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Fostering sustainable economic development and mitigating energy poverty through renewable energy communities

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Abstract

Background Energy poverty remains an urgent social and economic challenge, exacerbated by rising energy costs, climate change, and inequalities in access to renewable technologies. Renewable energy communities (RECs) offer a promising approach that combines local energy production, democratic participation, and shared benefits, with the potential to reduce costs and improve energy access for vulnerable households. However, their effectiveness depends on economic viability, equitable distribution of benefits, regulatory support, and active community involvement. This study is relevant in that it assesses the viability, critical success factors, and benefit-sharing mechanisms of a photovoltaic REC, providing insights into how such models can foster sustainable, inclusive, and socially cohesive energy transitions.

Results The analysis assesses the profitability of an 80 kW photovoltaic system for a REC located in Northern Italy. The project's profitability ranges from 2556 to 5791 €/kW for self-consumption levels of 30% to 70%. Even without incentives, the investment remains economically sustainable, with profits ranging from 1693 to 3777 €/kW. Profitability is strongly influenced by self-consumption, but the incentive also makes the project much more attractive to prosumers. Sensitivity, scenario, and risk analyses confirm the project's robustness with respect to other variables, including energy purchase and sale prices, investment costs, and the opportunity cost of capital. A new methodology for distributing benefits across stakeholder categories (producers, consumers, households in energy poverty, territorial redevelopment, and the State) is proposed, also including ESCOs as facilitators and catalysts for RECs.

Conclusions RECs can be a tool for energy transition, capable of generating economic and social benefits even without government incentives in a mature photovoltaic market. However, incentives significantly enhance the project's economic viability and promote broader participation in the creation of these communities. From a policy perspective, this suggests a shift from direct subsidies to creating conditions conducive to community development, through programs that protect vulnerable families and aim to balance the needs of all stakeholders. From a managerial point of view, profitability depends above all on optimising self-consumption, while the equitable distribution of benefits among stakeholders strengthens legitimacy, fairness, and social cohesion.

Keywords Economic analysis, Energy poverty, Prosumer, Renewable energy community, Sustainable development

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Background

The European Commission first addressed Energy Poverty in 2009 through Directives 2009/72/EC and 2009/73/EC, which urged Member States to develop national action plans or frameworks to tackle it. Rising energy costs and stagnant household incomes have increased energy expenditure, especially among low-income households, further highlighting the issue. The literature also reflects an ongoing debate over the interchangeable use of the terms fuel poverty and energy poverty, as well as related concepts of energy deprivation [1, 2]. At the European level, there has been a move toward using these terms synonymously to describe the same issue: the difficulty individuals and households face in affording adequate access to energy services [3, 4]. Some studies show significant regional heterogeneity in the relationship between renewable energy and poverty alleviation. Only in European countries the expansion of renewable energy shows a considerable effect in reducing energy poverty [5]. Direct support policies, such as social tariffs, provide immediate but temporary relief without addressing the structural causes of energy vulnerability. The latter is mainly linked to dependence on fossil fuels, low energy efficiency in buildings, and inequalities in access to renewable technologies [6]. Most policy measures addressing energy hardship focus on economic support. However, reviews of these programmes highlight a lack of reliable assessments regarding their cost-effectiveness and overall economic efficiency [7]. Some analyses indicate that renewable energy expansion has mixed effects on energy poverty, potentially limiting electricity access in urban areas and access to clean fuel in rural regions [8]. In Europe, income inequality and long-term unemployment are key drivers of energy poverty, while the energy transition can mitigate the problem in the most vulnerable countries [9]. Moreover, urban responses to energy poverty vary depending on the areas considered, as shown by the differing approaches adopted in Barcelona and Warsaw [10].

In this context, Renewable Energy Communities (RECs) emerge as instruments of socio-technical innovation that combine environmental sustainability, economic equity, and social cohesion [11]. REC promotes a model of local energy production and consumption based on democratic participation and the sharing of renewable resources [12]. This model allows citizens (as prosumers) to access forms of self-sufficiency in energy, while reducing dependence on large utilities and promoting a more equitable redistribution of economic benefits [13]. There are many reasons why prosumers join a REC. The literature identifies a combination of economic, social, and environmental factors: while the reduction in energy costs is an immediate incentive [14], there are also collective drivers linked to local solidarity and environmental protection [15, 16]. From this perspective, RECs are not only technical tools for energy management but also social institutions that promote new forms of energy citizenship and democratic participation [17, 18].

Numerous studies highlight the potential of RECs to combat energy poverty, owing to their ability to provide low-cost renewable energy accessible to the most vulnerable groups [19, 20]. By sharing local production, especially photovoltaic energy, RECs reduce supply costs and optimise energy flows, making investments sustainable even for low-income households [21]. In this way, they promote energy justice, ensuring equitable access to energy as part of social and environmental citizenship [22]. Energy poverty is multidimensional in nature: climate change exacerbates energy poverty, and it appears that environmental regulations play a moderating role, economic regulations reduce the effect, while legal or supervisory regulations intensify it [22]. The State's energy-dependent context can exacerbate the existing situation, which is influenced by socio-economic, demographic, and housing factors [23].

The sustainability of RECs depends on a transparent, stable, and inclusive regulatory framework that removes technical and legal barriers to participation [24, 25]. Energy communities (ECs) drive innovation in organizational, financial, and governance models to alleviate energy poverty, emphasizing multi-scalar knowledge exchange and cross-sectoral policy integration [26]. A common limitation in many countries is the loss of economic advantage when implementing small projects to meet local needs [27]. However, RECs can be adopted in both urban and rural contexts [28, 29].

Macroeconomic analyses demonstrate positive regional effects of low-carbon transitions on employment and value added [30], while digitalisation enhances operational efficiency and peer learning within ECs [31]. However, willingness to pay for local sustainable energy remains lower than expected, driven mainly by cost-control motivations [32].

RECs represent an energy model based on local autonomy, solidarity, and sustainability, as an alternative to centralised systems. Their effectiveness in reducing energy poverty depends on the balance between prosumer interests and collective objectives [33]. Energy education, transparency, and virtuous behaviour strengthen the sense of community [34, 35]. An integrated approach, supported by inclusive policies, can make RECs and prosumers key players in the transition, promoting equity, social cohesion, and the achievement of SDGs 7 and 11 [36, 37].

A key element in ensuring the stability and inclusiveness of RECs is the equitable distribution of benefits among members. Several studies [11, 38, 39] have explored models for optimising the allocation of profits from renewable energy, balancing individual incentives with collective goals. The data indicate that RECs are generally more cost-effective than individual self-consumption programmes [40]. Economic analyses are necessary for their development [41], as the economic dimension is key to fostering acceptance by prosumers [42]. The definition of different market and political contexts, combined with methods of distributing benefits, is essential for assessing how to support investments in public infrastructure and support for economically vulnerable households [37].

This work aims to fill this gap by first assessing the profitability of a PV system within a REC located in Italy (in the north, where insolation levels are lower), and then identifying the critical success factors (energy purchase price, energy sale price, investment cost, self-consumption percentage, opportunity cost of capital, incentives) and evaluates them through the analysis of alternative scenarios. Subsequently, the redistribution of benefits is analysed by evaluating scenarios that reward producers, consumers, households in economic difficulty, territorial redevelopment, the State, and harmonisation between the various stakeholders. Energy Service Companies (ESCOs) will also be involved in the analysis. The aim is to combine these perspectives to assess how RECs can support a civil society moving towards the use of sustainable energy.

