Cities 147 (2024) 104828

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Lighting the future of sustainable cities with energy communities: An economic analysis for incentive policy

Idiano D'Adamo[a,*], Massimo Gastaldi[b], S.C. Lenny Koh[c], Alessandro Vigiano[d]

[a] Department of Computer, Control and Management Engineering, Sapienza University of Rome, Via Ariosto 25, 00185 Rome, Italy
[b] Department of Industrial and Information Engineering and Economics, University of L'Aquila, Italy
[c] Sheffield University Management School, University of Sheffield, Sheffield S10 1FL, UK
[d] Sapienza University of Rome, Rome, Italy

ARTICLE INFO

Keywords:
Economic analysis
Energy communities
Subsidies
Smart cities
Sustainable cities

ABSTRACT

Inland areas are suffering from depopulation and a lack of services, with many citizens deciding to move to the city. Smart cities require a decentralised and collective energy model in the form of renewable energy communities (RECs). This work aims to propose an economic analysis of residential photovoltaic systems within a REC according to different incentive and market scenarios. For this scope, the Net Present Value (NPV) is used in both baseline and alternative scenarios showing a very good profitability, confirmed by sensitivity, scenario and risk analysis.

It is therefore evident how the avoided cost in the bill has a decisive impact on the result and how this is amplified by virtuous behaviour in consumption synchronous to the production phase. Subsequent analyses concern how the profits obtained are divided among the prosumers and it is shown that revenues shared according to a partial energy consumption profile may be the right compromise. In order to consider a more realistic case an additional consumer is analysed within REC. The proposed analyses show interesting policy implications: the subsidies and citizens behaviour are key factors for sustainable cities based on green energy production and consumption.

1. Introduction

The trend in the literature shows an increased focus on the Sustainable Development Goals (SDGs) (Ordonez-Ponce, 2023). Sustainable education, energy and commodity independence, the development of new jobs, subsidies for the development of the green economy, environmental protection and energy communities are the pillars of a sustainable society (Biancardi et al., 2023). Energy communities can support a number of sustainable goals, such as SDGs 7, 11, 13 and 17 (Wuebben, Romero-Luis, & Gertrudix, 2020).

Renewable energy communities (RECs) are able to assign greater responsibility to end-use customers in both urban and rural settings (Trevisan, Ghiani, & Pilo, 2023). However, the challenge is to value the interactions between different professionals, institutions and citizens (Musolino, Maggio, D'Aleo, & Nicita, 2023) and to define a new social model for the ecological transition (D'Adamo, Mammetti, Ottaviani, & Ozturk, 2023).

RECs are response mechanisms to the electricity consumption required for daily routines (Albouys-Perrois et al., 2022). However, the analysis of individual case studies does not only show strengths (Musolino et al., 2023) and the literature highlights some critical issues: (a) RECs are mainly conceptualised as places, instead of participatory processes (Bauwens et al., 2022), (b) RECs may have implementation problems due to the lack of initiative from local members (Koirala et al., 2018), (c) the cost of some digital technologies (Ceglia, Marrasso, Pallotta, Roselli, & Sasso, 2022) and the issue of trust (Moroni, Alberti, Antoniucci, & Bisello, 2019) for RECs remain unresolved.

The willingness to join energy communities is strongly and positively influenced by environmental concerns and social trust. The social contexts that support the development of RECs are structural interactions with neighbours and civic norms with family members (Caferra, Colasante, D'Adamo, Morone, & Morone, 2023). The topic of participation in RECs is also proposed in other studies. Economic benefits, achievement of renewable energy goals and participation in social activities based on energy improvement support such initiatives (Haji Bashi et al., 2023).

* Corresponding author.
E-mail addresses: idiano.dadamo@uniroma1.it (I. D'Adamo), massimo.gastaldi@univaq.it (M. Gastaldi), s.c.l.koh@sheffield.ac.uk (S.C.L. Koh), alessandrovigiano@gmail.com (A. Vigiano).

https://doi.org/10.1016/j.cities.2024.104828
Received 24 November 2023; Received in revised form 12 January 2024; Accepted 23 January 2024
Available online 1 February 2024

Nomenclature

C	Consumer
CSC	Collective self-consumption
DCF	Discounted cash flow
HM	High Market
HS	High Subsidies
LM	Low Market
LS	Low Subsidies
NPV	Net Present Value
PV	Photovoltaic
REC	Renewable energy community
RSC	Renewable self-consumer
SDG	Sustainable Development Goal

The economic theme prevails over social or political objectives (Bauwens et al., 2022), however, the most correct scope of analysis is to take a holistic view of the different dimensions (Heuninckx, te Boveldt, Macharis, & Coosemans, 2022). The development of RECs is linked to policy choices, which are considered more relevant than market factors (Petrovich, Carattini, & Wüstenhagen, 2021), and it is evident that renewable energies result in more significant savings as electricity prices rise (Kurdi, Alkhatatbeh, Asadi, & Jebelli, 2022) and as more conscious behaviour increases the percentage of self-consumption (D'Adamo, Gastaldi, & Morone, 2022a). When the marginal price is higher than the levelised cost of electricity, any additional investment makes the project more profitable and, beyond the environmental benefits (Sousa et al., 2023), such initiatives reduce energy poverty when low-income households are involved (Cutore, Volpe, Sgroi, & Fichera, 2023). Therefore, tools that can support the components of a REC during the planning and operational phases are also useful (Lazzari et al., 2023).

Once the limitations and potential of RECs have been highlighted, it must be emphasised that within future strategies for their implementation, a key role is played by risk-benefit sharing (Dorahaki, Rashidinejad, Fatemi Ardestani, Abdollahi, & Salehizadeh, 2023). In this regard, economic analyses highlight how the issue of political incentives is crucial for assessing the profitability of such investments (D'Adamo, Mammetti, et al., 2023). This is where the gap in the literature emerges. Each country is developing new incentive decrees, replacing previous ones, or completely new ones to support the transition to achieving the net zero goals. Therefore, the objective of economic analyses is to provide up-to-date profitability or otherwise, and these scenarios do not only vary according to political scenarios, but also market scenarios. This study considers the Italian context, as an example of a mature photovoltaic market, in which the new incentives envisaged by the REC Decree 2023 are applied; and evaluates how profitability varies as a function of several critical variables such as the percentage of self-consumption, the avoided energy cost in the bill, the energy selling price and the investment cost beyond the value of the incentive. In addition, prosumer benefit-sharing scenarios are proposed in which the energy consumption of individual prosumers is considered (D'Adamo, Mammetti, et al., 2023), to which new scenarios involving consumers are added in order to increase the real cases and represent the real world.

2. Literature review

The goal of a smart city, identified as a set of economic activities, is to support sustainable growth (Stamopoulos, Dimas, Siokas, & Siokas, 2024). Indeed, smart cities support the achievement of the SDGs by aiming to improve the quality of life of citizens through the production and consumption of renewable resources in the urban context. It is now necessary for carbon-based cities to modify their strategies by favouring sustainable practices (Yang et al., 2023), based on renewable sources and energy efficiency (Gallardo-Saavedra et al., 2022), supported by artificial intelligence (Mateo Romero et al., 2022). In a context of urban energy transition, a balance must be struck between buildings, open spaces and energy production systems (Marrone et al., 2023). Solar strategies need to be framed according to building type and street layout (Singh, Hachem-Vermette, & D'Almeida, 2023) and new technological developments are needed (Ahmed et al., 2017; Ibn-Mohammed et al., 2017). However, the challenge must also be extended to other renewables that contribute to the ecological transition (Hou, Man Li, & Sittihai, 2022). The combined effect of green technology innovation and renewable energy will have an effect in the long run on carbon neutrality (Shao, Zhong, Liu, & Li, 2021). Furthermore, also fiscal policies that are applied in the energy context are essential to limit carbon emissions (Shan et al., 2021).

The European Union is oriented towards combating climate change and tackling energy security aimed at reducing fossil fuel dependency and inflationary phenomena (Şanta, 2022). Such a challenge can be met with effective energy policies based on citizen cooperation (Piao & Managi, 2023). A keyword to define the literature on this topic is the prosumer, whose role is also to facilitate the transformation from a centralised to a decentralised system, as well as to identify a new paradigm that has changed the way energy is produced, used and exchanged as a resource (Onu, Zambroni de Souza, & Bonatto, 2023). The single prosumer, multiple aggregated prosumers and an energy community with peer-to-peer exchange possibilities (Gržanić, Capuder, Zhang, & Huang, 2022) are considered strategic for the transformation of cities (Gómez-Navarro, Brazzini, Alfonso-Solar, & Vargas-Salgado, 2021). Some key variables on this issue are the structure of prosumer supply and demand, the way costs are distributed within communities and the implementation of demand-response programmes (Volpato et al., 2022).

The European Commission proposes energy communities at the centre of creating sustainable cities and emphasises that citizens are at the forefront of a clean energy transition (European Commission, 2022a). The 2019 European Clean Energy Package introduced new concepts such as collective self-consumption (CSC) and RECs (Lowitzsch, Hoicka, & van Tulder, 2020). CSCs do not emphasise organizational structure, unlike RECs. Specifically, CSCs are composed of renewable self-consumers (RSCs) located in the same building or within a residential complex. RECs denote a set of entities that can produce energy between neighbouring renewable plants, even if they are not located in the same building (Frieden et al., 2020).

Promising examples are combinations of solar photovoltaics (PV) and storage to increase self-consumption or smart electric vehicles (Koh et al., 2021) that recharge with renewable energy (Kubli & Puranik, 2023) as well as when combined for hydrogen production (Raimondi & Spazzafumo, 2023). Algorithm applications can facilitate their self-sufficiency in order to maximise the cost of electricity bills (Aittahar et al., 2023) but this requires the development of an energy management system that predicts and monitors real-time production, energy demands, storage capacities and operational constraints (Ahmadifar, Ginocchi, Golla, Ponci, & Monti, 2023). Thus, the creation of a REC can bring both environmental and economic benefits (Felice et al., 2022), and even more significant benefits are achieved by implementing community-based projects and near-zero energy buildings (Liu et al., 2022). Moreover, RECs can also support industrial decarbonisation systems (Gribiss, Aghelinejad, & Yalaoui, 2023), enabling them to be more competitive due to lower costs.

3. Italian regulatory framework

Renewables will account for 23.0 % of the energy consumed in the European Union in 2022, up from 21.9 % in 2021 – Table S1. The growth is not high, but nevertheless important considering that in 2021 there was a slight decrease compared to 2020 (22.0 %). Among these countries, Sweden stands out with 66 % followed by Finland with 47.9 %. The renewable component in electricity will increase from 37.8 % to 41.2 % in 2022 compared to 2021. Sweden stands out with 83.3 % followed by Austria with 74.7 % (Eurostat, 2023). Among renewable energy sources, PV source has a significant growth. In 2022, 240 GW of additional power will be installed, reaching a cumulative value of 1185 GW – Table S2. China is the global leader with 414.5 GW followed by the European Union with 209.3 GW. Among these countries, Germany stands out, ahead of Spain and Italy (International Energy Agency, 2023). Some authors have pointed out the presence of several citizen-led energy initiatives (Schwanitz et al., 2023): energy cooperatives, renewable energy communities, energy communities, sustainable energy communities, housing cooperatives and associations, sustainable mobility cooperatives, energy clusters, historical rural electrification cooperatives and eco-villages. Results of this study estimated 10,540 number of initiatives, 2,010,600 people involved and 7.2–9.9 GW installed renewable capacities – Table S3. The choice of Italy as evidenced by the literature proposed in sections 1 and 2 appears to be justified. In particular, while this country together with Germany was the global leader in photovoltaic development several years ago, it now tends not to grow as much as compared to other countries and, for example, at European level it is overtaken by Spain. There is therefore a need to reverse the trend.

