 100$ kW$_p$.

From the REC’s perspective, there will be an economic benefit from the incentive linked to shared electricity. However, condominium inhabitants who do not adhere to the REC will also benefit from a reduction in the electric bill for the condominium. Energy communities are a promising approach to achieving energy sustainability goals, decentralizing energy systems, and empowering local communities to take control of their energy futures. They align with the broader transition toward a more sustainable and resilient energy landscape, which is essential for addressing climate change and ensuring energy security. Researchers, policymakers, and industry stakeholders must continue to explore ways to support and scale up the concept of energy communities.

These findings are consistent with previous works on REC feasibility in European contexts. For example [6], report similar reductions in payback period under collective self-consumption schemes. Our payback periods ranges also align with those reviewed by Ref. [10]. Compared with studies on smart REC management, our approach focuses on uncertainty quantification rather than scheduling optimization, thus offering complementary insights. Our methods and findings align with those of Pasqui et al. [8], who demonstrated that REC participation enhances self-consumption and that energy storage integration can amplify community energy independence. However, unlike their optimization of battery scheduling, our approach addresses broader stochastic uncertainties in both production and consumption and includes insights from the single REC-member point of view. Finally, recent analyses of smart flexibility mechanisms in energy communities [9] demonstrate the value of community-level coordination for peak shaving and congestion relief. While our study primarily addresses economic profitability and self-consumption, the integration of these flexibility activation mechanisms represents a promising extension of the present framework, as well as evaluating the cost of reducing greenhouse gas emissions [11]. Although demonstrated for a condominium-scale REC in Genoa, the proposed stochastic methodology is general and transferable. By adjusting local data inputs (irradiance, demand profiles, tariff structures), the framework can be replicated for other urban contexts. The results highlight that REC formation significantly enhances self-consumption and improves investment indicators, with the probability of positive NPV reaching 80 % under Italian incentives. This methodological contribution supports both local stakeholders and broader European policy objectives, offering a robust decision-support tool for citizen-led renewable energy communities.

The presented study has multiple limitations that could be addressed in future work to enhance the applied methodology. For example, the forecasting methodology implemented was based on a reduced database that needs to be expanded, and different future scenarios could be studied (for instance, in the case of an increasing inflation rate). Other simplifications and assumptions that could be improved are linked to some parameters considered fixed over time for each simulation, such as the discount rate or energy price, but they are intrinsically variable. Those parameters varied (from case to case during the 10000 Monte Carlo simulations) within a defined range to consider multiple possible values and account for uncertainty and indeterminacy; however, the values became fixed over time for each case. Another open research

Table 3
Summary statistics from 10,000 simulations (€), comparing PV installation with no REC and REC (100 members).

Metric	Scenario	P10	P50	P90	Mean
NPV (20 y)	No REC	−32450	48550	121450	45764
NPV (20 y)	REC	49350	126350	195650	124618
		Min	**Mean**	**Max**	**year**
CCF	No REC	−73694	45781	164747	20
CCF	REC	9691	124636	236530	20

perspective involves using batteries or accumulation systems, as well as incorporating electric vehicle charging infrastructure, which could further increase the self-consumption factor while introducing new operational and economic challenges.

The considered REC configuration can be regarded as intrinsically smart, as it requires the deployment of smart meters and a digital management platform to enable real-time monitoring and sharing of information between members and the grid. This embedded intelligence not only facilitates the allocation of shared energy and incentives but also lays the foundation for integrating advanced strategies, such as storage dispatch and demand-side flexibility, in line with recent contributions on smart energy communities.

4. Conclusions

This work presented a numerical study concerning a REC formed by a prosumer (producer and consumer) and a group of apartments in the same building where the installation is located. The energy balance was performed hourly to determine the shared energy and the net yearly production and consumption. The derived economic benefits associated with selling the energy to the grid, direct self-consumption, and virtual collective self-consumption were evaluated using a stochastic financial model. The study demonstrates the usefulness of a stochastic methodology for evaluating REC feasibility, capturing the combined effects of uncertain energy and economic parameters.