Methodology

Assessing the economic and financial profitability of a photovoltaic system requires adopting a methodological approach capable of accurately estimating the investment's cost-effectiveness over the system's entire life cycle. To this end, the economic analysis was conducted using the Discounted Cash Flow (DCF) method, widely used in the literature for the evaluation of investment projects in the energy sector [43, 44]. Based on the cash flows thus determined, various profitability indicators are calculated that summarise the economic performance of the investment: Net Present Value (NPV) represents the profits of a project; NPV/Size allows the profitability of projects of different scales to be compared, as it evaluates profits per unit of size; Profitability Index (PI) measures projects per unit of initial investment; Discounted Payback Time (DPBT) quantifies the time frame in which the initial investment is fully recovered; and Internal Rate of Return (IRR) is the percentage return on the project.

Economic model

The economic model adopted follows the approach proposed in the literature [36] and is articulated around cash inflow and outflow dynamics. There are three main items of revenue. The first is the savings on bills resulting from the product of the self-consumption percentage, the annual energy produced by the system, and the purchase price of energy. As this item is a missed cost, it can be interpreted as revenue. The energy produced by the system that is not self-consumed can be fed into the electricity grid and sold at a sale price. Finally, the self-consumed energy entitles the owner to subsidies. The product of the self-consumption percentage determines this source of revenue, the annual energy produced by the system, and the incentive tariff. As far as costs are concerned, the total investment cost, financed by third-party capital, stands out, obtained by multiplying the unit cost of the plant by its size. Below is a summary list of the formulas used in the economic model:

$$\mathrm{NPV} = \mathrm{DCI} - \mathrm{DCO} \tag{1}$$

$$\mathrm{DCI} = \sum_{t=1}^{N_{TaxD}} \frac{\left(\frac{C_{inv}}{N_{TaxD}}\right) \times TaxD_u}{(1+r)^t} + \sum_{t=1}^{N} \frac{\omega_{self,c} \times E_{out,t} \times p_t^c + (1-\omega_{self,c}) \times E_{out,t} \times p_t^s + \omega_{self,c} \times E_{out,t} \times S_{REC}^u + C_{val,u} \times \omega_{self,c} \times E_{out,t}}{(1+r)^t} \tag{2}$$

$$\mathrm{ECS}_t = \omega_{self,c} \times E_{out,t} \times p_t^c \tag{3}$$

$$E_{out,t} = t_r \times k_f \times \eta_m \times \eta_{bos} \times A_{cell} \times S \tag{4}$$

$$E_{out,t+1} = E_{out,t} \times (1 - dE_f) \tag{5}$$

$$p_{t+1}^c = p_t^c \times (1 + inf_{el}) \tag{6}$$

$$SP_{el,t} = (1-\omega_{self,c}) \times E_{out,t} \times p_t^s \tag{7}$$

$$p_{t+1}^s = p_t^s \times (1 + inf_{el}) \tag{8}$$

$$Subw_{self,c,t} = \omega_{self,c} \times E_{out,t} \times S_{REC}^u \tag{9}$$

$$TaxD_t = \left(\frac{C_{inv}}{N_{TaxD}}\right) \times TaxD_u \tag{10}$$

$$C_{val,t} = C_{val,u} \times \omega_{self,c} \times E_{out,t} \tag{11}$$

$$\mathrm{DCO} = \sum_{t=0}^{N_{debt}-1} \frac{\frac{C_{inv}}{N_{debt}} + (C_{inv} - C_{lcs,t}) \times r_d}{(1+r)^t} + \sum_{t=1}^{N} \frac{P_{Cm} \times C_{inv} \times (1+inf)^{t-1} + P_{Cass} \times C_{inv} \times (1+inf)^{t-1} + SP_{el,t} \times P_{Ctax} + T_{GSE,\,ann.} + T_{GSE,RID}}{(1+r)^t} + \frac{P_{CI} \times C_{inv}}{(1+r)^{10}} + C_{ae} + T_{GSE,\,var} \tag{12}$$

$$C_{inv,t} = \frac{C_{inv}}{N_{debt}} + (C_{inv} - C_{lcs,t}) \times r_d \tag{13}$$

$$C_{inv} = C_{inv,\,unit} \times (1 + VAT) \times S \tag{14}$$

$$C_{m,\,t} = P_{Cm} \times C_{inv} \times (1 + inf)^{t-1} \tag{15}$$

$$C_{tax,\,t} = SP_{el,t} \times P_{Ctax} \tag{16}$$

$$T_{GSE,\,RID} = t_{GSE,\,RID} \times S \tag{17}$$

$$C_{inverter} = P_{CI} \times C_{inv} \tag{18}$$

$$C_{ass,t} = P_{Cass} \times C_{inv} \times (1 + inf)^{t-1} \tag{19}$$

$$T_{GSE,\,var} = t_{GSE,\,var} \times S \tag{20}$$

Input data

The project analysed involves the installation of an 80 kW PV system. For each kW installed, an active surface area of approximately 7 m²/kW is considered necessary. The system is intended for the establishment of a REC in a residential context in a region of northern Italy and will be able to cover the energy consumption of multiple users acting as renewable self-consumers (RSCs). The reference area has an average annual insolation level of approximately 1300 kWh/m² (GSE data) and is located within a residential area consisting mainly of villas. The plant is located in a common area available to residents, such as a covered car park, with a total surface area of approximately 800 m². The useful life of the plant has been estimated at twenty years, during which electricity production will go from an initial value of 139,848 kWh in the first year to approximately 120,055 kWh in the last year.

The cost of electricity in the bill, based on various residential utility bills and Eurostat values, is estimated at 0.28 €/kWh and represents the amount saved through self-consumption. The energy fed into the grid is remunerated at an average price of 0.11 €/kWh, according to GSE data. For energy self-consumed in the community, the GSE recognises a premium tariff of 0.130 €/kWh, consisting of a fixed part of 0.08 €/kWh and a variable part defined as min (0.04; max (0; 0.180 – hourly zonal price) €/kWh, with a maximum ceiling of 0.120 €/kWh; an additional incentive of 0.01 €/kWh is added to this amount for photovoltaic systems located in the regions of Northern Italy. There is also a fee for self-consumed energy of 0.01057 €/kWh. The unitary investment cost per kW installed is 1400 €/kW, plus annual maintenance and insurance costs estimated at 2% and 1% of the total investment cost, respectively.

About the evolution of energy prices and operating costs, an inflation rate of 3% has been considered for both. The inverter is expected to be replaced in the tenth year, with an outlay equal to 15% of the total initial investment. Finally, an opportunity cost of capital of 5% has been assumed for discounting cash flows. All input data are proposed in Table 1.

Results

Base political scenario

The analysis of the base scenario allows us to evaluate the overall profitability of investing in an 80 kW photovoltaic system intended for collective self-consumption. The analyses were conducted based on the main critical variable, i.e., the percentage of self-consumption, which was varied in increments of 10% from 0% to 100%, yielding 11 different case studies for the same scenario Table 2.