The Italian incentive decree provided a subsidy of 100 €/MWh for CSC configurations and 110 €/MWh for RECs for a period of 20 years. Recently, a new REC decree 2023 promoted by the MASE (Ministry of the Environment and Energy Security) was made public that defines the new incentive mechanisms. Recipients of the measures include (i) renewable energy communities; (ii) collective self-consumption of energy from renewable sources, carried out by groups of consumers operating within the same building or residential complex; and (iii) personal self-consumption of energy from remote renewable sources, in which an individual independently uses energy from various production and consumption sites under his or her management. Energy can be sold through dedicated offtake, and a premium tariff is charged on the shared energy. This incentive remains stable for 20 years and varies according to the capacity of the renewable source plants generating the shared energy:

- For plants with power less than or equal to 200 kW → Tariff = 80 + max (0; 180 - Zonal Price) with a maximum of 120 €/MWh.
- For systems with power greater than 200 kW and less than or equal to 600 kW → Tariff = 70 + max (0; 180 - Zonal Price) with a maximum of 110 €/MWh.
- For plants with power greater than 600 kW and less than or equal to 1 MW → Tariff = 60 + max (0; 180 - Zonal Price) with a maximum of 100 €/MWh.

In addition, there is an addition of 4 €/MWh for PV systems located in central Italian regions (including also Abruzzo) due to lower insolation, while in northern Italian regions, the addition amounts to 10 €/MWh.

4. Materials and methods

This section first proposes the model used for the economic evaluation of the photovoltaic system (section 4.1). Next, the reference scenarios for the PV plant are described (section 4.2) and the models for the distribution of benefits in the RECs are then proposed (section 4.3). Finally, the input data are presented (section 4.4).

4.1. Economic model for a PV system

The discounted cash flow (DCF) method assesses the profitability of a project and the Net Present Value (NPV) indicates the wealth or loss generated by an investment (D'Adamo, Dell'Aguzzo, & Pruckner, 2023; de Jesus, Pinheiro Neto, & Domingues, 2023). Among the sources of revenues, we consider: i) tax deductions; ii) incentives related to energy communities; iii) energy cost savings, i.e. avoided costs in energy bills; and iv) sale of unused energy for self-consumption. Among the cost components, investment costs prevail and it is assumed that the inverter will be replaced after ten years. The profitability model is that proposed in the literature (D'Adamo, Mammetti, et al., 2023) and reported in the Supplementary File.

4.2. Identification of scenarios within PV configuration

The mix of scenarios analysed in this study aims to combine the market context and policy choices. The selling price is set equal to 120 €/MWh calculated based on the monthly average prices per time slot and market area provided by GSE S.p.A.. The residential sector is the focus of our study, and a 20 kW size is chosen because it may be adequate to meet the energy requirements of an apartment building with four households (D'Adamo, Mammetti, et al., 2023). The location of the system is on the roof of this dwelling and possibly on spaces designated for car parking, with no additional land requirements.

For 20 kW size, section 3 indicated that the incentive tariff can vary and two distinctive scenarios were identified according to Decree REC 2023:

- Low subsidy (LS) scenario - 84 €/MWh, including a bonus of 4 €/MWh;
- High subsidy (HS) scenario - 124 €/MWh, including a bonus of 4 €/MWh.

In the months of 2023, average monthly prices by time slot and Central Italy market zone were found to exceed the 180 €/MWh benchmark for calculating the tariff. In addition, developments in the energy sector led to fluctuations in electricity costs. Therefore, two separate market scenarios were considered in order to evaluate the energy cost:

- High market (HM) scenario - 500 €/MWh;
- Low market (LM) scenario - 350 €/MWh.

These are obtained based on literature and data collected from Italian consumers. In particular, they are higher than what has been proposed in the literature (D'Adamo, Mammetti, et al., 2023), i.e. 250 €/MWh and 400 €/MWh in order to take into account the increased energy costs in the bills and to be able to extend the case study example.

4.3. Profit distribution model in the REC

We now proceed to analyse the different approaches for distributing the benefits obtained from the PV system described in the reference case. The prosumer is expected to consist of four RSCs and there are no intermediate figures to be given economic consideration. Their consumption profiles are assumed as follows:

- RSC1 → 80 % self-consumed and 20 % not self-consumed;
- RSC2 → 65 % self-consumed and 35 % not self-consumed;
- RSC3 → 35 % self-consumed and 65 % not self-consumed; and
- RSC4 → 20 % self-consumed and 80 % not self-consumed.

Thus, the assumption is that the overall self-consumption profile is 50 %. The literature (D'Adamo et al., 2022a) is again considered to evaluate the scenarios in which the division of benefits within RECs is proposed. Specifically, three scenarios for revenue distribution are identified:

1. Scenario "revenues split equally", where all RSC benefits are dispersed equally among them irrespective of their energy consumption profiles.

2. Scenario "revenues shared entirely according to energy consumption profile", and benefits are distributed based on the energy

consumption profile of each RSC. In this scenario, users who use self-consumption more frequently tend to benefit from it. It will also consider the possibility of having an additional consumer that does not produce energy but only consume it.

3. Scenario "revenues shared according to a partial energy consumption profile", wherein only a portion of the energy consumed by the user is considered beneficial. Nonetheless, an exchange price within REC is required because it is the only way to initiate an intermediary mechanism between the two previously mentioned.

The exchange price is higher than the selling price to which RSC 1 and 2 are eligible, because they are virtuous and have high self-consumption rates. At the same time, the exchange price is lower than the billed purchase price, which should be paid by RSC 3 and 4 (that instead have lower self-consumption rates). This creates a win-win solution. The exchange described in this scenario is considered only by an economic point of view and does not involve any changes from a technical point of view, as no storage systems are planned.

Thus, in this third scenario, a fixed exchange price that does not vary according to various parameters (Heilmann, Wensaas, Crespo del Granado, & Hashemipour, 2022). Considering that the costs incurred by the RSCs are the same, the distribution of benefits among these RSCs will be calculated according to the literature (D'Adamo, Mammetti, et al., 2023). Once the NPV value has been identified, benefits will be reported according to these specific percentages for each RSCs. The profit distribution model is reported in the Supplementary Material File.

4.4. Input data

This work considers a plant size of 20 kW as mentioned above with four RSCs. The region of central Italy, where the plant is situated, has a moderate amount of insolation. In the first year, energy production is 38,996 kWh, and by the twentieth year, it has dropped to 33,477 kWh. There is a third party financing the investment. The DCF model sets the plant's time horizon at 20 years and its opportunity cost of capital at 5 %.

When evaluating a PV system's profitability, the self-consumption percentage is a critical factor to consider. Accordingly, several scenarios were considered, ranging from 0 % to 100 %. Scenarios with low percentages, especially 0 %, might be unrealistic in a residential context but are still included for mathematical purposes. In contrast, the scenario with high percentages is the one in which we tend towards energy self-sufficiency and in particular 100 % of all the energy produced is self-consumed.

Within the energy community, an exchange price is charged which is assumed equal to the average value between the purchase and selling prices of electricity. Thus, the values chosen are:

- 235 €/MWh for the low market scenario;
- 310 €/MWh for the high market scenario.

In addition, unitary investment cost is assumed equal to 2000 €/kW. All data used in this paper are proposed in Table S4 and were defined according to literature (Cerino Abdin & Noussan, 2018; Chiacchio, Famoso, D'Urso, & Cedola, 2019; D'Adamo et al., 2022a; D'Adamo, Dell'Aguzzo, & Pruckner, 2023; D'Adamo, Mammetti, et al., 2023; Luthander, Widén, Munkhammar, & Lingfors, 2016; Ramli, Hiendro, Sedraoui, & Twaha, 2015; Talavera, Muñoz-Cerón, Ferrer-Rodríguez, & Pérez-Higueras, 2019). PV system is characterised by monocrystalline modules.

5. Results

This section presents the profitability analysis of a 20 kW PV plant within a REC in a baseline context (section 5.1) and evaluating alternative scenarios (section 5.2). It then proceeds to describe how the profits can be divided among the RSCs (section 5.3) and including both prosumers and an additional consumer (section 5.4). Finally, reflections on the relationship between RECs and smart cities are proposed (section 5.5).

5.1. Photovoltaic system - baseline scenario

The economic model described in section 4 and the related input data allow the NPV to be calculated in the different cases of the baseline scenario where the percentage of self-consumption has been chosen as the key variable. Forty-four cases are considered from the following combinations – Table 1:

- eleven self-consumption values, where the extremes 0 % and 100 % are considered with a delta of 10 %;
- two market scenarios, in which a low market scenario (350 €/MWh) and a high market scenario (500 €/MWh) are presented;
- two policy scenarios, in which a low subsidy scenario (84 €/MWh) and a high subsidy scenario (124 €/MWh) are proposed.

The results show that profitability is verified in most cases and only when the energy is totally sold, the NPV is negative. Since the purchase price on the grid is higher than the sale price to the grid, rising self-consumption increases the bill savings much more than the decrease in benefits from selling energy to the grid. In this regard, it is useful to evaluate the Break-Even point that identifies at what percentage of self-consumption the project starts to be profitable (Fig. 1): this value is below 3 % in the Low market scenarios and below 2 % in the High market scenarios.

These results therefore indicate that the implementation of a PV plant within a REC is profitable even in contexts where self-consumption is low; however, the prosumer's goal is to have synchronous behaviour between energy production and consumption. In this respect, it will therefore tend to reach those values that are typically reported in the literature and that vary between 30 and 60 % (D'Adamo, Dell'Aguzzo, & Pruckner, 2023; Fett, Keles, Kaschub, & Fichtner, 2019; Lang, Ammann, & Girod, 2016; Luthander et al., 2016) – Fig. 2.

The results show that the NPV varies between 2953 €/kW in a LS-LM context with 30 % self-consumption percentage to 9584 €/kW in a HS-HM context with 60 % self-consumption percentage. It is possible to make some considerations on the three variables that have the greatest impact on this result, but it should be noted that the comparison is not homogeneous since the difference between the HS and LS scenarios is 40 €/MWh while that between HM and LM is 150 €/MWh. The HM scenarios have a higher NPV of 1401–2802 €/kW compared to LM this value is evidently derived from the higher cost in the bill which is a positive element for the prosumer as it increases its savings following the installation of a PV system. Furthermore, the difference increases as the percentage of self-consumption increases since the share of energy produced and consumed by prosumers increases. The same reasoning applies to assessing the difference in NPV between the HS and LS

Table 1
NPV (€) for PV plant – Baseline scenario.

