

# Renewable energy communities design: A decision support tool for integrated impact assessment. Insights from the first REC in Cagliari, Italy

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## ABSTRACT

Renewable Energy Communities (RECs) play a crucial role in advancing the European green transition and achieving key environmental, social, and economic objectives, such as reducing carbon emissions, improving energy efficiency, and ensuring affordable energy access for disadvantaged and low-income populations. However, most research and initiatives tend to address these issues in isolation, thereby overlooking the full potential of RECs. This paper presents an integrated approach led by a multidisciplinary team from the University of Cagliari and the Municipality of Cagliari (Italy), aimed at establishing the first REC in Cagliari, Italy. The project was established in a social housing neighbourhood to comprehensively address complex social, economic, and environmental needs. A participatory design methodology was adopted to actively involve residents, fostering community engagement and raising awareness of the benefits of RECs, thereby promoting long-term community commitment.

A key contribution of this work is the introduction of a decision support tool developed to model energy and cash flows, as well as environmental benefits, thereby optimizing energy consumption, financial outcomes, and CO<sub>2</sub> reduction. The case study offers an empirical evaluation of both design and implementation phases, assessing the project's feasibility and overall impact. The tool is designed to be highly replicable in other contexts, particularly for addressing energy poverty in public housing neighbourhoods. The findings highlight also underscore its broader policy implications, demonstrating its usefulness for public administrations and stakeholders in guiding investment and planning decisions that prioritize social value over profit.

## 1. Introduction

The world is waking up to the climate crisis, pushing both global and local efforts towards sustainable development and greener transition. Renewable energy is at the heart of this movement, sparking intense debates on the international stage and shaping the way we plan and design our cities. The rising costs of energy, the surge in greenhouse gas emissions, and urban pollution are all pressing issues, creating economic and social impacts that can't be ignored. These interconnected challenges demand comprehensive solutions, as outlined in the 2030 Agenda (United Nations, 2015).

But here's the thing, many of these sustainability efforts often focus heavily on technological fixes without really considering the social, economic and political factors that influence how resources are

distributed and accessed. The 2030 Agenda's pledge to "Leave no one behind" underlines the importance of addressing the many overlapping disparities that limit access to resources and decision-making processes. This makes it crucial to design energy initiatives that are fair and inclusive, essential for a just green transition (World Economic Forum, 2021).

In this context, energy poverty is a major issue. According to the International Energy Agency (IEA), energy poverty means lacking access to modern, reliable, and affordable energy, which hits developing nations particularly hard (IEA, 2014). There's a huge gap in clean energy investment, with 80 % of the funds concentrated in just 25 countries (The World Bank, 2024). Moreover, within countries, the richest 10 % consume energy at a rate 20 times than poorest 10 % (World Economic Forum, 2020).

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This inequality is made worse by the current global energy crisis, intensified by geopolitical tensions such as the Russia's invasion of Ukraine, the long-term impacts of the COVID-19 pandemic, and extreme weather events. These factors have severely impacted many countries' budgets, creating a "perfect storm" for governments (Mišák and Nosko, 2023). Policymakers now face the dual challenge of securing energy supplies while dealing with skyrocketing energy costs, which hit low-income groups the hardest (Hussain et al., 2023; Zakeri et al., 2022). These vulnerable populations spend a larger portion of their income on energy and often can't afford to invest in energy-efficient housing (Baute, 2024; Carley and Konisky, 2020).

The lack of access to funding for clean energy investments is a significant barrier in the shift to renewable energy. To avoid increasing inequalities and falling into energy poverty traps, policies and economic incentives must consider the socio-economic realities of society, aiming to close the gap in energy access and affordability (Kowalska-Pyzalska, 2018; Primc and Slabe-Erker, 2020; van der Kroon et al., 2013). Therefore, promoting the spread of renewable energy and tackling energy poverty are goals that are intertwined and must be pursued together to achieve a successful renewable energy transition and address the challenges of climate change (Adom et al., 2021; Qadir et al., 2021).