The results show that the NPV ranges from a minimum of 10,407 € in the case of zero self-consumption to a maximum of 657,375 € with total self-consumption. This means that even without self-consumption – and therefore considering only the revenues from the sale of energy produced in the grid – the investment is still profitable. The project has intrinsic financial robustness, achieving very high profitability as self-consumption increases. For every 10% increase in self-consumption, the NPV increases by approximately 64.7 k€. The NPV/Size will also allow comparison with other plant sizes. This ratio ranges from 130 to 8217 €/kW in the 0–100% self-consumption range, with a value of 4174 €/kW for a reference configuration of 50% self-consumption. The trend shows an average increase of approximately 809 €/kW for every additional 10% of self-consumption, highlighting that virtuous consumption behaviours not only support the prosumer's greater energy independence but also translate into a tangible increase in the economic value generated by the investment.

The PI varies in the range 0.09–5.87, considering the two extremes of self-consumption and is equal to 2.98,

Table 1 [36, 37, 45–49]

Acronym	Description	Value
AC_{ell}	Active surface area	7 m²/kWp
C_{ae}	Administrative/electrical connection cost	1000 €
$C_{ass,t}$	Assurance cost in t	
C_{inv}	Total investment cost	
$C_{inv,t}$	Investment cost in t	
$C_{inv,unit}$	Unitary investment cost	1400 €/kW
$C_{inverter}$	Inverter cost	
$C_{lcs,t}$	Loan capital share cost in t	
$C_{m,t}$	Maintenance cost in t	
$C_{tax,t}$	Taxes on revenue from grid sales in t	
$C_{val,u}$	Unitary enhancement fee	0.01057 €/kWh
$C_{val,t}$	Enhancement fee in t	
DCI	Discounted cash inflows	
DCO	Discounted cash outflows	
dE_f	Decrease in system efficiency	0.80%
ECS_t	Savings on bills in t	
$E_{out,t}$	Energy production in t	
$E_{out,t+1}$	Energy production in t + 1	
inf	Rate of inflation	3%
inf_{el}	Rate of energy inflation	3%
K_f	Optimum tilt angle	1.13
N	PV system lifetime	20 y
N_{debt}	Loan period	10 y
N_{TaxD}	Deduction period	10 y
η_{BoS}	Balance of system efficiency	85%
η_m	Module efficiency	20%
p_0^c	Electricity purchase price at time 0	0.28 €/kWh
p_t^c	Electricity purchase price at time t	
p_{t+1}^c	Electricity purchase price at time t + 1	
P_{Cass}	Percentage of assurance cost	1%
P_{CI}	Percentage of inverter cost	15%
P_{Cm}	Percentage of maintenance cost	2%
P_{Ctax}	Percentage of tax cost	27.5%
p_0^s	Electricity selling price at time 0	0.11 €/kWh
p_t^s	Electricity selling price at time t	
p_{t+1}^s	Electricity selling price at time t + 1	
R	Opportunity cost of capital	5%
r_d	Loan interest rate	3%
S	Plant size	80 kW
S_{REC}^u	Unitary premium tariff subsidy	0.130 €/kWh
$Sp_{el,t}$	Sale of energy produced in t	
$Subw_{self,c,t}$	Premium tariff incentives in t	
T	Time	
t_r	Average annual insolation	1300 kWh/m²
$TaxD_u$	Unitary tax deduction	36%
$TaxD_t$	Tax deduction in t	
$T_{GSE,ann.}$	Annual GSE fees	15 €
$t_{GSE,RID}$	Unitary fee due to GSE dedicated withdrawal	0.65 €/kW
$T_{GSE,RID}$	Fee due to GSE dedicated withdrawal	52 €
$t_{GSE,var.}$	Variable unitary GSE taxes	1 €/kW
$T_{GSE,var.}$	Variable GSE taxes	80 €
Vat	Value-added tax	10%
$\omega_{self,c}$	Percentage of self-consumed energy	0–100%

Table 2 Financial indicators–baseline policy scenario

Self-consumption (%)	NPV (€)	NPV/Size (€/kW)	PI (–)	DPBT (y)	IRR (%)
0	10,407	130	0.09	17.38	7
10	75,104	939	0.67	7.81	22
20	139,801	1748	1.25	3.00	42
30	204,497	2556	1.83	1.71	67
40	269,194	3365	2.40	1.18	93
50	333,891	4174	2.98	0.90	121
60	398,588	4982	3.56	0.72	148
70	463,285	5791	4.14	0.61	176
80	527,982	6600	4.71	0.52	203
90	592,678	7408	5.29	0.46	231
100	657,375	8217	5.87	0.41	259

Table 3 Financial indicators - alternative political scenario

Self-consumption (%)	NPV (€)	NPV/Size (€/kW)	PI (–)	DPBT (y)	IRR (%)
0	10,407	130	0.09	17.38	7
10	52,088	651	0.47	11.51	16
20	93,770	1172	0.84	6.13	26
30	135,451	1693	1.21	3.67	38
40	177,132	2214	1.58	2.35	52
50	218,814	2735	1.95	1.74	67
60	260,495	3256	2.33	1.38	82
70	302,176	3777	2.70	1.14	98
80	343,858	4298	3.07	0.97	114
90	385,539	4819	3.44	0.84	130
100	427,220	5340	3.81	0.74	146

indicating a gain of approximately 2.98 € for every euro invested when self-consumption is set at 50%. The DPBT in the worst case is 17.4 years, which is lower than the worst cut-off period that could be proposed (corresponding to 20 years of useful life). It should be noted that even with only 20% self-consumption, the payback period drops to 3 years. With an average self-consumption level of 50%, the payback period is drastically reduced to approximately 0.9 years, equivalent to just under 11 months, while in the most favourable case (100% self-consumption), the payback period is less than 5 months. Finally, the IRR is well above the opportunity cost of capital, with a minimum of 7%. For 50% self-consumption, the IRR rises to 121%, while with total self-consumption, it reaches an exceptional level of 259%. These values may seem high, but the PI results show that the investment cost has a negligible impact, which justifies them.

Alternative policy scenario

The analysis of the base scenario showed a high return on investment and, in order to provide useful information to public decision-makers, a second simulation was carried out in an alternative policy scenario in which the incentives for self-consumption - i.e., the incentive tariff and the ARERA valuation fee - were eliminated. The aim was to understand whether, and to what extent, investment in a REC could remain economically viable even in the absence of public support instruments Table 3.

The results indicate that, starting from the case study with 10% self-consumption, the NPV/Size value is already 288 €/kW lower than in the base scenario. This difference increases progressively as self-consumption increases: 863 €/kW at 30%, 1439 €/kW at 50%, 2014 €/kW at 70% and up to 2877 €/kW in the most extreme case of total self-consumption (100%). This trend is consistent with the logic of the system, since the eliminated incentive acts precisely on the share of self-consumed energy, thus generating a loss proportional to its increase.

The PI confirms the decline in profitability: for the reference case with 50% self-consumption, the return on investment falls from 2.98 to 1.95 € per euro invested. Similarly, the DPBT increases from 0.9 years (approximately eleven months) to 1.74 years (approximately one year and nine months), indicating a more extended payback period for the invested capital. The IRR also declines significantly, from 121% in the incentivised scenario to 67% in the scenario without incentives.