Self-consumption	Low Subsidy & Low Market	Low Subsidy & High Market	High Subsidy & Low Market	High Subsidy & High Market
0 %	−5877	−5877	−5877	−5877
10 %	15,767	25,105	17,711	27,049
20 %	37,411	56,088	41,299	59,976
30 %	59,055	87,071	64,887	92,902
40 %	80,699	118,053	88,475	125,829
50 %	102,343	149,036	112,063	158,755
60 %	123,987	180,018	135,651	191,682
70 %	145,631	211,001	159,239	224,608
80 %	167,275	241,984	182,827	257,535
90 %	188,920	272,966	206,415	290,461
100 %	210,564	303,949	230,003	323,388

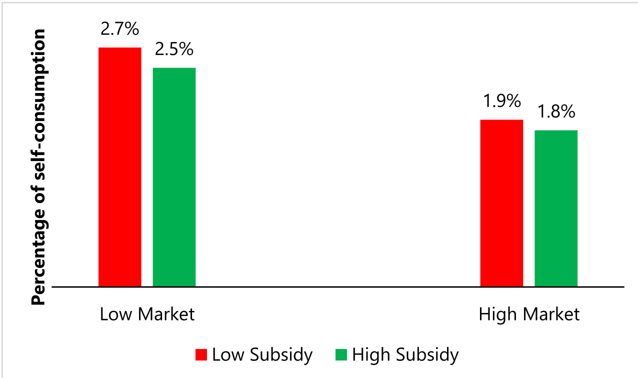

Fig. 1. Break-even point analysis – Share of self-consumption.

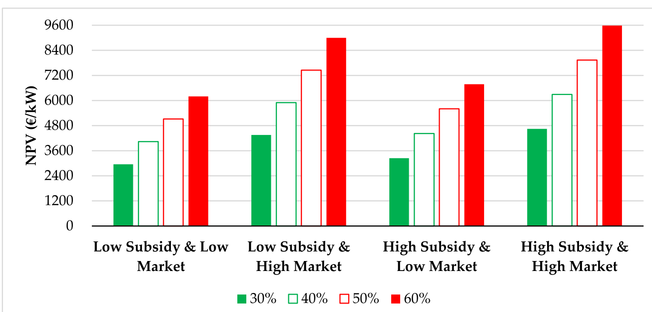

Fig. 2. NPV (€/kW) for PV plant – Baseline scenario.

scenarios, which turns out to be 292–583 €/kW. Finally, it should also be pointed out that the prosumer's virtuous behaviour means that each 10 % increase in self-consumed energy results in an increase in NPV of 1082 and 1179 €/kW in the LM context for the LS and HS policy scenarios, respectively. In contrast, the increase in NPV is 1549 and 1646 €/kW in the HM for the two different policy scenarios.

The results of this work can be compared with the literature. Some focus on the residential sector of a PV system without its inclusion within a REC: 2802–3022 €/kW (Campoccia, Dusonchet, Telaretti, & Zizzo, 2014), 2123 €/kW (Squatrito, Sgroi, Tudisca, Trapani, & Testa, 2014), 960 €/kW (Paiano, Lagioia, & Ingrao, 2023) and 98–1967 €/kW (D'Adamo, Gastaldi, & Morone, 2022b). There are also more significant values such as 3300 €/kW (Bortolini, Gamberi, Graziani, Mora, & Regattieri, 2013), 3000–5500 €/kW (Tudisca, Di Trapani, Sgroi, Testa, & Squatrito, 2013) and 1061–7426 €/kW (D'Adamo, Dell'Aguzzo, & Pruckner, 2023). The lowest values occur at low self-consumption rates and in the absence of incentives.

In addition, there are also several economic analyses on the values obtained in relation to RECs. Consequently, NPV is assumed equal to 700–1400 k€ (Viti, Lanzini, Minuto, Caldera, & Borchiellini, 2020), 90–140 k€ (Cutore, Volpe, et al., 2023), 74–248 k€ (Barbaro & Napoli, 2023), (−2317) - (−399) k€ (Cutore, Fichera, & Volpe, 2023), (−254) - 1211 k€ (Aruta, Ascione, Bianco, & Mauro, 2023), 40–52 k€ (De Santi et al., 2022) and 50–1174 k€ (Iazzolino et al., 2022). Negative values are recorded when considering a short plant lifetime or when the market price of energy is very low and therefore the convenience of installing the plant is lost. Other authors quantify the economic savings from its installation as 32 % (Canova et al., 2022).

Further comparison examples highlighted the relevance of alternative analyses based on sensitivity, scenario and risk analysis. The baseline scenario proposes values varying between 106 and 3025 €/kW depending on the political and market contexts, rising to 3557 €/kW in the alternative scenario (D'Adamo et al., 2022a). Other analyses show that the NPV varies between 1919 and 8084 €/kW considering a self-consumption percentage between 30 % and 60 % and reaches 9952 €/kW and 11,770 €/kW in the sensitivity and scenario analyses respectively (D'Adamo, Mammetti, et al., 2023).

5.2. Photovoltaic system - alternative scenarios

In order to give robustness to the results obtained, several analyses were conducted analysing alternative scenarios. The critical variables are chosen according to the literature analysis (D'Adamo et al., 2022a, 2023b; Jiménez-Castillo, Muñoz-Rodriguez, Rus-Casas, & Talavera, 2020). Specifically, variations of 50 €/MWh for the energy purchase price, 50 €/MWh for the energy selling price and 200 €/kW on the unit investment cost are considered. Analyses are conducted for self-consumption percentages ranging from 30 % to 60 %. The combination of critical variables in market and political contexts results in ninety-six case studies including pessimistic and optimistic variations. Sensitivity analysis shows the variation of a single variable – Table 2.

The results confirm that profitability is verified even in the pessimistic scenarios, and the NPV value reaches its lowest value in correspondence of the Low Subsidy context, with a percentage of self-consumption at 30 % and with the variation of the purchase price variable: 2390 €/kW and 3790 €/kW in the LM and HM scenarios respectively. Similarly, the NPV increases in correspondence with the optimistic scenarios, reaching its maximum value in correspondence with the High Subsidy context, with a percentage of self-consumption at 60 % in correspondence with the variation of the energy purchase price variable: 7716 €/kW and 10,518 €/kW in the LM and HM scenarios respectively. This thus indicates how, depending on the case study analysed, different variables can have more influence. In these contexts, both the selling price and the purchase price are made to vary in the same way, and it emerges that clearly in a context of greater synchronisation between energy production and consumption, the variable relating to bill savings has a greater impact. While it is true that at 30 % the selling price has a greater impact than the purchase price, analysing

Table 2
NPV (€) for PV plant – Sensitivity analysis.

	Low Subsidy			High Subsidy	
	Pessimistic	Optimistic		Pessimistic	Optimistic
	Purchase price (Low Market)			Purchase price (Low Market)	
30 %	49,717	68,394	30 %	55,548	74,225
40 %	68,248	93,151	40 %	76,023	100,926
50 %	86,779	117,907	50 %	96,499	127,627
60 %	105,310	142,664	60 %	116,974	154,328
	Purchase price (High Market)			Purchase price (High Market)	
30 %	77,732	96,409	30 %	83,564	102,241
40 %	105,602	130,505	40 %	113,378	138,280
50 %	133,472	164,600	50 %	143,191	174,320
60 %	161,341	198,695	60 %	173,005	210,359
	Selling price (Low Market)			Selling price (Low Market)	
30 %	47,790	70,320	30 %	53,622	76,152
40 %	71,196	90,203	**40 %**	78,971	97,978
50 %	94,602	110,085	**50 %**	104,321	119,805
60 %	118,007	129,967	**60 %**	129,671	141,631
	Selling price (High Market)			Selling price (High Market)	
30 %	75,806	98,336	30 %	81,637	104,167
40 %	108,505	127,557	40 %	116,326	135,332
50 %	141,294	156,777	50 %	151,014	166,497
60 %	174,038	185,998	60 %	185,702	197,662
	Investment cost (Low Market)			Investment cost (Low Market)	
30 %	54,595	63,515	30 %	60,427	69,347
40 %	76,239	85,159	40 %	84,015	92,935
50 %	97,884	106,803	50 %	107,603	116,523
60 %	119,528	128,447	60 %	131,191	140,111
	Investment cost (High Market)			Investment cost (High Market)	
30 %	82,611	91,530	30 %	88,443	97,362
40 %	113,593	122,513	40 %	121,369	130,289
50 %	144,576	153,496	50 %	154,296	163,215
60 %	175,559	184,478	60 %	187,222	196,142

the results shows that this is no longer the case with 40 % of self-consumption. In fact, the amount of energy sold is greater than the amount of energy self-consumed, but the self-consumption price has a greater impact than the selling price. Analysing the impact of the individual variables from a mathematical point of view, it emerges that a change of 50 €/MWh in the purchase price implies that the NPV varies between 467 and 934 €/kW as the percentage of self-consumption increases. Conversely, a variation of 50 €/MWh in the selling price implies that the NPV varies between 299 and 563 €/kW as the percentage of self-consumption decreases. Finally, the variation of 200 €/kW in the investment cost results in a variation of 223 €/kW.

The subsequent scenario analysis allows an assessment of what happens when at least two variables change simultaneously. Again, optimistic and pessimistic scenarios are proposed for the two policy scenarios considering self-consumption rates from 30 % to 60 %. On the revenue side, both the purchase price of energy and the selling price are varied by 50 €/MWh. On the cost side, in addition to the investment, maintenance and insurance percentages were also included in order not to generate the same scenario as the one considered in the sensitivity analysis. The delta considered is 0.5 %. The number of cases examined is sixty-four – Table 3.

Profitability is also confirmed in all the new case studies examined. The results see the scenarios relating to changes in revenues affecting more than costs. In fact, the NPV under the 30 % self-consumption percentage in the LS policy context is 1923 €/kW with the reduction of the value relating to revenue components and 2379 €/kW that relating to the increase in costs. In contrast, in the HS scenario with 60 % self-consumption, the NPV is 10,094 €/kW with a reduction in cost components and 10,817 €/kW associated with the increase in revenue components. These figures also show how significantly the value of profitability can vary.

Finally, the risk analysis is conducted in which 1000 iterations of the NPV are proposed using the Monte Carlo simulation method – Fig. 3. The 3 critical variables (energy selling price, energy purchase price and unit investment cost) are associated with an average value equal to that used for the base case and a standard deviation corresponding to the delta considered for the previous alternative analyses. It is assumed that 50 % is considered as the percentage of self-consumption (D'Adamo, Mammetti, et al., 2023).

The results show the previous findings where profitability is verified in all cases. This 100 % is a result that is consistent with what has been proposed in the literature, where only a low energy purchase price led to some individual case studies where the NPV might not be positive (D'Adamo, Mammetti, et al., 2023). Evidently, the percentage of self-consumption may also influence this result. Therefore, 30 % was considered in the least favourable conditions (LS and HS), but only in a single case study was the NPV negative (Fig. S1). These results confirm that the investment of a PV plant within a REC can be very profitable and characterised by an almost zero economic risk component.

Table 3
NPV (€) for PV plant – Scenario analysis.