### 1.1. European actions for energy efficiency and poverty reduction: the role of RECs

The European Union has shown is strongly committed to tackling socio-economic challenges in the green transition. Central to this effort is the European Green Deal (European Parliament, 2020), which aims for climate neutrality by 2050 while ensuring that efficiency costs do not disproportionately impact low-income households. To support this inclusive transition, the EU has established financial mechanisms such as the Social Climate Fund (SCF), which aids vulnerable groups in managing rising energy costs (European Commission, 2021; European Parliament, 2023a), and the Next Generation EU (NGEU), which allocates funding through the Recovery and Resilience Facility (RRF) and the Recovery assistance for cohesion and the territories of Europe (REACT-EU), to help member states meet climate goals and recover post-pandemic. These initiatives align with the European Pillar of Social Rights, promoting a fair and sustainable transition.

EU Directives highlight that energy poverty results from multiple factors, including low income, high energy costs, and poor housing energy efficiency (European Parliament, 2023b). These factors are tracked by the EU Energy Poverty Observatory (EPOV), established in 2018 under the Energy Poverty Advisory Hub (EPAH), which provides a comprehensive framework for understanding and addressing energy poverty (Energy Poverty Advisory Hub, n.d.).

In this context, Renewable Energy Communities (RECs) have emerged as a key strategy addressing these challenges and accelerating the transition to renewables (Hoicka et al., 2021). They improve access to technology and financial resources while empowering citizens in energy production, fostering local ownership and strengthening community engagement (Aruta et al., 2023; Belaïd et al., 2023; Hoicka et al., 2021; UNSDG, 2019; Wang, 2024).

Although energy communities existed long before their formal recognition in the EU, they gained legal status through the Renewable Energy Directive 2018/2001/EU (RED II) (European Parliament and Council of the European Union, 2018) and the Internal Market for Electricity Directive (IMED) 2019/944/EU (European Parliament and Council of the European Union, 2019), under the Clean Energy for All Europeans Package ("Clean energy for all Europeans package," 2019). These frameworks define RECs as entities prioritizing environmental, social, or economic benefits over profit (De Juan-Vela et al., 2023; Mengolini and Masera, 2021). Over the past two decades, RECs have expanded across various contexts, adopting various technologies, organizational structures, and management models, each shaped by distinct social and economic dynamics (Hicks and Ison, 2018; Hoicka and

MacArthur, 2018; Walker and Devine-Wright, 2008).

This place-based approach is crucial for effectively addressing energy poverty through REC initiatives. Targeted policy measures must be implemented to direct resources toward the most disadvantaged groups, particularly where low household incomes and thermally inefficient homes intersect, leading to severe energy deprivation (Bouzarovski, 2014; Hoicka et al., 2021).

In Europe, energy poverty is particularly prevalent among public housing tenants, who are often excluded from the traditional housing market and face greater socio-economic challenges (Croon et al., 2024; Desvallées, 2022). This issue is particularly acute in Southern Europe, where there is less tradition of energy efficiency improvements (Desvallées, 2022; Scanlon and Whitehead, 2008) and where poor building maintenance by public administrations exacerbates the problem (Axon and Morrissey, 2020; Lacey-Barnacle, 2020). Although renewable energy installations offer significant potential to address these challenges, also due to the climatic characteristics of these countries, progress has been slow (Barbaro and Napoli, 2023).

The potential of RECs in public housing is often overlooked, despite offering a dual opportunity: reducing the high energy consumption of this housing segment and fostering social inclusion (McCabe et al., 2018a, 2018b). Achieving this requires targeted incentives, consulting services, and flexible policies to effectively include low-income and energy-vulnerable populations (Hoicka et al., 2021). Local authorities must proactively promote such initiatives. However, recognizing energy injustices and establishing formal engagement process alone is not enough (Hanke et al., 2021), as structural and cultural barriers still hinder participation, leaving vulnerable populations underrepresented in such initiatives (McGee and Greiner, 2019).