While highlighting a general decrease in profitability, the results show that the investment remains sustainable, even in the absence of direct economic support. This evidence allows us to make an important consideration from a public policy perspective. The still high profitability observed in the absence of incentives suggests the possibility of gradually reducing economic support measures for self-consumption without compromising the sustainability of private investment. In this way, the public resources currently used to finance these incentives could be reallocated to other initiatives of collective interest.

Break-even point (BEP) analysis

The self-consumption percentage is one of the most influential variables in the project's profitability. Still, in these analyses, it cannot be used in a BEP analysis because the NPV remains positive even in the energy sales-only scenario. It was therefore decided to focus on the cost of purchasing energy in the bill, and the BEP allows us to identify the minimum energy price above which the investment becomes profitable, i.e., the value at which the NPV becomes zero.

In the case of the baseline policy scenario, the results show that even at zero purchase cost (0 €/kWh), the NPV remains positive. This is due to revenues generated from both the sale of energy to the grid and self-consumption incentives provided by current legislation.

In the economic model under the political scenario without incentives, the trend in BEP as a function of energy cost shows behaviour that is directly proportional to the share of self-consumption. The value ranges from 0.03 to 0.075 €/kWh, which is lower than the market average electricity price, confirming that the investment remains economically sustainable even in the absence of direct incentives (Table 4). The increase in the BEP threshold value observed in cases of higher self-consumption is attributable to the fact that, without the remuneration guaranteed by incentives, energy not sold to the grid does not generate additional economic benefits. The value tends to increase with self-consumption,

Table 4 BEP - Energy purchase cost

Self-consumption	Energy purchase cost (€/kWh)
0	0
10	0.0298
20	0.0548
30	0.0631
40	0.0673
50	0.0698
60	0.0714
70	0.0726
80	0.0735
90	0.0742
100	0.0748

Table 5 Sensitivity analysis – energy purchase price

Self-consumption	Optimistic		Pessimistic	
	NPV (€)	NPV/Size (€/kW)	NPV (€)	NPV/Size (€/kW)
0	10,407	130	10,407	130
10	85,511	1069	64,697	809
20	160,615	2008	118,986	1487
30	235,719	2946	173,276	2166
40	310,824	3,885	227,565	2845
50	385,928	4824	281,855	3523
60	461,032	5,763	336,144	4202
70	536,136	6702	390,434	4880
80	611,240	7641	444,723	5559
90	686,344	8579	499,013	6,238
100	761,449	9518	553,302	6916

Table 6 Sensitivity analysis – energy sales price

	Optimistic		Pessimistic	
Self-consumption	NPV (€)	NPV/Size (€/kW)	NPV (€)	NPV/Size (€/kW)
0	85,860	1073	−65,046	−813
10	139,737	1747	7196	90
20	193,614	2420	79,438	993
30	247,491	3094	151,680	1896
40	301,368	3,767	223,922	2799
50	355,245	4441	296,165	3702
60	409,122	5114	368,407	4605
70	462,999	5787	440,649	5508
80	516,876	6461	512,891	6411
90	570,752	7134	585,133	7314
100	624,629	7808	657,375	8217

Table 7 Sensitivity analysis – investment cost

Self-consumption	Optimistic		Pessimistic	
	NPV (€)	NPV/Size (€/kW)	NPV (€)	NPV/Size (€/kW)
0	32,361	405	−11,547	−144
10	97,057	1213	53,150	664
20	161,754	2022	117,847	1473
30	226,451	2831	182,544	2,282
40	291,148	3639	247,241	3091
50	355,845	4448	311,938	3899
60	420,542	5257	376,634	4708
70	485,238	6065	441,331	5517
80	549,935	6874	506,028	6325
90	614,632	7683	570,725	7134
100	679,329	8492	635,422	7943

Table 8 Sensitivity analysis – opportunity cost of capital

Self-consumption	Pessimistic	
	NPV (€)	NPV/Size (€/kW)
0	−1385	−17
10	51,107	639
20	103,599	1295
30	156,090	1951
40	208,582	2607
50	261,074	3263
60	313,565	3920
70	366,057	4576
80	418,549	5232
90	471,040	5888
100	523,532	6544

but revenues from energy sales (which have a higher economic reference value) decrease.

Sensitivity analysis

The economic model was further examined through a sensitivity analysis to assess the robustness of the results and the impact of the key critical variables on investment profitability. The study was conducted exclusively for the base scenario under current policies, modifying one variable at a time relative to the reference case. On the revenue side, two variables were considered: the cost of purchasing energy from the grid and the selling price of energy to the grid, which, as shown in previous analyses, have a high leverage effect on the NPV. Both were varied by ± 0.05 €/kWh (Tables 5 and 6). On the cost side, the unit investment cost per kW installed was analysed with a variation of ± 200 €/kW (Table 7). In addition, a key variable in the discounted cash flow method is the opportunity cost of capital, which is increased by 2.5% (Table 8).

For each variable, positive and negative variations were assumed, generating a total of seven alternative scenarios relative to the base case; in each scenario, the 11 case studies corresponding to self-consumption levels from 0% to 100% were maintained.

Table 9 Sensitivity analysis–alternative policy scenario

	NPV/Size (€/kW)	NPV/Size (€/kW)
	Optimistic	Pessimistic
Energy purchase price	3386	2085
Energy selling price	3207	2264
Investment cost	3010	2461
Opportunity cost of capital	-	2080

The results show that a variation of ± 0.05 €/kWh in the cost of purchasing energy on the bill produces, for the reference case of 50% self-consumption, a variation in NPV/Size equal to 650 €/kW. This effect is not uniform for all self-consumption percentages: considering the levels of 30% and 70%, which may represent the typical average range of prosumers [36], the variation is 390 €/kW and 911 €/kW, respectively. This trend is explained by the fact that, as self-consumption increases, savings on bills take on greater weight within overall revenues. In other words, the greater the share of self-consumed energy, the greater the impact of energy costs as an economic lever and the greater the variation in NPV as this parameter changes. Changes in the opposite direction (optimistic and pessimistic) produce symmetrical effects in absolute value but in the opposite direction.

As regards the energy sale price, a positive change of 0.05 €/kWh generates an increase in NPV/Size of + 267 €/kW for the reference case at 50% self-consumption, + 537 €/kW for 30% and a slight reduction of −4 €/kW for 70%. Conversely, a negative change of the same magnitude results in decreases of −660 €/kW (30%), −472 €/kW (50%), and − 283 €/kW (70%), respectively. It can therefore be seen that the sale price does not produce perfectly symmetrical effects for positive or negative variations in its value. In fact, in the event of a fall in the sale price, the incentive remains unchanged (as it is already at the maximum value provided for); conversely, in the event of a price increase, the incentive tariff tends to decrease. Consequently, in cases of high self-consumption, the increase in the sale price does not fully offset the reduction in the premium tariff.

A variation of ± 200 €/kW generates a change of 274 €/kW in terms of NPV/Size, regardless of the percentage of self-consumption. This result is consistent with expectations, as the investment cost does not directly influence other variables in the model and is not related to self-consumption.