	Low Subsidy			High Subsidy	
	Pessimistic	Optimistic		Pessimistic	Optimistic
	Revenues (Low Market)			Revenues (Low Market)	
30 %	38,452	79,659	30 %	44,283	85,490
40 %	58,744	102,654	40 %	66,520	110,430
50 %	79,037	125,649	50 %	88,757	135,369
60 %	99,330	148,644	60 %	110,994	160,308
	Revenues (High Market)			Revenues (High Market)	
30 %	66,467	107,674	30 %	72,299	113,506
40 %	96,098	140,008	40 %	103,874	147,784
50 %	125,730	172,342	50 %	135,450	182,061
60 %	155,361	204,675	60 %	167,025	216,339
	Costs (Low Market)			Costs (Low Market)	
30 %	47,571	69,262	30 %	53,403	75,094
40 %	69,215	90,906	40 %	76,991	98,682
50 %	90,859	112,550	50 %	100,579	122,270
60 %	112,503	134,194	60 %	124,167	145,858
	Costs (High Market)			Costs (High Market)	
30 %	75,586	97,278	30 %	81,418	103,109
40 %	106,569	128,260	40 %	114,345	136,036
50 %	137,552	159,243	50 %	147,271	168,962
60 %	168,534	190,225	60 %	180,198	201,889

5.3. *Renewable energy community – Prosumers*

A REC indicates that the profit obtained in the different baseline (section 5.1) and alternative (section 5.2) scenarios must be divided among the RSCs. It is assumed that the combination of the consumption habits of these RSCs leads to an average self-consumption rate of 50 %. Starting from the equations proposed in the Supplementary Material, it is possible to break down the potential profits in the three scenarios. In order to allow for replicability of the model, the way in which the revenues are broken down is proposed. In fact, the value of the profits associated with each RSC is calculated by multiplying the percentage revenue split by the NPV that has been obtained. As for the revenues split equally scenario, one simply has to divide the NPV by the number of RSCs, resulting in a 25 % revenue split in this work. Before proceeding to examine the other two scenarios, it is considered that the total energy produced is 38,996 kWh and dividing 38,996 by 4 as if entitled to handle 9749 kWh. Relative to the "revenues shared entirely according to energy consumption profile" scenario, the amount of energy self-consumed by individual RSCs must then be assessed – Table 4. For example, RSC1 self-consumes 7799 kWh (80 % of 9749) and this results in revenues of either 2730 € or 3900 € of avoided cost in the bill depending on whether the bill price is 350 €/MWh or 500 €/MWh. The remaining amount of energy, which corresponds to 1950 kWh, is sold to the grid, generating revenue of 234 €, considering that the selling price is 120 €/MWh. The sum of these contributions determines the revenue associated with RSC1. The same is repeated for the other RSCs. At this point, the percentage value associated with each RSCs can be calculated, which in the example above is 32.3 % and 34.2 % depending on the LM and HM scenario respectively. It can be seen that RSC4, which unlike RSC1 has the lowest percentage of self-consumption, records a percentage of revenue of 17.7 % and 15.8 % in the LM and HM scenarios respectively. In fact, RSC4 self-consumes 20 % of the energy (1950 kWh) and thus saves 682 € and 975 € on the bill depending on whether the energy purchase price is 350 €/MWh or 500 €/MWh. To this revenue must be added that 80 % of the energy (7799 kWh) is sold at 120 €/MWh resulting in revenue of 936 €. The sum of these revenues results in 1618 € and 1911 € from which the percentages expressed above are obtained.

We now proceed to examine the scenario revenues shared according to a partial energy consumption profile. Taking RSC1 as an example, which self-consumes 80 % of its energy, its benefits associated with this form of revenue are those associated with the 50 % self-consumption rate (overall average value). Consequently, the savings avoided on the bill amount to 1706 € and 2437 € in the two market scenarios LM and HM respectively – Table 5. In addition, 20 % of the energy is sold to the grid, generating revenue of 234 €. This leaves 30 % of the energy consumed that cannot be valued at the energy purchase price. The value identified is the so-called exchange price, which corresponds to 235 €/MWh and 310 €/MWh in the LM and HM scenarios respectively. Thus, the benefits RSC 1 obtains are 687 € and 907 € respectively. The total revenues amount to 28.7 % and 29.6 % of total revenues in the LM and HM scenarios respectively. Let us now consider the situation of RSC 4, which values its self-consumption of energy at 20 %, obtaining revenue of 682 € and 975 € in the LM and HM scenarios respectively. The amount of energy sold would be 7799 kWh, but 50 % of this remains sold to the grid (4874 kWh yielding 585 €) and the remaining 20 % becomes energy exchanged with the other RSCs (687 € and 907 € in the two market scenarios). Thus, total revenues amount to 21.3 % and 20.4 % of total revenues in the LM and HM scenarios respectively. Thus, these percentage distributions represent intermediate values between the two

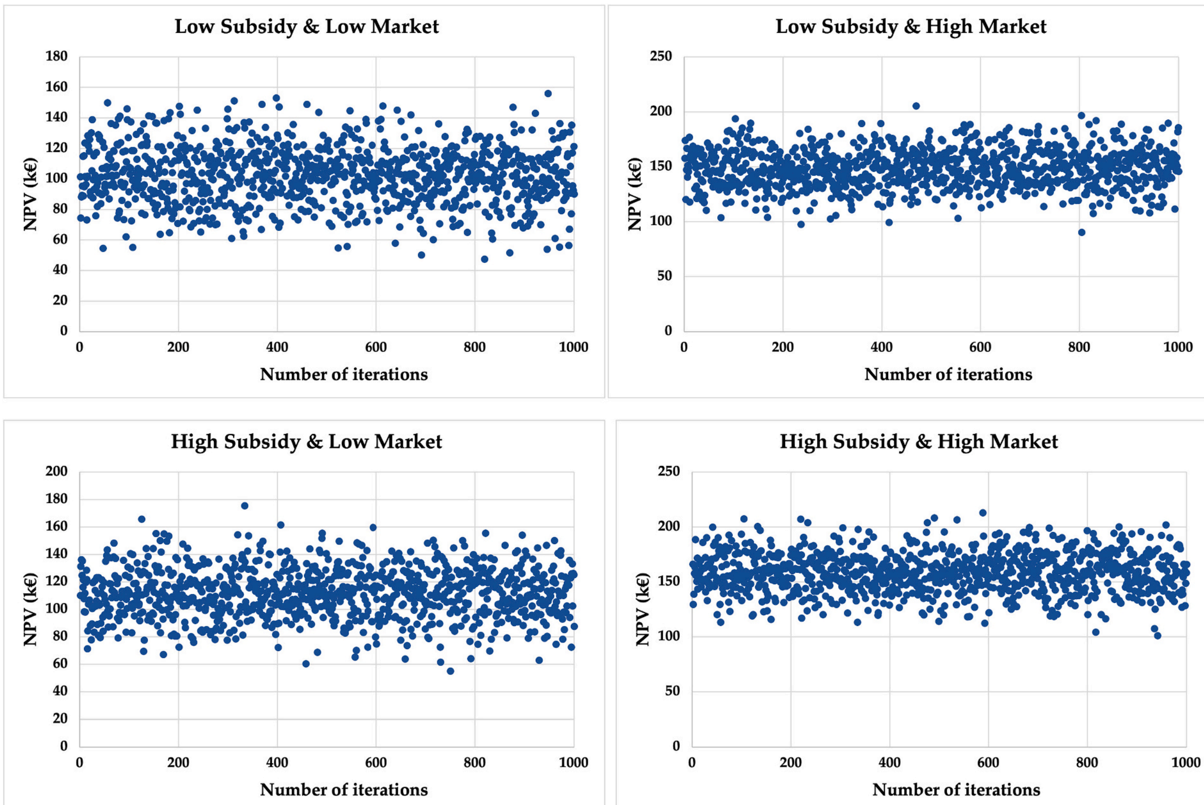

Fig. 3. NPV (€) for PV plant – Risk analysis (self-consumption 50 %).

Table 4
Scenario "revenues shared entirely according to energy consumption profile".

	RSC 1	RSC 2	RSC 3	RSC 4	Total
Energy produced (kWh)	9749	9749	9749	9749	38,996
Self-consumed energy (kWh)	7799	6337	3412	1950	19,498
Energy not self-consumed (kWh)	1950	3412	6337	7799	19,498
Scenario p^c 350 €/MWh and p^s 120 €/MWh					
Avoided costs in the bill (€)	2730	2218	1194	682	6824
Energy sales (€)	234	409	760	936	2340
Revenues (€)	2964	2627	1955	1618	9164
Percentage distribution of benefits	32.3 %	28.7 %	21.3 %	17.7 %	100 %
Scenario p^c 500 €/MWh and p^s 120 €/MWh					
Avoided costs in the bill (€)	3900	3168	1706	975	9749
Energy sales (€)	234	409	760	936	2340
Revenues (€)	4134	3578	2466	1911	12,089
Percentage distribution of benefits	34.2 %	29.6 %	20.4 %	15.8 %	100 %

Table 5
Scenario "revenues shared according to a partial energy consumption profile".

	RSC 1	RSC 2	RSC 3	RSC 4	Total
Energy produced (kWh)	9749	9749	9749	9749	38,996
Self-consumed energy (kWh)	7799	6337	3412	1950	19,498
Energy not self-consumed (kWh)	1950	3412	6337	7799	19,498
Partial self-consumed energy (kWh)	4874	4874	3412	1950	15,111
Partial not self-consumed energy (kWh)	1950	3412	4874	4874	15,111
Energy Exchange (kWh)	2925	1462	1462	2925	8774
Scenario p^c 350 €/MWh p^s 120 €/MWh and p^{ex} 235 €/MWh					
Avoided costs in the bill (€)	1706	1706	1194	682	5289
Energy sales (€)	234	409	585	585	1813
Energy Exchange (€)	687	344	344	687	2062
Revenues (€)	2627	2459	2123	1955	9164
Percentage distribution of benefits	28.7 %	26.8 %	23.2 %	21.3 %	100 %
Scenario p^c 500 €/MWh p^s 120 €/MWh and p^{ex} 310 €/MWh					
Avoided costs in the bill (€)	2.437	2.437	1.706	975	7.555
Energy sales (€)	234	409	585	585	1.813
Energy Exchange (€)	907	453	453	907	2.720
Revenues (€)	3.578	3.300	2.744	2.466	12.089
Percentage distribution of benefits	29.6 %	27.3 %	22.7 %	20.4 %	100 %

revenue distribution scenarios proposed above. Let us highlight why this mechanism could converge between the RSCs from a mathematical point of view: RSC4 would have to pay the 30 % named as energy exchange at the energy purchase price of 350 €/MWh or 500 €/MWh and would instead pay 235 €/MWh or 310 €/MWh depending on the two market scenarios. RSC1 would have to sell the 30 % named as energy exchange at the energy selling price of 120 €/MWh and instead get 235 €/MWh or 310 €/MWh depending on the two reference market scenarios. Everything benefits with the important feature that a premium is maintained for the most virtuous RSCs in synchronising energy consumption and production.

The distribution of revenues allows us to apply this percentage to the division of profits generated within the different case studies examined in the previous subsections. First, it is emphasised that profits and not losses are divided because these plants generate economic prosperity thanks to the economic support of the incentive decree. For example, Fig. 4 proposes this distribution considering that the percentage of self-consumption is 50 % and relative values of NPV are referred to Table 1: 102,343 € (LS & LM); 149,036 € (LS & HM); 112,063 € (HS & LM) and 158,755 € (HS & HM).