### 1.2. Technological and social consideration in RECs: state of the art and research gap

Current research and interventions on RECs often prioritize technological advancements while overlooking their broader social impacts. For instance, Ceglia et al. (2022) analysed the energy and environmental performance of a CER in Benevento (Southern Italy), comparing two potential configurations of the same end-users. Their assessment of REC scenarios focused exclusively on electricity sharing and self-consumption without considering social dynamics (Ceglia et al., 2022). Similarly, Marrone and Montella (2022) examined the opportunities and limitations of decentralized energy production in urban environments, particularly investigating how the spatial organization of different built-up districts in Rome influences the configuration and sizing of renewable energy systems. Their study emphasizes the challenge of balancing local energy demand and supply but did not explore social inclusion factors (Marrone and Montella, 2022). Further, Trevisan et al. (2024) introduced a multi-criteria techno-economic simulation framework to evaluate various investment scenarios based on plant size and energy prices, yet without considering social implications (Trevisan et al., 2024). In line with this trend, Cirone et al. (2022) assessed different scenarios for an implementable energy community in a small mountain municipality in Southern Italy (Cirone et al., 2022). Their study utilized commercial software to simulate multiple community schemes, integrating photovoltaic generators and electric batteries with heat pump systems to maximize self-consumed electricity. The focus remained on identifying the optimal solution in terms of technical and economic performance.

Other research highlights the importance of social considerations and educational initiatives in the spread and success of RECs, particularly in socio-economically disadvantaged areas where CERs face difficulties in implementation. The causes of this condition are multifaceted.

On one hand, limitation stem from the characteristics of the user base. Numerous studies emphasize that only certain social groups possess the necessary resources – such as financial capital, time, and expertise – to actively participate in RECs (Axon and Morrissey, 2020).

Other studies examine energy-related behaviours and domestic space usage, noting that the lack of adoptive thermal comfort practices is a significant factor contributing to energy poverty in these contexts (Caballero and Della Valle, 2021; Kearns et al., 2019). Residents are often reluctant to change their consumption patterns, especially if they are not actively involved from the early stages of REC design or if the management mechanisms are too complex (Botsaris et al., 2021).

In public housing neighbourhoods, the prevalence of ‘uninformed users’ leads to disproportionately high energy consumption, largely due to a lack of awareness. In this regard, Bahaj and James (2007) demonstrate that renewable energy systems, such as photovoltaic panels, have the potential to serve as educational tools, helping residents develop more efficient energy consumption habits (Bahaj and James, 2007).

On the other hand, structural barriers imposed by housing authorities and property managers play a crucial role. As Desvallées (2022) points out, public housing providers tend to favour retrofitting building envelopes while resisting the installation of renewable energy equipment, primarily due to the challenge to recouping costs (Desvallées, 2022). The high upfront costs associated with purchasing and installing technological infrastructure require substantial investments, which are often difficult for public entities and social housing operators to sustain. Additionally, long payback periods resulting from energy bill savings may not be immediately offset the initial investment.

Adequate incentives and sustainable financing models to support these initiatives without overburdening housing authorities or tenants are not always available. This underscores the need for targeted measures and dedicated funds to cover a significant portion of the initial investment. Furthermore, adopting innovative business models – such as public-private partnerships, energy leasing, or the involvement of energy cooperatives – could help make these investments financially viable in the long term.

### 1.3. Aim and novelties

Despite the growing interest in establishing RECs in social housing areas, targeted public policies remain limited, as do studies investigating their potential and barriers (see sub-section 1.1). In Italy, a significant disconnect exists between energy and social goals, and the role of public housing in advancing energy transition and social justice is often overlooked. This housing stock, predominantly built over 50 years ago, is often poorly maintained, with inefficient systems leading to higher heating costs. Unlike other European contexts, this stock is mostly managed by public companies that oversee energy services and allocate costs to tenants, resulting in extremely high non-payment rates. According to the Nomisma Observatory, 83 % of social inclusion funds are used to cover energy costs (Legambiente, 2021). As a result, these families experience energy insecurity, often being forced to forgo essential energy needs to reduce expenses (Betto et al., 2020; Faiella and Lavecchia, 2014).