Finally, for a more complete assessment, an alternative case was hypothesised, characterised by a higher level of risk aversion, corresponding to an opportunity cost of capital of 7.5%, to simulate the behaviour of more risk-averse investors. The results show a reduction in NPV/Size values that is proportional to the share of self-consumption: at 30%, the variation is −605 €/kW; at 50%, it is −911 €/kW; and at 70%, it is −1215 €/kW. The growing impact of this variation is explained by the fact that, as self-consumption increases, so do the positive cash flows generated by energy savings. Consequently, discounting these flows at a higher discount rate yields a greater absolute loss of value than in the base scenario. Overall, the increase in opportunity cost significantly reduces economic results, without compromising the investment's overall profitability.

The summary of the results shows that profitability is consistently within the self-consumption range of 30% to 70%. The only contexts in which the NPV is negative are when self-consumption is zero in pessimistic scenarios regarding the sale price of energy, investment costs, and the opportunity cost of capital.

To complete the sensitivity analysis, Table 9 shows the results for the political scenario without incentives, considering again the same variations applied to the critical variables, but limited to the reference configuration with 50% self-consumption. The base scenario had a value of 2735 €/kW.

The results show that a change of ± 0.05 €/kWh in the cost of purchasing energy on the bill results in a change of approximately 650 €/kW in the NPV; a change in the sale price of energy results in a change of 471 €/kW. For the latter variable, the perfect symmetry in positive and negative effects is explained by the absence of incentives compared to the baseline policy scenario. The change in the unit investment cost per kW installed generates a change of 275 €/kW, and the increase in the opportunity cost of capital results in a decrease of approximately 655 €/kW.

Scenario analysis

Following the sensitivity analysis, the study of the economic model was expanded through a scenario analysis that considers the joint variation of the main critical variables. Two extreme configurations (low probability of occurrence) were then defined: Table 10, an optimistic one in which the variables change in a direction favourable to profitability, and a pessimistic one in which they change in the opposite direction. In the optimistic scenario, an increase in the energy purchase price in the bill and the energy sale price in the grid was assumed, together with a reduction in the plant's unit investment cost. Conversely, in the pessimistic scenario, the same variables follow the opposite direction. The variations considered are the same as those used in the sensitivity analysis.

The results show that in the optimistic scenario, the NPV/Size value increases significantly compared to the base scenario, with variations of approximately 1191 €/kW when self-consumption is 50%; in the pessimistic scenario, the reduction is 1397 €/kW. The additional information provided by this analysis is that the combined effect of the pessimistic scenarios makes the project unprofitable with self-consumption percentages of 0% and 10%.

Table 10 Scenario analysis

Self-consumption	Optimistic		Pessimistic	
	NPV (€)	NPV/Size (€/kW)	NPV (€)	NPV/Size (€/kW)
0	107,814	1348	−87,000	−1087
10	172,098	2151	−25,165	−315
20	236,382	2955	36,670	458
30	300,666	3758	98,505	1231
40	364,951	4562	160,340	2004
50	429,235	5365	222,174	2777
60	493,519	6169	284,009	3550
70	557,803	6973	345,844	4323
80	622,088	7776	407,679	5096
90	686,372	8580	469,514	5869
100	750,656	9383	531,349	6642

Table 11 Risk analysis. Number of case studies

Base policy scenario	NPV > 0	NPV > Base NPV (333,891 €)	> Minimum NPV (261,074 €)
Base scenario 50% self-consumption	100	447	865
Energy purchase price €0.23/kWh	1000	209	609
Opportunity cost of capital 7.5%	1000	63	478
Self-consumption 30%	1000	14	160
Alternative political scenario	NPV > 0	NPV > Base NPV (218,813 €)	> Minimum NPV (166,390 €)
Base scenario with 50% self-consumption	100	486	765
Energy purchase price €0.23/kWh	991	210	496
Opportunity cost of capital 7.5%	1000	164	501
Self-consumption 30%	985	89	289

Risk analysis

Finally, a risk analysis is conducted using Monte Carlo simulation with 1000 iterations. For each iteration, the three critical variables considered above (energy purchase price, energy sale price, investment cost) have an average value equal to the base case and a standard deviation equal to that proposed in the sensitivity analysis. The proposed output was evaluated considering the probability that the NPV: (i) is greater than zero, therefore profitable; (ii) is greater than the NPV obtained in the base scenario (50% self-consumption), and (iii) is greater than the NPV obtained in the worst-case scenario among those obtained in the sensitivity analysis (50% self-consumption).

These analyses were conducted for both policy scenarios (with or without incentives), evaluating four types of simulation: (i) baseline scenario simulation with fixed self-consumption at 50%; (ii) simulation with an initial electricity price of 0.23 €/kWh; (iii) simulation with an opportunity cost of capital set at 7.5%; and (iv) simulation with self-consumption set at 30%, to represent a case of lower efficiency in the use of the energy produced Table 11.

In the current political scenario, the results confirm almost certain profitability: the share of iterations with NPV > 0 is 100% for all scenarios. As expected, the simulation on the base scenario exceeds its NPV in 44.7% of cases, while the comparison with the other three configurations shows more marked effects: setting the purchase price at 0.23 €/kWh, the probability of exceeding the NPV of the base scenario drops to 20.9%, with opportunity cost at 7.5% dropping to 6.3%, and with self-consumption at 30% down to 1.4%. These results confirm what emerged previously: the project's sensitivity to negative variations in these variables. However, when compared with the result obtained in the 'worst' case study, the base scenario has an 86.5% probability of exceeding this NPV value. The only remaining context to consider is self-consumption, where only 16% of case studies achieve a higher NPV. This reading of the results clearly confirms the criticality of the variables considered. The decrease in self-consumption is the dominant risk driver, but attention must also be paid to the opportunity cost of capital and changes in the purchase price of energy.

In the second policy scenario, i.e., in the absence of incentives, profitability is confirmed. However, there are rare cases in which the NPV is negative when the self-consumption percentage and the energy purchase price vary. The percentages comparing the results obtained with the base NPV tend to mirror those observed previously for the base policy scenario, and the same applies to the minimum NPV, where, at 30% self-consumption, it is higher in 28.9% of cases.

Method of distributing benefits among stakeholders

Preliminary social analysis

As part of a larger research project, a survey was conducted involving 403 people in Italy, 54% of whom were men with an average age of 36. One specific question concerned the distribution of benefits among multiple categories of stakeholders, each assigned a percentage share of the total benefits, which would then be divided among the members of the relevant category. The identification of both the stakeholder categories and the reference percentages to be assigned to them was carried out through interviews with experts in the field. There are five stakeholder categories:

- P (Producers) = those who support the investment in the energy production plant;
- C (Consumers) = those who contribute to the community's self-consumption virtuous energy producers and self-consumers;
- DE (Economic Difficulty) = quota allocated to families with lower incomes;
- RT (Territorial Redevelopment) = share allocated to the redevelopment of the community's territory;
- S (State) = share allocated to public institutions.