At this point, considering to evaluate the HS & LM scenario, it is necessary to divide 112,063 € among the different RSCs. For the

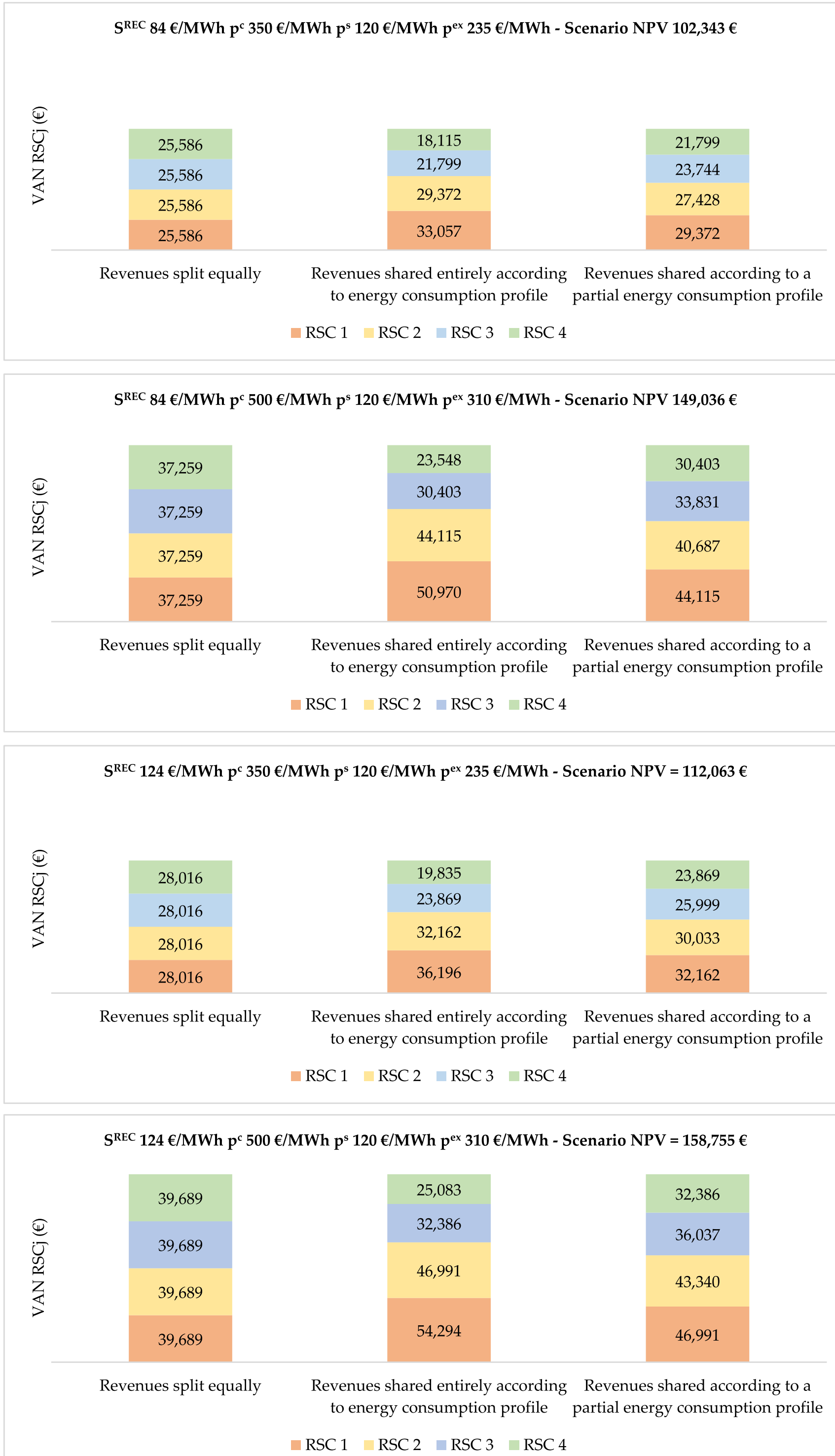

Fig. 4. NPV (€) distribution among RSCs with 50 % self-consumption.

revenues split equally scenario, simply divide this value by 4 and you get 28,016 €. In the scenario revenues shared entirely according to energy consumption profile the 32.3 %, 28.7 %, 21.3 % and 17.7 % associated respectively with the four RSCs result in the following NPV split: 36,196 €, 32,162 €, 23,869 € and 19,835 €. Finally, in the scenario revenues shared according to a partial energy consumption profile we have the following percentages for the four RSCs 28.7 %, 26.8 %, 23.2 % and 21.3 % from which we have the following NPV breakdown: 32,162 €, 30,033 €, 25,999 € and 23,869 €.

Interestingly, the distribution of revenues based on the partial energy consumption profile leads to a percentage distribution of benefits that lies somewhere in between the previous allocation methodologies. This result depends on the assumptions made in this work, where the value of the energy distribution was perfectly symmetric between the four RSCs and where the exchange price was set as the average value. Clearly, these assumptions may not be reflected in the real world, but this does not change the management mode. There is a need to reward virtuous behaviour and thus the model of equally divided profits distribution is not congruous. Similarly, not all citizens would accept to be part of a REC if revenues were distributed unevenly. Sometimes the non-synchronism of consumption could be related to business reasons and not to a lesser attention to these aspects, but these citizens could prevent the realisation of a REC. The less bargaining power they have, the more the exchange price can be chosen close to the selling price of energy, leading to a higher percentage of benefits for the more energy-synchronising RSCs. Thus, the revenue sharing model based on a partial energy consumption profile is rewarded in this direction. Finally, it should be noted that a share of these profits may be lost as a third-party figure may be paid to manage the accounts of a REC. Evidently, it was assumed in this work that this task would fall to the four RSCs in turn.

5.4. Renewable energy community – Prosumers and an additional consumer

In terms of energy participation, a consumer is someone who consumes power provided by the grid, whereas a prosumer both produces and consumes energy. In a REC a new consumer can buy energy directly from prosumers. In this way, both prosumers and consumers gain an economic advantage. The former can sell energy to the latter at a higher price than they sell on the grid, the latter can buy from the former at a lower price than they buy from the grid. Thus, in this new context, in addition to what was proposed in section 5.3, a new stakeholder is introduced, represented by the consumer. This choice is made in order to provide a further real-world scenario that this paper attempts to describe.

In the LM & LS scenario with a fixed RSCs self-consumes (80 % for RSC1, 65 % for RSC2, 35 % for RSC3 and 20 % for RSC4), we consider a consumer who wants to be part of the REC. This consumer may be a residential user or a business who did not initially participate in the establishment of the REC.

Consider, for example, the second scenario concerning the distribution of benefits among RSCs "revenues shared entirely according to energy consumption profile" (see Table 4). In addition, the new REC's actor requests an amount of energy equal to 7792 kWh/year (about 20 % of the total energy produced) covered equally by the four prosumers (1949.8 kWh/year for each one). Thus, all the energy not self-consumed by RSC1 is not sold on the grid but made available to the REC. In this way, all actors have an economic advantage, the four prosumers have the same benefits (224 € and 380 €) while for the new consumer this advantage is equal to 897 € and 1443 € (Fig. 5). The benefit tends to coincide since, as pointed out above, the exchange price is exactly intermediate between the buying and selling price.

The new percentage distributions of benefits are presented in Fig. 6 where a new bar is added representing the benefit shares of consumer. In monetary terms, all actors (prosumers and consumers) benefited. In percentage terms, prosumers' benefits decreased given the presence of the new actor in the REC. In future works, these analyses should be deepened by considering different selling and purchase prices on the grid, different exchange prices, different shares of self-consumption by prosumers, new energy demands by consumers and different operating conditions of the RECs.

Thus, in the NPV allocation scenario considering a 50 % self-consumption percentage for a LM & LS scenario, the NPV is 102,343 € (Table 1). In this new context in which 20 % of the energy is no longer sold to the grid but sold to the consumer, the NPV is 145,631 €. In the distribution of this NPV, the consumer who did not participate in the initial investment is not included. For the percentage distribution of the benefits, it is necessary to consider what is shown in Fig. 6 but without considering the contribution associated with the consumer: 31.7 %, 28.3 %, 21.7 % and 18.3 % for RSC1, RSC2, RSC3 and RSC4 respectively (these values are different from those proposed in Table 4). In this way, these percentages will be applied to the value of 145,631 €.

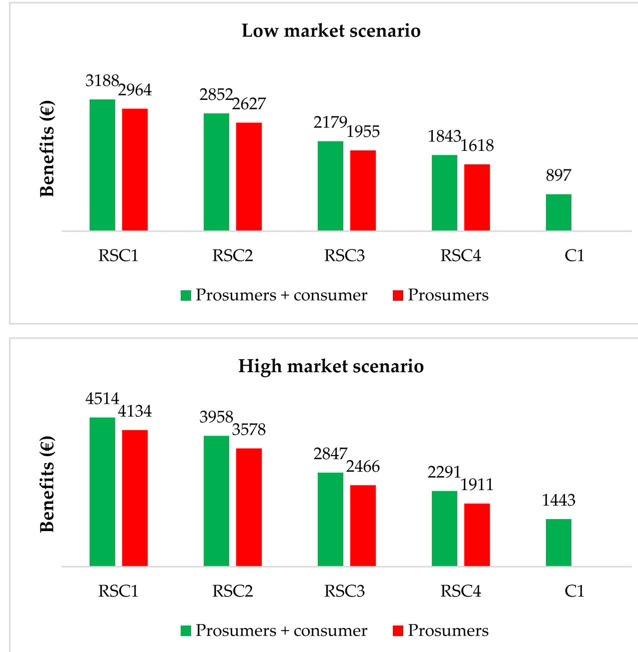

Fig. 5. Benefits distribution among prosumers (RSC1, RSC2, RSC3 and RSC4) and consumer (C1). Data in €.

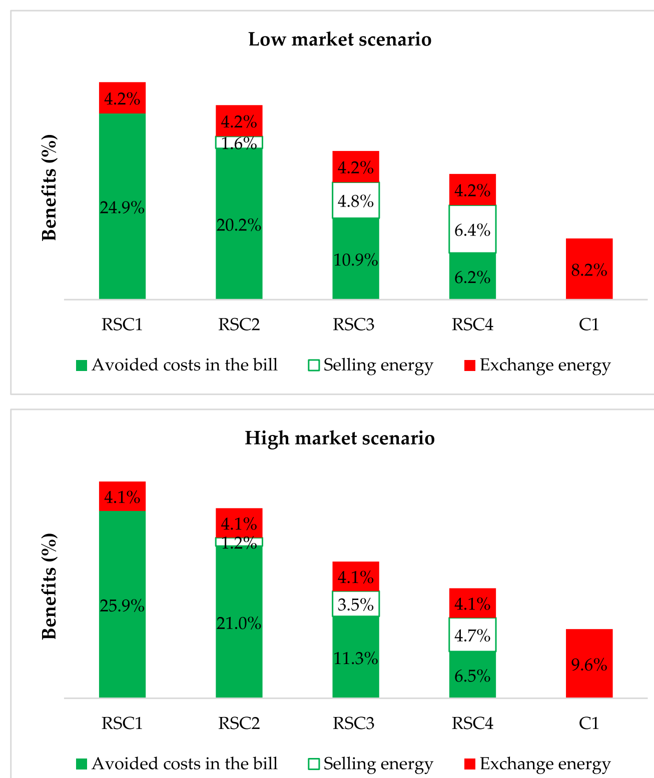

Fig. 6. Benefits distribution among prosumers (RSC1, RSC2, RSC3 and RSC4) and consumer (C1). Data in percentage.