- In the case study, it was found that, thanks to the incentive implemented in the considered European Union country (Italy), it is highly likely to recover the investment in installing a solar PV system during its 20-year lifespan. For a 100 kWp PV system, the median discounted payback period decreased from ~10 years (single prosumer) to ~6 years (100-member REC). The probability of achieving a positive NPV exceeded 95 % under the REC configuration (100 members), compared to less than 60 % for the single prosumer case. From the energy-related point of view, this economic performance is due to the increase of the self-consumption factor from ~0.05 (single prosumer) to above 0.80 with sufficient members (100). These results demonstrate the strong potential of REC adoption under Italian incentive schemes. Nevertheless, the estimation of potential economic profit should be regarded as indicative rather than precise, since it depends on uncertain parameters such as future market conditions and incentive schemes.
- Although the methodology was applied, as an example, to a condominium-scale REC in Genoa, the framework is transferable to other urban contexts by adapting location-specific parameters (e.g., solar resources, tariffs, and incentives).
- A balance must be achieved between the collective profitability of the REC and the benefits perceived by individual members, since a higher number of participants increases the overall self-consumption factor but may dilute the economic advantage per member.

The results highlight the general potential of RECs to enhance self-consumption and improve investment performance, supporting both local decision-making and broader policy design in line with EU targets. Of course, the results of this analysis are indicative of the overall trend. They must be taken with care because they correspond to stochastic simulations that are sensitive to the parameter range selected for the random conditions of each case. Future steps could include conducting a sensitivity analysis and considering more complex parameter configurations.

CRediT authorship contribution statement

Johan Augusto Bocanegra: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Vincenzo Bianco:** Writing – review & editing, Supervision, Methodology, Data curation. **Mattia De Rosa:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation. **Federico Scarpa:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation. **Corrado Schenone:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition. **Luca Antonio Tagliafico:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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During the preparation of this work, the authors utilized Grammarly to enhance language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data availability

Data will be made available on request.

References

[1] Bauwens T, Schraven D, Drewing E, Radtke J, Holstenkamp L, Gotchev B, Yildiz Ö. Conceptualizing community in energy systems: a systematic review of 183 definitions. Renew Sustain Energy Rev 2022;156:111999. https://doi.org/10.1016/j.rser.2021.111999.

[2] Adu-Kankam KO, Camarinha-Matos LM. Renewable energy communities or ecosystems: an analysis of selected cases. Heliyon 2022;8:e12617. https://doi.org/10.1016/j.heliyon.2022.e12617.

[3] Kyriakopoulos GL. Energy communities overview: managerial policies, economic aspects, technologies, and models. JRFM 2022;15:521. https://doi.org/10.3390/jrfm15110521.

[4] Haji Bashi M, De Tommasi L, Le Cam A, Relaño LS, Lyons P, Mundó J, Pandelieva-Dimova I, Schapp H, Loth-Babut K, Egger C, Camps M, Cassidy B, Angelov G, Stancioff CE. A review and mapping exercise of energy community regulatory challenges in European member states based on a survey of collective energy actors. Renew Sustain Energy Rev 2023;172:113055. https://doi.org/10.1016/j.rser.2022.113055.

[5] Yiasoumas G, Berbakov L, Janev V, Asmundo A, Olabarrieta E, Vinci A, Baglietto G, Georghiou GE. Key aspects and challenges in the implementation of energy communities. Energies 2023;16:4703. https://doi.org/10.3390/en16124703.

[6] Ceglia F, Marrasso E, Pallotta G, Roselli C, Sasso M. The state of the art of smart energy communities: a systematic review of strengths and limits. Energies 2022;15:3462. https://doi.org/10.3390/en15093462.

[7] Hernandez-Matheus A, Löschenbrand M, Berg K, Fuchs I, Aragüés-Peñalba M, Bullich-Massagué E, Sumper A. A systematic review of machine learning techniques related to local energy communities. Renew Sustain Energy Rev 2022;170:112651. https://doi.org/10.1016/j.rser.2022.112651.

[8] Pasqui M, Becchi L, Bindi M, Intravaia M, Grasso F, Fioriti G, Carcasci C. Community battery for collective self-consumption and energy arbitrage: independence growth vs. investment cost-effectiveness. Sustainability 2024;16:3111. https://doi.org/10.3390/su16083111.

[9] Askeland M, Bjarghov S, Rana R, Morch A, Taxt H. Smart flexibility in energy communities: scenario-based analysis of distribution grid implications and economic impacts. Smart Energy 2025;18. https://doi.org/10.2139/ssrn.5061422.

[10] Gjorgievski VZ, Cundeva S, Georghiou GE. Social arrangements, technical designs and impacts of energy communities: a review. Renew Energy 2021;169:1138–56. https://doi.org/10.1016/j.renene.2021.01.078.

[11] Verleyen L, Arroyo J, Helsen L. The cost of CO2 emissions abatement in a micro energy community in a Belgian context. Smart Energy 2024;16:100162. https://doi.org/10.1016/j.segy.2024.100162.