There are six alternatives for distributing the benefits, each of which tends to favour a particular category of stakeholders. In addition to the five proposals mentioned above, it was deemed appropriate to include another one that involved all stakeholders:

- (P) Scenario in favour of producers: 50% P, 25% C, 7.5% DE, 15% RT, 2.5% S;
- (C) Scenario in favour of consumers: 30% P, 45% C, 7.5% DE, 15% RT, 2.5% S;
- (PC) Stakeholder harmonisation (e.g., prosumer) scenario: 37.5% P, 30% C, 10% DE, 20% RT, 2.5% S;
- (DE) Scenario in favour of families in economic difficulty: 30% P, 25% C, 30% DE, 12.5% RT, 2.5% S;
- (RT) Scenario in favour of the redevelopment of the territory: 30% P, 22.5% C, 10% DE, 35% RT, 2.5% S;
- (S) Scenario in favour of the State: 37.5% P, 30% C, 5% DE, 15% RT, 12.5% S.

A new method of distributing benefits by stakeholder category

The results show a high level of profitability. However, a distinctive feature of RECs is the absence of a regulatory obligation imposing binding criteria for the distribution of benefits. This has given rise to a line of research aimed at identifying distribution methods that maximise plant installation and community participation while pursuing sustainability objectives. In this context, the existing literature [36, 37] has mainly considered configurations that divide the benefits among prosumers alone, possibly including consumers as well: among the most common proposals are equal distribution among participants, distribution proportional to each prosumer's contribution to the REC's total self-consumption, and, finally, schemes that assume an internal exchange price for shared energy.

Compared to these approaches, this work proposes a new one: the distribution of benefits is organized around multiple categories of stakeholders, each assigned a percentage share of the total benefits, which are then divided

Table 12 Benefit distribution methods (without ESCO)

	Most voted scenario	Weighted average scenario
Producers	37.5	35.0
Consumers	30.0	31.0
Economic difficulty	10.0	13.0
Territorial redevelopment	20.0	18.5
State	2.5	2.5

among the members of the relevant category. This approach aims to provide an overview of all possible participants in a REC without considering only specific categories, and, above all, to include stakeholders relevant from a sustainable development perspective (e.g., citizens in energy poverty; local development; state institutions).

The previous subsection identifies six distribution scenarios, each of which specifies the percentages of benefits to be allocated to the five categories of stakeholders defined above. In fact, each distribution scenario indicates the share of benefits allocated to each stakeholder type. Considering that the questionnaire asked respondents to choose only one of the six alternatives proposed. It is possible to derive the initial distribution of benefits from real data. In fact, this distribution method coincides with the scenario that received the most support among the 403 respondents, namely the alternative called PC. This configuration was created to reward all stakeholders in a balanced manner, with 37.5% for producers and 30% for consumers. The remaining share is distributed as follows: 20% for territorial redevelopment, 10% for economic difficulty, and 2.5% for the State (Table 12).

To define a second method of allocation, it was decided not to limit ourselves to the majority result alone, but to use the entire preference profile expressed by the sample, thus maintaining the objectivity of the data obtained. In concrete terms, the overall frequencies of choice for the six alternatives were considered: 28% voted for (PC), 25% for (C), 20% for (DE), 13.6% for (P), 12.7% for (RT), and 0.7% for (S). Since, as mentioned, each alternative specifies a percentage of benefits to be allocated to each stakeholder category, a summary scenario was constructed by calculating, category by category, a weighted average of the shares provided for in the six alternatives. The procedure is straightforward: for each stakeholder category (P, C, DE, RT, S), the percentage of benefits envisaged in each of the six alternative scenarios is multiplied by the percentage of respondents who selected that scenario; the six products are then added together to obtain the final percentage for that stakeholder category. Repeating the operation for all categories yields a distribution that encompasses the entire spectrum of expressed preferences. For example, to calculate the percentage to be associated with the stakeholder category of producers, i.e., P, the product of 28% of the sample of respondents who voted for the benefit distribution scenario (PC) and 37.5% of the share of benefits assigned to that stakeholder category in this mode is considered. This operation is repeated for each scenario, e.g., 25% x 30% for the mix of stakeholder category (P) and distribution scenario (C), and so on for all other benefit distribution scenarios. The sum of these six products gives 35% as the final percentage for this category.

Below (Tables 13 and 14) are the actual calculations of the percentages associated with each stakeholder category in the model, obtained from the weighted average of respondents' choices. The results show a reduction in the weight assigned to producers, as well as to territorial development. At the same time, there is an increase for consumers, especially for those living in economic hardship.

Table 13 Explicit calculations of values for the distribution model with weighted averages

Stakeholder category	Benefit distribution scenarios					
	(PC)	(C)	(DE)	(*P*)	(RT)	(S)
P	28%x37.5%	25%x30%	20%x30%	13.6%x50%	12.7% x 30%	0.7%x37.5%
C	28%x30%	25%x45%	20%x25%	13.6%x25%	12.7%x22.5%	0.7%x30%
DE	28%x10%	25%x7.5%	20%x30%	13.6%x7.5%	12.7%x10%	0.7%x5%
RT	28%x20%	25%x15%	20%x12.5%	13.6%x15%	12.7%x35%	0.7%x15%
S	28%x2.5%	25%x2.5%	20%x2.5%	13.6%x2.5%	12.7%x2.5%	0.7%x2.5%

Table 14 Final values for the distribution model with weighted averages

Stakeholder category	Benefit allocation scenarios						
	(PC)	(C)	(DE)	(*P*)	(RT)	(S)	Weighted average
P	10.50	7.50	6.00	6.80	3.81	0.26	35
C	8.40	11.25	5.00	3.40	2.86	0.21	31
DE	2.80	1.88	6.00	1.02	1.27	0.04	13
RT	5.60	3.75	2.50	2.04	4.45	0.11	18.5
S	0.70	0.63	0.50	0.34	0.32	0.02	2.5

Table 15 Calculation of the distribution of collective benefits

Members	Stakeholder categories		
	Producers *P*	Consumers C	Energy poverty DE
Member 1	(15,611/26,019)·6481.4€	(15,611/52,039)·5740.7€	0
Member 2	0	(13,010/52,039)·5740.7€	2407.4/2 €
Member 3	(10,408/26,019)·6481.4€	(10,408/52,039)·5740.7€	0
Member 4	0	(7806/52,039)·5740.7€	2407.4/2 €
Member 5	0	(5204/52,039)·5740.7€	0

Table 16 Final results distribution of collective benefits

Members	Stakeholder categories			Total
	Producers *P*	Consumers C	Energy poverty DE	
Member 1	3888.7€	1722.1€	0	5610.9€
Member 2	0	1435.2€	1203.7€	2638.9€
Member 3	2592.7€	1148.2€	0	3740.8€
Member 4	0	861.1€	1203.7€	2064.8€
Member 5	0	574.1€	0	574.1€
Total	6481.4€	5740.7€	2407.4€	14,629.5€

Benefit distribution model in a REC with families living in energy poverty

The next step in the work is to propose a case study focused on energy poverty. The overall benefits of distributing the NPV among the various components of a REC are determined by personal and collective shares. The personal share includes the cost avoided in the bill and any tax deduction if you are also an investor (producer). In contrast, the collective share refers to the sale of energy, subsidies, and the ARERA valuation fee.