5.5. The combination of smart city and renewable energy community

The European Commission emphasises that the smart city concept goes beyond the use of digital technologies as they are based not only on political commitment but also on citizen involvement. The underlying objective is to find sustainable and inclusive solutions that make cities more resilient. At present, already three quarters of the European population live in urban areas (European Commission, 2022b). The three dimensions of sustainability are associated with the concept of intelligent local energy communities hence the term smart energy community (Schwartz, 2014). In this direction, it is necessary to go beyond the use of renewable energies by also using energy sharing with storage in order to maximise the economic benefits (Ceglia, Esposito, Marrasso, & Sasso, 2020). The smart city concept is based on the use of modern, environmentally friendly technologies, in which renewable energies have a key role to play, with solar energy being one of them (Lewandowska, Chodkowska-Miszczuk, Rogatka, & Starczewski, 2020). The topic of energy goes hand in hand with that of complex networks (Guo, Xia, & Chen, 2022; Shamoushaki & Koh, 2023) in order to optimise the energy consumption of smart buildings (Selvaraj, Kuthadi, & Baskar, 2023), but the involvement of citizens with respect to digital devices and the role of infrastructure also needs to be framed (Caputo, Magliocca, Canestrino, & Rescigno, 2023). An integrated resource efficiency view is based on organizational resilience (Koh, Suresh, Ralph, & Saccone, 2023).

This work points out that the formation of a REC is essential in an inner-city context, but in reality, should be extended to other realities as well, since the decentralised model of energy has now replaced centralised systems. In particular, sustainability is not against energy consumption, but simply to optimise it in order to avoid inefficiencies and green economy rebound phenomena. The goal is to jointly pursue SDGs 7, 11, 13 and 17 (Wuebben et al., 2020). This requires parsimonious waste management, attention to water waste and air quality, but also intelligent energy use. Storage has an environmental impact on decentralised systems compared to the simple presence of a PV plant (D'Adamo, Dell'Aguzzo, & Pruckner, 2023; Peters, Baumann, Zimmermann, Braun, & Weil, 2017), but it can harmonise and foster the development of decentralised models that will only be truly autonomous when they are totally disconnected from the grid. Sustainability requires answers but a pragmatic view leads us to identify suitable solutions that then need time to be implemented. The social aspects concerning RECs must be well addressed (Gjorgievski, Cundeva, & Georghiou, 2021) even though the economic factor is then a determining factor in favouring changes in consumer habits (D'Adamo et al., 2022a). However, participatory processes (Bauwens et al., 2022) and citizen cooperation (Piao & Managi, 2023) cannot be neglected for the realisation of a REC. Although when it comes to the use of renewables, the environmental benefit is often taken for granted, it is crucial to emphasise the contribution of RECs to climate change adaptation (Ceglia, Marrasso, Roselli, & Sasso, 2021; Fan et al., 2022; Felice et al., 2022).

This analysis focuses on the Italian territory well investigated in the literature (Cutore, Volpe, et al., 2023; Musolino et al., 2023; Raimondi & Spazzafumo, 2023) and this work proposes the economic results of the REC 2023 decree. Its application is to provide support to policy makers to assess the impact of the new decree but it is obviously of interest to different stakeholders considering the economic amount available with this decree. Moreover, these new economic values can be compared with those of the previous decree (D'Adamo, Mammetti, et al., 2023). This work does not consider the presence of energy managers who could coordinate the business of RECs with the aim of facilitating their deployment and at the same time the presence of intelligent equipment and IT support to optimise the demand-supply combination such as smart energy decentralisation distribution management powered by blockchain.

Considering the energy bill tariff systems in force in Italy, it is therefore necessary to educate consumers that compared to the past, energy should not be consumed in the evening, if possible, characterised by a lower cost on the bill, and when possible, intelligent machines should be used that allow activities to be scheduled. The challenge is then made even more complex by the idea that there is not just one prosumer but also an aggregation of them.

Moreover, RECs can also be composed of consumers, as proposed in section 5.4, and this work emphasises the strategic point associated with risk minimisation in cases of benefit sharing in accordance with the literature (Dorahaki et al., 2023), as this aspect cannot be classified as a potential dividing element but rather a new decentralised risk-and-revenue sharing model. Similarly, energy policies must be planned to support even the economically poorest people (Caferra et al., 2023; Cutore, Volpe, et al., 2023).

Finally, the issue of energy independence and security is crucial for a country's policy in order to avoid geopolitical risks and to enable its businesses and citizens to pay competitive prices. Regulations are therefore called upon to grasp these changes (Haji Bashi et al., 2023) and sustainable education is the basis for these new communities aiming at the achievement of the SDGs (Biancardi et al., 2023) and net zero goals. Smart cities, being at the service of the people who make them up, can only have a decentralised, local and collective energy model that corresponds exactly to the REC concept.

Finally, phenomena such as the 'Not in My Back Yard' and the 'Not in My Term of Office' that led to a blocking of investments are not appropriate in an energy context where some countries, including Italy, see energy independence as an element of national security and competitiveness. Furthermore, the Mattei Plan (a forward-looking political strategy between Italy and African countries), would see major changes in the economic balance and energy exchanges between Europe and Africa with potential positive spillovers globally.

6. Conclusions and policy implications

Sustainability has long been ignored first and underestimated later. The policies of many governments are pushing towards a green transition that directly involves both citizens and businesses. RECs are proposed as a social model to foster the green transition, placing the role of the prosumer at the centre of change. The one who produces the renewable energy is also the one who consumes it, and since the source of production is green, this action counteracts climate change. RECs make it possible to extend this concept to a range of people.

The baseline scenarios show that the NPV is positive in the cases examined varying between 59 and 192 k€ in the different market and policy scenarios when the percentage of self-consumption varies between 30 % and 60 %. The profitability is also confirmed in the alternative scenarios and it is therefore concluded that building a residential PV system within a REC leads to significant economic returns and low levels of risk. The incentive provided plays an important role in this outcome, and clear and consistent planning over time can give investors security. However, it can be seen that a decisive role is played by the avoided cost on the bill, which led some families into severe social hardship but is a positive element for those who join a REC due to greater savings achieved by adopting a green choice.

Here the first limitations of this work emerge. From an economic point of view to apply storage to the model to assess its cost-effectiveness, from an environmental point of view to assess the value of the most suitable subsidy, and from a political point of view to apply such investments in social housing or in any case in all those realities that are at risk of social hardship. The concept of pragmatic sustainability emphasises that in addition to clean energy, it is essential that it is also accessible (not only technically, but also economically). Another decisive parameter in a profitability analysis is the percentage of self-consumption, which can be significantly large in a smart city model that has managed to optimise the needs of different citizens with the aid of sustainable technologies (e.g. intelligent devices). Other limitations of the work concern the configuration of RECs that can and should also cover non-residential contexts, involve multiple prosumers and consumers, and propose a dynamic model on the components of economic values that characterise the distribution of benefits and risks within a REC.

This work made two important new contributions to the existing literature. The first one concerns the definition of profitability related to the new Italian REC 2023 and its comparison with the previous one.

Furthermore, it has provided results referred to different benefit-sharing schemes (initially only between prosumers and then involving a new consumer within the REC) in order to highlight that a correct benefit-sharing prevents this from being an inhibiting factor for the realisation of a REC. Consequently, this work supports the policy maker as it estimates the impact that the planned incentives would have on the profitability of these PV investments, as it allows the investors to have a benchmark. Furthermore, from a methodological point of view, it exemplifies application cases in which economic analyses, incentive decrees, market energy values and profit distribution models in a REC are correlated.

The political implications of this work provide further points of perspective. Incentive decrees, defined in advance and lasting over time, are able to reduce risk and attract investors. They are also a tangible sign of a government's focus on green issues. This decree also has the great advantage of including other renewable forms, but it is clearly necessary for citizens to understand the extent of this change in order to use all available public capital. Therefore, information and awareness-raising campaigns on these issues are essential, promoting the idea that a sustainable production and consumption model must be pursued. In this way, SDG 12 can also be achieved.

RECs can support a nation's energy independence and resilience by mitigating risks related to geopolitics and financial speculation. Currently, RECs concern small realities but the challenges of the smart city require their development in the context of large urban centres. Joining a REC, where there are significant profits and environmental benefits supported by social awareness, would position citizens to be part of a change that is not simple but strategic for the challenges of the future. Furthermore, the goal of the Mattei Plan could be to exchange and share energy, which is also based on renewable sources and allows for an exchange of resources and expertise between Europe and Africa and enables the sustainable global development to which we are called to respond. The concept and implication of RECs shown in this study are applicable in wider energy, economic and social policies globally. Climate change is an objective fact, policies based on ideology and lacking in pragmatism do not allow for a reversal, and future generations deserve the same opportunities as we do.

CRediT authorship contribution statement

Idiano D'Adamo: Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Massimo Gastaldi:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **S.C. Lenny Koh:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Alessandro Vigiano:** Writing – review & editing, Writing – original draft, Methodology, 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.

Data availability

Data will be made available on request.

Acknowledgements

This study was carried out within the PEACE (Protecting the Environment: Advances in Circular Economy) which received funding from the "Fondo per il Programma Nazionale di Ricerca e Progetti di Rilevante Interesse Nazionale (PRIN)" Investimento 1.1-D.D. 104.02-02-2022, 2022ZFBMA4 funded by the European Union - Next Generation EU. This manuscript reflects only the authors' views and opinions, and can be considered responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2024.104828.