[12] Lode ML, Te Boveldt G, Coosemans T, Ramirez Camargo L. A transition perspective on energy communities: a systematic literature review and research agenda. Renew Sustain Energy Rev 2022;163:112479. https://doi.org/10.1016/j.rser.2022.112479.

[13] European Commission. The European green deal. 2019.
[14] European Commission. Clean energy for all Europeans. 2019.
[15] European Parliament. Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. 2018.
[16] Ahmed S, Ali A, D'Angola A. A review of renewable energy communities: concepts, scope, progress, challenges, and recommendations. Sustainability 2024;16:1749. https://doi.org/10.3390/su16051749.
[17] Taromboli G, Campagna L, Bergonzi C, Bovera F, Trovato V, Merlo M, Rancilio G. Renewable energy communities: frameworks and implementation of regulatory, technical, and social aspects across EU member states. Sustainability 2025;17:4195. https://doi.org/10.3390/su17094195.
[18] GSE. DECRETO CACER e TIAD – Regole operative per l'accesso al servizio per l'autoconsumo diffuso e al contributo PNRR. https://www.gse.it/documenti_site/Documenti%20GSE/Servizi%20per%20te/AUTOCONSUMO/Gruppi%20di%20autoconsumatori%20e%20comunita%20di%20energia%20rinnovabile/Regole%20e%20procedure/ALLEGATO%201%20Regole%20Operative%20CACER.pdf; 2023.
[19] MASE Ministero dell'Ambiente e della Sicurezza Energetica. Decreto CER. 2024. 2024.
[20] Tatti A, Ferroni S, Ferrando M, Motta M, Causone F. The emerging trends of renewable energy communities' development in Italy. Sustainability 2023;15:6792. https://doi.org/10.3390/su15086792.
[21] Brunoro S, Bizzarri G, Boldrin E. Exploring the potential of energy communities in the Italian territory. Front Built Environ 2024;10:1365115. https://doi.org/10.3389/fbuil.2024.1365115.
[22] Blečić I, Carrus AS, Congiu E, Desogus G, Muroni E, Saiu V. Renewable energy communities design: a decision support tool for integrated impact assessment. Insights from the first REC in Cagliari, Italy. J Clean Prod 2025;510:145600. https://doi.org/10.1016/j.jclepro.2025.145600.
[23] Belloni E, Fioriti D, Poli D. Optimal design of renewable energy communities (RECs) in Italy: influence of composition, market signals, buildings, location, and incentives. Elec Power Syst Res 2024;235:110895. https://doi.org/10.1016/j.epsr.2024.110895.
[24] Magni GU, Bricca D, Familiari S. Economic incentives for renewable energy communities: a scenario analysis in the transition process between the experimental and definitive Italian policy framework. J Sustain Dev Energy Water Environ Syst 2025;13:1–23. https://doi.org/10.13044/j.sdewes.d13.0589.
[25] Volpato G, Carraro G, De Giovanni L, Dal Cin E, Danieli P, Bregolin E, Lazzaretto A. A stochastic optimization procedure to design the fair aggregation of energy users in a renewable energy community. Renew Energy 2024;237:121580. https://doi.org/10.1016/j.renene.2024.121580.
[26] Budin L, Delimar M. Renewable energy community sizing based on stochastic optimization and unsupervised clustering. Sustainability 2025;17:600. https://doi.org/10.3390/su17020600.
[27] Municipality of Genoa. Genoa 2050 action plan for a Lighthouse City. 2021.
[28] Monforti F, Huld T, Bódis K, Vitali L, D'Isidoro M, Lacal-Arántegui R. Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach. Renew Energy 2014;63:576–86. https://doi.org/10.1016/j.renene.2013.10.028.
[29] European Communities. PVGIS photovoltaic geographical information system. EU Sci Hub 2022.
[30] ARERA. Analisi dei consumi dei clienti domestici. https://www.arera.it/en/dati-e-statistiche/dettaglio/analisi-dei-consumi-dei-clienti-domestici; 2022.
[31] IRENA. Renewable power generation costs in 2024. Abu Dhabi: International Renewable Energy Agency; 2025.
[32] Cruz-De-Jesús Emely, Martínez-Ramos Jose L, Marano-Marcolini Alejandro. Optimal Scheduling of Controllable Resources in Energy Communities: An Overview of the Optimization Approaches. Energies 2022;16(1). https://doi.org/10.3390/en16010101.