Assessing the 80 kW PV system installed in a region of Northern Italy and considering the input data proposed in Table 1, a REC consisting of five members is considered. Two of them (Member 1 and Member 3) are RSC, meaning they have contributed to the investment in the system and therefore fall into the stakeholder category of Producers (P), while at the same time consuming the energy produced and therefore falling into the category of Consumers (C). Two other members (Member 2 and Member 4) are Consumers who belong to the category of citizens in Energy Poverty (DE). The last one (Member 5) is exclusively a consumer. It should be noted that, in a real application, the same system could be associated with a different number of participants and different combinations of characteristics; the configuration described here is for illustrative purposes only, intended to concretely illustrate the application of the allocation models presented in the previous sections.

To demonstrate an application case, it is necessary to identify a technical dataset within a given time frame. During year t = 10 of the plant's useful life, the expected

Table 17 Collective benefit distribution among members of the REC

	With the Energy Poverty rate	No Energy Poverty rate
Member 1	38.4	45.9
Member 2 (Energy Poverty)	18.0	11.7
Member 3	25.6	30.6
Member 4 (Energy Poverty)	14.1	7.0
Member 5	3.9	4.7

annual production is approximately 130,096 kWh (see Eq. (4)), and it is also assumed that the five members consume the following amounts of energy, respectively: (i) Member 1–15,611 kWh; (ii) Member 2–13,010 kWh; (iii) Member 3–10,408 kWh; (iv) Member 4–7806 kWh and Member 5–5204 kWh. The total self-consumption of the REC is therefore 52,039 kWh, corresponding to approximately 40% of the plant's total energy production.

Equations (3) and (10) refer to individual benefits, while Eqs. (7), (9), and (11) refer to collective benefits. Consequently, the focus is on the latter, as follows: the revenues deriving from the sale of non-self-consumed energy to the grid ($SP_{el,10}$ = 11,203.3€), the revenues linked to self-consumed energy valorised through the incentive premium tariff ($Subw_{self,c,10}$ = 6765€), and the revenues associated with self-consumed energy valorised through the ARERA valorisation fee ($C_{val,10}$ = 550€). The total collective benefits are equal to 18,518.3 €.

Applying the "Weighted Average" allocation model described above, the total benefits are attributed to the five stakeholder categories as follows: (i) Producers (P) = 6481.4 €; (ii) Consumers (C) = 5740.7 €; (iii) Energy Poverty (DE) = 2407.4 €; (iv) Territorial Redevelopment (RT) = 3333.3 € and (v) State (S) = 555.5 €. For example, Producers earn 6481.4 € by multiplying 18,518.3 € by 0.35 (see Table 14). For each of these categories, the benefits are then distributed among the individuals within it according to a criterion of proportionality based on their self-consumption contribution. Within the same category, those who self-consume more receive a greater share of the benefits. The only exception concerns the benefits intended for families experiencing energy poverty (DE), which are divided equally among all members of this category. Tables 15 and 16 show the resulting distribution under this model, highlighting the collective benefits for each of the five REC members.

It should be noted that the 14,629.5 € refers to the benefits associated with three of the five stakeholder categories (Territorial Redevelopment and State are missing, bringing the total to 18,518.3 €). To understand whether this mechanism rewards the most vulnerable households, we need to assume that the 13% allocated to energy poverty is no longer applicable and that it is not allocated to the producer or consumer to provide a comparison between these two distributions, which shows that Members 2 and 4 earn between 6.3% and 7.1% - Table 17.

These benefit distributions concern the collective share of the CER, but future analyses will also have to extend them to the collective share. Similarly, the results may change depending on the number of members, the number of members divided into specific categories, and the percentage distributions between the different categories. The general rule will be that where the number of members within a category increases, for example, that of energy poverty, the benefits for individual RSCs will inevitably decrease.

A new method of benefit sharing involving ESCOs

ESCOs can promote the creation and dissemination of RECs [18, 50]. Their role has been defined as that of catalysts capable of increasing uptake by limiting the use of incentives: users transfer part of the benefits to ESCOs in exchange for the elimination of management costs and, above all, the transfer of investment risk. In this perspective, it was considered appropriate to assess the impact of ESCOs on the distribution of benefits among stakeholders, treating them as an additional category to those already defined. The percentage of benefits to be associated with ESCOs was again derived from the questionnaire defined above, which included a specific question on the subject, namely, the share considered fair to allocate to ESCOs. The average, as reported by the 403 respondents, is 19.4% (which, in this study, will be approximated to 19%); the standard deviation is 14.5% in the sample. Based on this empirical evidence, the two benefit allocation scenarios defined above are recalibrated to include the ESCO category with the indicated share (Table 18). In this study, it was decided to allocate the percentage to ESCOs only between the producer and consumer categories, as they are considered the primary beneficiaries of these entities' work. It should also be noted that the percentage associated with consumers remains higher than that associated with ESCOs, and producers confirm their priority in the allocation of benefits.

In conclusion, the allocation methods presented here are in line with existing literature but modify its approach slightly: the share of benefits to be allocated to each stakeholder category is determined before establishing the criteria for internal distribution within the category. However, it should be emphasised that these two dimensions – percentage allocation to categories and intra-category allocation rules – are not alternatives but complementary, and should be developed jointly. It is therefore suggested that research continue along this dual path, testing different combinations of weights between stakeholders and internal criteria, such as equal distribution or distribution proportional to self-consumption, to assess which distribution architecture maximises participation, efficiency, and social acceptability simultaneously.

Table 18 Method of distribution of benefits (with ESCOs)

	Most voted scenario	Weighted average scenario
Producers	28.0	25.5
Consumers	20.5	21.5
Economic difficulty	10.0	13.0
Territorial Redevelopment	20.0	18.5
State	2.5	2.5
ESCO	19.0	19.0

Discussion

Achieving sustainable development requires integrating low-carbon transitions [51], green growth [52], circular economy strategies [53], and ecological footprint management [54], while accounting for trade, investment, natural resource use, and unemployment [55].

Green growth requires integrated models to assess different perspectives [56], and combining technical expertise into public administration can increase citizen engagement and collaboration with local communities, thereby promoting the adoption of renewable energy in RECs [57]. Some analyses indicate that older people with higher levels of education are less at risk of energy poverty [58]. However, this work emphasises the need to involve all categories of stakeholders.

Economic analyses are crucial in the energy sector, as they help evaluate the viability of renewable energy projects, optimize the distribution of benefits, and ensure that investments support both infrastructure development and the needs of economically vulnerable households [11, 38, 39, 41, 42].

The literature offers multiple studies highlighting that the analysis depends on the political context of reference and the different variables involved in the model: 23–353 k€ [59], 300 k€ [60], 7.4–11 k€ [61], 490–648 k€ [62], 1.293–8.537 M€ [63], 3.21–21.35 M€ [64], 1300–2119 €/kW [40], 233–769 k€ [65], 12–38,702 € [66] and (−3759)–2,886,482 € [67]. The role of incentives also emerges in other studies with a NPV ranging between 639 and 1463 k€ [68], to which is added the key role of the percentage of self-consumption: 2706–6309 €/kW [42], 2042–8195 €/kW [37], and 2953–11,230 €/kW [11] when it varies in the range of 30–70% self-consumption.