References

Ahmadifar, A., Ginocchi, M., Golla, M. S., Ponci, F., & Monti, A. (2023). Development of an energy management system for a renewable energy community and performance analysis via global sensitivity analysis. *IEEE Access, 11*, 4131–4154. https://doi.org/10.1109/ACCESS.2023.3235590

Ahmed, A., Hassan, I., Ibn-Mohammed, T., Mostafa, H., Reaney, I. M., Koh, L. S. C., … Wang, Z. L. (2017). Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerators. *Energy & Environmental Science, 10*, 653–671. https://doi.org/10.1039/C7EE00158D

Aittahar, S., de Villena, M. M., Derval, G., Castronovo, M., Boukas, I., Gemine, Q., & Ernst, D. (2023). Optimal control of renewable energy communities with controllable assets. *Front. Energy Res., 11*. https://doi.org/10.3389/fenrg.2023.879041

Albouys-Perrois, J., Sabouret, N., Haradji, Y., Schumann, M., Charrier, B., Reynaud, Q., … Inard, C. (2022). Multi-agent simulation of collective self-consumption: Impacts of storage systems and large-scale energy exchanges. *Energy and Buildings, 254*, Article 111543. https://doi.org/10.1016/j.enbuild.2021.111543

Aruta, G., Ascione, F., Bianco, N., & Mauro, G. M. (2023). Sustainability and energy communities: Assessing the potential of building energy retrofit and renewables to lead the local energy transition. *Energy, 282*, Article 128377. https://doi.org/10.1016/j.energy.2023.128377

Barbaro, S., & Napoli, G. (2023). Energy communities in urban areas: Comparison of energy strategy and economic feasibility in Italy and Spain. *Land, 12*, 1282. https://doi.org/10.3390/land12071282

Bauwens, T., Schraven, D., Drewing, E., Radtke, J., Holstenkamp, L., Gotchev, B., & Yildiz, Ö. (2022). Conceptualizing community in energy systems: A systematic review of 183 definitions. *Renewable and Sustainable Energy Reviews, 156*, Article 111999. https://doi.org/10.1016/j.rser.2021.111999

Biancardi, A., Colasante, A., D'Adamo, I., Daraio, C., Gastaldi, M., & Uricchio, A. F. (2023). Strategies for developing sustainable communities in higher education institutions. *Scientific Reports, 13*, 20596. https://doi.org/10.1038/s41598-023-48021-8

Bortolini, M., Gamberi, M., Graziani, A., Mora, C., & Regattieri, A. (2013). Multi-parameter analysis for the technical and economic assessment of photovoltaic systems in the main European Union countries. *Energy Conversion and Management, 74*, 117–128. https://doi.org/10.1016/j.enconman.2013.04.035

Caferra, R., Colasante, A., D'Adamo, I., Morone, A., & Morone, P. (2023). Interacting locally, acting globally: Trust and proximity in social networks for the development of energy communities. *Scientific Reports, 13*, 16636. https://doi.org/10.1038/s41598-023-43608-7

Campoccia, A., Dusonchet, L., Telaretti, E., & Zizzo, G. (2014). An analysis of feed'in tariffs for solar PV in six representative countries of the European Union. *Solar Energy, 107*, 530–542. https://doi.org/10.1016/j.solener.2014.05.047

Canova, A., Lazzeroni, P., Lorenti, G., Moraglio, F., Porcelli, A., & Repetto, M. (2022). Decarbonizing residential energy consumption under the Italian collective self-consumption regulation. *Sustainable Cities and Society, 87*, Article 104196. https://doi.org/10.1016/j.scs.2022.104196

Caputo, F., Magliocca, P., Canestrino, R., & Rescigno, E. (2023). Rethinking the role of Technology for Citizens’ engagement and sustainable development in smart cities. *Sustainability, 15*, 10400. https://doi.org/10.3390/su151310400

Ceglia, F., Esposito, P., Marrasso, E., & Sasso, M. (2020). From smart energy community to smart energy municipalities: Literature review, agendas and pathways. *Journal of Cleaner Production, 254*, Article 120118. https://doi.org/10.1016/j.jclepro.2020.120118

Ceglia, F., Marrasso, E., Pallotta, G., Roselli, C., & Sasso, M. (2022). The state of the art of smart energy communities: A systematic review of strengths and limits. *Energies, 15*, 3462. https://doi.org/10.3390/en15093462

Ceglia, F., Marrasso, E., Roselli, C., & Sasso, M. (2021). Small renewable energy community: The role of energy and environmental indicators for power grid. *Sustainability, 13*, 2137. https://doi.org/10.3390/su13042137

Cerino Abdin, G., & Noussan, M. (2018). Electricity storage compared to net metering in residential PV applications. *Journal of Cleaner Production, 176*, 175–186. https://doi.org/10.1016/J.JCLEPRO.2017.12.132

Chiacchio, F., Famoso, F., D'Urso, D., & Cedola, L. (2019). Performance and economic assessment of a grid-connected photovoltaic power plant with a storage system: A comparison between the north and the south of Italy. *Energies, 12*, 2356. https://doi.org/10.3390/en12122356

Cutore, E., Fichera, A., & Volpe, R. (2023). A roadmap for the design, operation and monitoring of renewable energy communities in Italy. *Sustainability, 15*, 8118. https://doi.org/10.3390/su15108118

Cutore, E., Volpe, R., Sgroi, R., & Fichera, A. (2023). Energy management and sustainability assessment of renewable energy communities: The Italian context. *Energy Conversion and Management, 278*, Article 116713. https://doi.org/10.1016/j.enconman.2023.116713

D'Adamo, I., Dell'Aguzzo, A., & Pruckner, M. (2023). Residential photovoltaic and energy storage systems for sustainable development: An economic analysis applied to incentive mechanisms. *Sustain. Dev.*. https://doi.org/10.1002/sd.2652. n/a.
D'Adamo, I., Gastaldi, M., & Morone, P. (2022a). Solar collective self-consumption: Economic analysis of a policy mix. *Ecological Economics, 199*, Article 107480. https://doi.org/10.1016/j.ecolecon.2022.107480
D'Adamo, I., Gastaldi, M., & Morone, P. (2022b). The impact of a subsidized tax deduction on residential solar photovoltaic-battery energy storage systems. *Utilities Policy, 75*, Article 101358. https://doi.org/10.1016/j.jup.2022.101358
D'Adamo, I., Mammetti, M., Ottaviani, D., & Ozturk, I. (2023). Photovoltaic systems and sustainable communities: New social models for ecological transition. The impact of incentive policies in profitability analyses. *Renewable Energy, 202*, 1291–1304. https://doi.org/10.1016/j.renene.2022.11.127
De Santi, F., Moncecchi, M., Prettico, G., Fulli, G., Olivero, S., & Merlo, M. (2022). To join or not to join? The energy community dilemma: An Italian case study. *Energies, 15*, 7072. https://doi.org/10.3390/en15197072
Dorahaki, S., Rashidinejad, M., Fatemi Ardestani, S. F., Abdollahi, A., & Salehizadeh, M. R. (2023). An integrated model for citizen energy communities and renewable energy communities based on clean energy package: A two-stage risk-based approach. *Energy, 277*, Article 127727. https://doi.org/10.1016/j.energy.2023.127727
European Commission, 2022a. Energy Communities Repository [WWW Document]. URL https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en (accessed 10.5.23).
European Commission, 2022b. In focus: Energy and smart cities [WWW Document]. URL https://commission.europa.eu/news/focus-energy-and-smart-cities-2022-07-13_en (accessed 10.5.23).
Eurostat, 2023. Renewable energy statistics [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Share_of_renewable_energy_more_than_doubled_between_2004_and_2022 (accessed 12.23.23).
Fan, G., Liu, Z., Liu, X., Shi, Y., Wu, D., Guo, J., … Zhang, Y. (2022). Energy management strategies and multi-objective optimization of a near-zero energy community energy supply system combined with hybrid energy storage. *Sustainable Cities and Society, 83*, Article 103970. https://doi.org/10.1016/j.scs.2022.103970
Felice, A., Rakocevic, L., Peeters, L., Messagie, M., Coosemans, T., & Ramirez Camargo, L. (2022). Renewable energy communities: Do they have a business case in Flanders? *Applied Energy, 322*, Article 119419. https://doi.org/10.1016/j.apenergy.2022.119419
Fett, D., Keles, D., Kaschub, T., & Fichtner, W. (2019). Impacts of self-generation and self-consumption on German household electricity prices. *Journal of Business Economics, 1–25*. https://doi.org/10.1007/s11573-019-00936-3
Frieden, D., Tuerk, A., Neumann, C., JoanneumResearch, D'Herbemont, S., Roberts, J., REScoop.eu, 2020. Collective self-consumption and energy communities: Trends and challenges in the transposition of the EU framework. https://www.rescoop.eu/toolbox/collective-self-consumption-and-energy-communities-trends-and-challenges-in-the-transposition-of-the-eu-framework.
Gallardo-Saavedra, S., Redondo-Plaza, A., Fernández-Martínez, D., Alonso-Gómez, V., Morales-Aragonés, J. I., & Hernández-Callejo, L. (2022). Integration of renewable energies in the urban environment of the city of Soria (Spain). *World Dev. Sustain., 1*, Article 100016. https://doi.org/10.1016/j.wds.2022.100016
Gjorgievski, V. Z., Cundeva, S., & Georghiou, G. E. (2021). Social arrangements, technical designs and impacts of energy communities: A review. *Renewable Energy, 169*, 1138–1156. https://doi.org/10.1016/j.renene.2021.01.078
Gómez-Navarro, T., Brazzini, T., Alfonso-Solar, D., & Vargas-Salgado, C. (2021). Analysis of the potential for PV rooftop prosumer production: Technical, economic and environmental assessment for the city of Valencia (Spain). *Renewable Energy, 174*, 372–381. https://doi.org/10.1016/j.renene.2021.04.049
Gribiss, H., Aghelinejad, M. M., & Yalaoui, F. (2023). Configuration selection for renewable energy community using MCDM methods. *Energies, 16*, 2632. https://doi.org/10.3390/en16062632
Gržanić, M., Capuder, T., Zhang, N., & Huang, W. (2022). Prosumers as active market participants: A systematic review of evolution of opportunities, models and challenges. *Renewable and Sustainable Energy Reviews, 154*, Article 111859. https://doi.org/10.1016/j.rser.2021.111859
Guo, M., Xia, M., & Chen, Q. (2022). A review of regional energy internet in smart city from the perspective of energy community. *Energy Reports, 8*, 161–182. https://doi.org/10.1016/j.egyr.2021.11.286
Haji Bashi, M., De Tommasi, L., Le Cam, A., Relaño, L. S., Lyons, P., Mundó, J., … Stancioff, C. E. (2023). A review and mapping exercise of energy community regulatory challenges in European member states based on a survey of collective energy actors. *Renewable and Sustainable Energy Reviews, 172*, Article 113055. https://doi.org/10.1016/j.rser.2022.113055
Heilmann, J., Wensaas, M., Crespo del Granado, P., & Hashemipour, N. (2022). Trading algorithms to represent the wholesale market of energy communities in Norway and England. *Renewable Energy, 200*, 1426–1437. https://doi.org/10.1016/j.renene.2022.10.028
Heuninckx, S., te Boveldt, G., Macharis, C., & Coosemans, T. (2022). Stakeholder objectives for joining an energy community: Flemish case studies. *Energy Policy, 162*, Article 112808. https://doi.org/10.1016/j.enpol.2022.112808
Hou, W., Man Li, R. Y., & Sittihai, T. (2022). Management optimization of electricity system with sustainability enhancement. *Sustainability, 14*, 6650. https://doi.org/10.3390/su14116650
Iazzolino, G., Sorrentino, N., Menniti, D., Pinnarelli, A., De Carolis, M., & Mendicino, L. (2022). Energy communities and key features emerged from business models review. *Energy Policy, 165*, Article 112929. https://doi.org/10.1016/j.enpol.2022.112929
Ibn-Mohammed, T., Koh, S. C. L., Reaney, I. M., Acquaye, A., Schileo, G., Mustapha, K. B., & Greenough, R. (2017). Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies. *Renewable and Sustainable Energy Reviews, 80*, 1321–1344. https://doi.org/10.1016/j.rser.2017.05.095
International Energy Agency, 2023. Snapshot of Global PV Markets 2022 [WWW Document]. URL https://iea-pvps.org/snapshot-reports/snapshot-2023/ (accessed 3.6.23).
de Jesus, Á. X. C., Pinheiro Neto, D., & Domingues, E. G. (2023). Computational tool for technical-economic analysis of photovoltaic microgeneration in Brazil. *Energy, 271*, Article 126962. https://doi.org/10.1016/j.energy.2023.126962
Jiménez-Castillo, G., Muñoz-Rodriguez, F. J., Rus-Casas, C., & Talavera, D. L. (2020). A new approach based on economic profitability to sizing the photovoltaic generator in self-consumption systems without storage. *Renewable Energy, 148*, 1017–1033. https://doi.org/10.1016/j.renene.2019.10.086
Koh, S. C. L., Smith, L., Miah, J., Astudillo, D., Eufrasio, R. M., Gladwin, D., … Stone, D. (2021). Higher 2nd life Lithium Titanate battery content in hybrid energy storage systems lowers environmental-economic impact and balances eco-efficiency. *Renewable and Sustainable Energy Reviews, 152*, Article 111704. https://doi.org/10.1016/j.rser.2021.111704
Koh, S. C. L., Suresh, K., Ralph, P., & Saccone, M. (2023). Quantifying organisational resilience: An integrated resource efficiency view. *International Journal of Production Research, 1–20*. https://doi.org/10.1080/00207543.2023.2296018
Koirala, B. P., Araghi, Y., Kroesen, M., Ghorbani, A., Hakvoort, R. A., & Herder, P. M. (2018). Trust, awareness, and independence: Insights from a socio-psychological factor analysis of citizen knowledge and participation in community energy systems. *Energy Research and Social Science, 38*, 33–40. https://doi.org/10.1016/j.erss.2018.01.009
Kubli, M., & Puranik, S. (2023). A typology of business models for energy communities: Current and emerging design options. *Renewable and Sustainable Energy Reviews, 176*, Article 113165. https://doi.org/10.1016/j.rser.2023.113165
Kurdi, Y., Alkhatatbeh, B. J., Asadi, S., & Jebelli, H. (2022). A decision-making design framework for the integration of PV systems in the urban energy planning process. *Renewable Energy, 197*, 288–304. https://doi.org/10.1016/j.renene.2022.07.001
Lang, T., Ammann, D., & Girod, B. (2016). Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. *Renewable Energy, 87*, 77–87. https://doi.org/10.1016/j.renene.2015.09.059
Lazzari, F., Mor, G., Cipriano, J., Solsona, F., Chemisana, D., & Guericke, D. (2023). Optimizing planning and operation of renewable energy communities with genetic algorithms. *Applied Energy, 338*, Article 120906. https://doi.org/10.1016/j.apenergy.2023.120906
Lewandowska, A., Chodkowska-Miszczuk, J., Rogatka, K., & Starczewski, T. (2020). Smart energy in a Smart City: Utopia or reality? Evidence from Poland. *Energies*. https://doi.org/10.3390/en13215795
Liu, Z., Fan, G., Sun, D., Wu, D., Guo, J., Zhang, S., Yang, X., Lin, X., & Ai, L. (2022). A novel distributed energy system combining hybrid energy storage and a multi-objective optimization method for nearly zero-energy communities and buildings. *Energy, 239*, Article 122577. https://doi.org/10.1016/j.energy.2021.122577
Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J. (2020). Renewable energy communities under the 2019 European Clean Energy Package–Governance model for the energy clusters of the future? *Renewable and Sustainable Energy Reviews, 122*, Article 109489. https://doi.org/10.1016/j.rser.2019.109489
Luthander, R., Widén, J., Munkhammar, J., & Lingfors, D. (2016). Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment. *Energy, 112*, 221–231. https://doi.org/10.1016/J.ENERGY.2016.06.039
Marrone, P., Fiume, F., Laudani, A., Montella, I., Palermo, M., & Fulginei, F. R. (2023). Distributed energy systems: Constraints and opportunities in urban environments. *Energies, 16*, 2718. https://doi.org/10.3390/en16062718
Mateo Romero, H. F., González Rebollo, M.Á., Cardeñoso-Payo, V., Alonso Gómez, V., Redondo Plaza, A., Moyo, R. T., & Hernández-Callejo, L. (2022). Applications of artificial intelligence to photovoltaic systems: A review. *Applied Sciences, 12*, 10056. https://doi.org/10.3390/app121910056
Moroni, S., Alberti, V., Antoniucci, V., & Bisello, A. (2019). Energy communities in the transition to a low-carbon future: A taxonomical approach and some policy dilemmas. *Journal of Environmental Management, 236*, 45–53. https://doi.org/10.1016/j.jenvman.2019.01.095
Musolino, M., Maggio, G., D'Aleo, E., & Nicita, A. (2023). Three case studies to explore relevant features of emerging renewable energy communities in Italy. *Renewable Energy, 210*, 540–555. https://doi.org/10.1016/j.renene.2023.04.094
Onu, U. G., Zambroni de Souza, A. C., & Bonatto, B. D. (2023). Drivers of microgrid projects in developed and developing economies. *Utilities Policy, 80*, Article 101487. https://doi.org/10.1016/j.jup.2022.101487
Ordonez-Ponce, E. (2023). Exploring the impact of the sustainable development goals on sustainability trends. *Sustainability, 15*, 16647. https://doi.org/10.3390/su152416647
Paiano, A., Lagioia, G., & Ingrao, C. (2023). A combined assessment of the energy, economic and environmental performance of a photovoltaic system in the Italian context. *Sci. Total Environ., 866*, Article 161329. https://doi.org/10.1016/j.scitotenv.2022.161329
Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-ion batteries and the role of key parameters – A review. *Renewable and Sustainable Energy Reviews, 67*, 491–506. https://doi.org/10.1016/j.rser.2016.08.039

Petrovich, B., Carattini, S., & Wüstenhagen, R. (2021). The price of risk in residential solar investments. *Ecological Economics, 180*, Article 106856. https://doi.org/10.1016/j.ecolecon.2020.106856
Piao, X., & Managi, S. (2023). Household energy-saving behavior, its consumption, and life satisfaction in 37 countries. *Scientific Reports, 13*, 1382. https://doi.org/10.1038/s41598-023-28368-8
Raimondi, G., & Spazzafumo, G. (2023). Exploring renewable energy communities integration through a hydrogen power-to-power system in Italy. *Renewable Energy, 206*, 710–721. https://doi.org/10.1016/j.renene.2023.02.074
Ramli, M. A. M., Hiendro, A., Sedraoui, K., & Twaha, S. (2015). Optimal sizing of grid-connected photovoltaic energy system in Saudi Arabia. *Renewable Energy, 75*, 489–495. https://doi.org/10.1016/J.RENENE.2014.10.028
Şanta, A.-M. I. (2022). Prosumers-a new mindset for citizens in smart cities. *Smart Cities, 5*, 1409–1420. https://doi.org/10.3390/smartcities5040072
Schwanitz, V. J., Wierling, A., Arghandeh Paudler, H., von Beck, C., Dufner, S., Koren, I. K., … Zeiss, J. P. (2023). Statistical evidence for the contribution of citizen-led initiatives and projects to the energy transition in Europe. *Scientific Reports, 13*, 1342. https://doi.org/10.1038/s41598-023-28504-4
Schwartz, H. (2014). A review of "beyond smart cities: How cities network, learn and innovate". *Journal of the American Planning Association, 80*, 97–98. https://doi.org/10.1080/01944363.2014.935679
Selvaraj, R., Kuthadi, V. M., & Baskar, S. (2023). Smart building energy management and monitoring system based on artificial intelligence in smart city. *Sustain. Energy Technol. Assessments, 56*, Article 103090. https://doi.org/10.1016/j.seta.2023.103090
Shamoushaki, M., & Koh, S. C. L. (2023). Heat pump supply chain environmental impact reduction to improve the UK energy sustainability, resiliency and security. *Scientific Reports, 13*, 20633. https://doi.org/10.1038/s41598-023-47850-x
Shan, S., Ahmad, M., Tan, Z., Adebayo, T. S., Man Li, R. Y., & Kirikkaleli, D. (2021). The role of energy prices and non-linear fiscal decentralization in limiting carbon emissions: Tracking environmental sustainability. *Energy, 234*, Article 121243. https://doi.org/10.1016/j.energy.2021.121243
Shao, X., Zhong, Y., Liu, W., & Li, R. Y. M. (2021). Modeling the effect of green technology innovation and renewable energy on carbon neutrality in N-11 countries? Evidence from advance panel estimations. *Journal of Environmental Management, 296*, Article 113189. https://doi.org/10.1016/j.jenvman.2021.113189
Singh, K., Hachem-Vermette, C., & D'Almeida, R. (2023). Solar neighborhoods: The impact of urban layout on a large-scale solar strategies application. *Scientific Reports, 13*, 18843. https://doi.org/10.1038/s41598-023-43348-8
Sousa, J., Lagarto, J., Camus, C., Viveiros, C., Barata, F., Silva, P., Alegria, R., & Paraíba, O. (2023). Renewable energy communities optimal design supported by an optimization model for investment in PV/wind capacity and renewable electricity sharing. *Energy, 283*, Article 128464. https://doi.org/10.1016/j.energy.2023.128464
Squatrito, R., Sgroi, F., Tudisca, S., Trapani, A. M., & Testa, R. (2014). Post feed-in scheme photovoltaic system feasibility evaluation in Italy: Sicilian case studies. *Energies, 7*, 7147–7165. https://doi.org/10.3390/en7117147
Stamopoulos, D., Dimas, P., Siokas, G., & Siokas, E. (2024). Getting smart or going green? Quantifying the Smart City Industry's economic impact and potential for sustainable growth. *Cities, 144*, Article 104612. https://doi.org/10.1016/j.cities.2023.104612
Talavera, D. L., Muñoz-Cerón, E., Ferrer-Rodríguez, J. P., & Pérez-Higueras, P. J. (2019). Assessment of cost-competitiveness and profitability of fixed and tracking photovoltaic systems: The case of five specific sites. *Renewable Energy, 134*, 902–913. https://doi.org/10.1016/J.RENENE.2018.11.091
Trevisan, R., Ghiani, E., & Pilo, F. (2023). Renewable energy communities in positive energy districts: A governance and realisation framework in compliance with the Italian regulation. *Smart Cities, 6*, 563–585. https://doi.org/10.3390/smartcities6010026
Tudisca, S., Di Trapani, A. M., Sgroi, F., Testa, R., & Squatrito, R. (2013). Economic analysis of PV systems on buildings in Sicilian farms. *Renewable and Sustainable Energy Reviews, 28*, 691–701. https://doi.org/10.1016/j.rser.2013.08.035
Viti, S., Lanzini, A., Minuto, F. D., Caldera, M., & Borchiellini, R. (2020). Techno-economic comparison of buildings acting as single-self consumers or as energy community through multiple economic scenarios. *Sustainable Cities and Society, 61*, Article 102342. https://doi.org/10.1016/j.scs.2020.102342
Volpato, G., Carraro, G., Cont, M., Danieli, P., Rech, S., & Lazzaretto, A. (2022). General guidelines for the optimal economic aggregation of prosumers in energy communities. *Energy, 258*, Article 124800. https://doi.org/10.1016/j.energy.2022.124800
Wuebben, D., Romero-Luis, J., & Gertrudix, M. (2020). Citizen science and citizen energy communities: A systematic review and potential alliances for SDGs. *Sustainability, 12*, 10096. https://doi.org/10.3390/su122310096
Yang, Y., Cheng, D., Zhang, B., Guan, C., Cheng, X., & Cheng, T. (2023). Coal resource-based cities at the crossroads: Towards a sustainable urban future. *Cities, 140*, Article 104424. https://doi.org/10.1016/j.cities.2023.104424