PV systems are rapidly spreading and support the achievement of sustainability objectives in various sectors and applications [69, 70]. Energy transitions produce both opportunities and challenges, underscoring the need for inclusive, participatory governance. Citizen energy cooperatives play a key role in transforming the European energy system from centralised structures to decentralised networks, mainly powered by renewable energy [71]. European citizen energy communities can empower local stakeholders, yet engagement is often limited by social, economic, and regulatory barriers [72, 73]. There is a strong link between PV and REC [74], with applications in other technologies, such as storage batteries [67]. These studies show conditions of economic convenience. RECs are emerging as one of the most promising tools for combining ecological transition and social inclusion. Thanks to the collective participation model, RECs enable reductions in energy costs, improved access to energy, and a more equitable redistribution of the economic benefits of the green transition, thereby contributing directly to the fight against energy poverty [19, 75]. The design and management of communities require customised strategies to maximise the energy yield and economic benefits of prosumers [76]. However, to generate a lasting social impact, these strategies must be integrated with welfare objectives and climate policy instruments, such as carbon credits, which encourage the use of renewable sources, especially in areas with high emission costs [77, 78].

Energy efficiency is crucial, but vulnerable groups risk being left behind [79]. When supported by clear, stable, and inclusive public policies [80], RECs can become drivers of energy equity, ensuring affordable energy for vulnerable households and reducing territorial inequalities. Integrating RECs with social housing effectively generates economic and environmental benefits, as self-production and energy sharing in working-class neighbourhoods reduce bills and boost community resilience [81]. ECs can support sustainable and inclusive energy transition, but while some of them involve vulnerable households, others fail due to market pressures and limited regulatory support [82]. In this way, the energy transition takes on a truly inclusive dimension, capable of strengthening the sense of belonging and local solidarity.

A decisive aspect of community sustainability concerns the equitable distribution of benefits. Recent studies [11, 38, 39] show that transparent and participatory profit-sharing models are essential for maintaining internal cohesion and preventing inequalities among members. In this regard, some intermediate benefit-sharing approaches [37] represent innovative solutions by distributing revenues based on consumption and virtuous behaviour, rewarding efficiency and individual responsibility; or by adding a bonus for low-income members, integrating social justice criteria into the economic functioning of the community.

From an economic perspective, evidence indicates that RECs are more advantageous and stable than individual self-consumption models [40]. This greater efficiency, combined with the possibility of redistributing benefits, increases the model's social legitimacy and acceptance among citizens [42]. Energy communities thus become an integral part of a new paradigm of sustainable development, based on cooperation, the reduction of inequalities, and the enhancement of local resources.

Looking ahead, RECs are not only a way to produce energy in a decentralised manner, but also a space for collaboration between citizens and institutions. They represent a model of energy transition that is not only sustainable from a technical and economic point of view but also fair and shared, grounded in equity, solidarity, and responsibility towards the territory.

Conclusions

The analysis carried out has shown that investing in an 80 kW PV system, designed for a collective self-consumption model, is an economically sound and socially sustainable option, capable of guaranteeing significant returns even in scenarios of progressive reduction of public support. The results obtained highlight the maturity of the REC model as an energy transition tool, capable of combining economic competitiveness, social equity and territorial cohesion.

In the baseline political scenario, which envisages the application of the incentives currently in force, the economic and financial parameters take on extremely positive values: the NPV increases from 10,407 to 657,375 € as the share of self-consumption increases. Focusing on the self-consumption range between 30 and 70% the following results emerge: NPV/Size between 2556 and 5791 €/kW, PI between 1.83 and 4.14, DPBT between 0.61 and 1.71 years, and IRR between 67 and 176%. This shows how energy sharing incentives have a multiplier effect on profitability, promoting the spread of cooperative energy models and accelerating local investment. However, even in the alternative scenario, without incentives, the project remains highly attractive: the NPV ranges from 1693 to 3777 €/kW, and the IRR ranges from 38 to 98% for self-consumption between 30 and 70%.

Sensitivity and risk analysis further confirmed the robustness of the economic model. Monte Carlo simulations showed a 100% probability of positive NPV in the incentivised scenario and over 98% in the non-incentivised scenario, even in the presence of unfavourable changes in the primary economic variables. The percentage of self-consumption emerges as the most critical driver: a reduction in this percentage has significantly more negative effects than changes in investment costs or energy prices. This data reinforces the need for management policies and strategies to maximise the share of locally shared energy, including through coordination tools between producers and consumers.

The managerial implications suggest that the lever for improving profitability does not necessarily lie in increasing incentives, but rather in optimising self-consumption levels and reducing investment costs. The increase in NPV of approximately 809 €/kW for every additional 10% of self-consumption highlights how intelligent demand management and energy flexibility (including through storage systems or intelligent management of electrical equipment) are key tools for economic sustainability.

These results have important political implications. They show that the REC model is now mature enough to function even without strong economic support from the State. For this reason, public policies should shift their focus from direct incentives to creating favourable conditions for community growth. In practice, it would be useful to focus on simpler rules, streamlined administrative procedures, and better digital infrastructure to make it easier to set up and manage RECs. In this way, the State could focus on building a stable, accessible environment that ensures everyone has the opportunity to participate in and benefit from the energy transition. The results indicate that coordinated action between public bodies is needed. At the national level, it is important to define a clear, long-term strategy for RECs with simple rules, stable incentives, and faster procedures. At the local level, on the other hand, it is necessary to encourage collaboration between the public and private sectors, reuse brownfield sites for new plants, and support projects in weaker areas. In this way, RECs can become a concrete tool for local development, social cohesion, and ecological transition.

A further innovative contribution of this study concerns the in-depth analysis of the distributive dimensions. The methods of distributing benefits among stakeholders – producers, consumers, public bodies, vulnerable households, and local entities – are a key element in the political and social legitimacy of RECs. The simulations showed examples of benefit distribution aimed at promoting social support and territorial redevelopment, with a view to supporting equity and inclusion criteria. The introduction of ESCOs as an additional stakeholder also highlights the importance of partnerships with specialised technical and financial operators, which can reduce investment risks and improve the operational efficiency of communities.

The work has some limitations. The analyses can be replicated across different geographical contexts, depending on the number of renewable self-consumers involved. The sphere of incentives requires more specific assessments in terms of public economics, as markets should eventually become self-sufficient without relying on incentive policies. However, energy policies need to protect the most vulnerable sections of the population. Decentralised systems also need to reduce the share of fixed costs in the grid, and economic analyses of the integration of storage batteries can play a key role in this direction, helping increase energy independence. Similarly, the incentive decree also covers other forms of renewable energy, in addition to photovoltaics, proposed in this study. In addition, this work has proposed benefit distributions for the collective share of the REC, but future analyses will also need to extend them to the collective share. Similarly, the results may change depending on the number of members, the number of members divided into specific categories, and the percentage distributions between the different categories. The general rule will be that where the number of members within a category increases, for example, that of energy poverty, the benefits for individual RSCs will inevitably decrease.

Looking ahead, RECs that move towards SDGs 7 and 11 are not only a means of producing clean energy but also an example of collaboration among citizens, businesses, and institutions. They show that the energy transition can be not only technically and economically sustainable but also fair and shared, grounded in equity, solidarity, and participation.

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Data availability
Data are available from the authors upon reasonable request.

Declarations

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Competing interests
The authors declare no competing interests.

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