This issue is not adequately addressed in the Italian National Recovery and Resilience Plan (NRRP). Through Mission 2, “Green Revolution and Ecological Transition”, 2.2 billion euros are allocated to develop RECs (Italian Government, 2021), primarily targeting municipalities under 5000 inhabitants, mostly located in northern Italy, potentially exacerbating regional disparities. The broad demographic target lacks comprehensive assessments of energy poverty, making it difficult to ensure that the funds effectively reach the most vulnerable (Studio Accenture-Agici, 2023). As a result, the investments of Mission 5, “Inclusion and Cohesion”, are disconnected from energy-related concerns.

Similar gaps between energy efficiency measures and the inclusion of vulnerable populations are present in other Italian and European initiatives, which perpetuate existing inequalities and hinder the potential for energy transition efforts to promote social justice across Europe. This research aims to highlight the potential and challenges of implementing RECs in public housing, using a concrete case study to provide insights

into the effectiveness of these interventions and their impact on energy poverty. We introduce a decision support tool for integrated REC assessment, based on scenario analyses of energy and financial flows to determine optimal configurations. The results, alongside insights from the participation process carried out to engage REC participants, critique current design approaches and funding mechanisms that focus solely on profitability. This underscores the need to account for non-financial benefits of RECs, emphasising a shift in evaluation criteria to support more inclusive and sustainable energy transition models. These insights are relevant to other public housing context and provide a framework for developing more equitable energy solutions that integrate both social and environmental factors in future energy transition strategies.

The following sections outline the proposed tool (Section 2), the case study application (Section 3), and a discussion of the results (Section 4). Finally, the conclusions aim to inform and identify key insights for future policy implications and future research directions.

## 2. Methodology

The literature review in Section 1 highlights significant gaps in addressing social issues within RECs, particularly in relation to energy poverty in public housing neighbourhoods. This issue remains largely underexplored in the Italian context, where research and policy initiatives have primarily focused on the technical and economic aspects of RECs, with limited attention to their social implications. To bridge these gaps, the creation of the first REC in Cagliari (Italy), the “CER-CA” project presented in this paper, adopted a highly integrated design approach, incorporating a comprehensive assessment of technical, economic, environmental and social factors.

The “CER-CA” project is established in a disadvantaged public housing neighbourhood of the city, funded from PON Metro 2014–2020 React EU program and “Energy Efficiency in 40 Schools Support Communities - EE(40)Sco” initiative under the NESOI (New Energy Solutions Optimized for Islands) programs. The latter is aimed at establishing new RECs around about half of the city school buildings (Blečić et al., 2024; 2023). The REC project is a collaborative initiative led by the Municipality of Cagliari, responsible for the overall project management, including the design and installation of the PV system. Partnering with the multidisciplinary research team from the Department of Civil, Environmental Engineering, and Architecture (DICAAR) at the University of Cagliari, which, the project integrates comprehensive social, economic, environmental and technological assessment through the CER-CA initiative.

This paper retraces the development of this empirical case study (Fig. 1), focusing on the methodology used to establish the decision support tool for REC design. Special attention is given to the most critical phases, such as citizen engagement and the technical-economic feasibility assessment, which also includes environmental and social analysis.

### 2.1. Citizen engagement and data collection

Given the complexity of the project and the socio-economic context, engaging residents of the housing complex was a fundamental component of the initiative. This process was structured into different distinct phases, involving both primary school children and adult residents through a range of targeted activities, as detailed in the sub-section 4.1. This approach represents an exploratory study, specifically tailored to the local socio-economic context. It draws on experience from previous local initiatives (Blečić et al., 2024b, 2024c), which, although resource-intensive in terms of time and personnel, proved effective in building trust and fostering active community participation. At the core of this methodology is the emphasis on interpersonal interaction as a key facilitator of communication and engagement. This strategy enabled the research team to collect in-depth data on energy consumption through a custom-designed questionnaire, administered via the Computer-Assisted

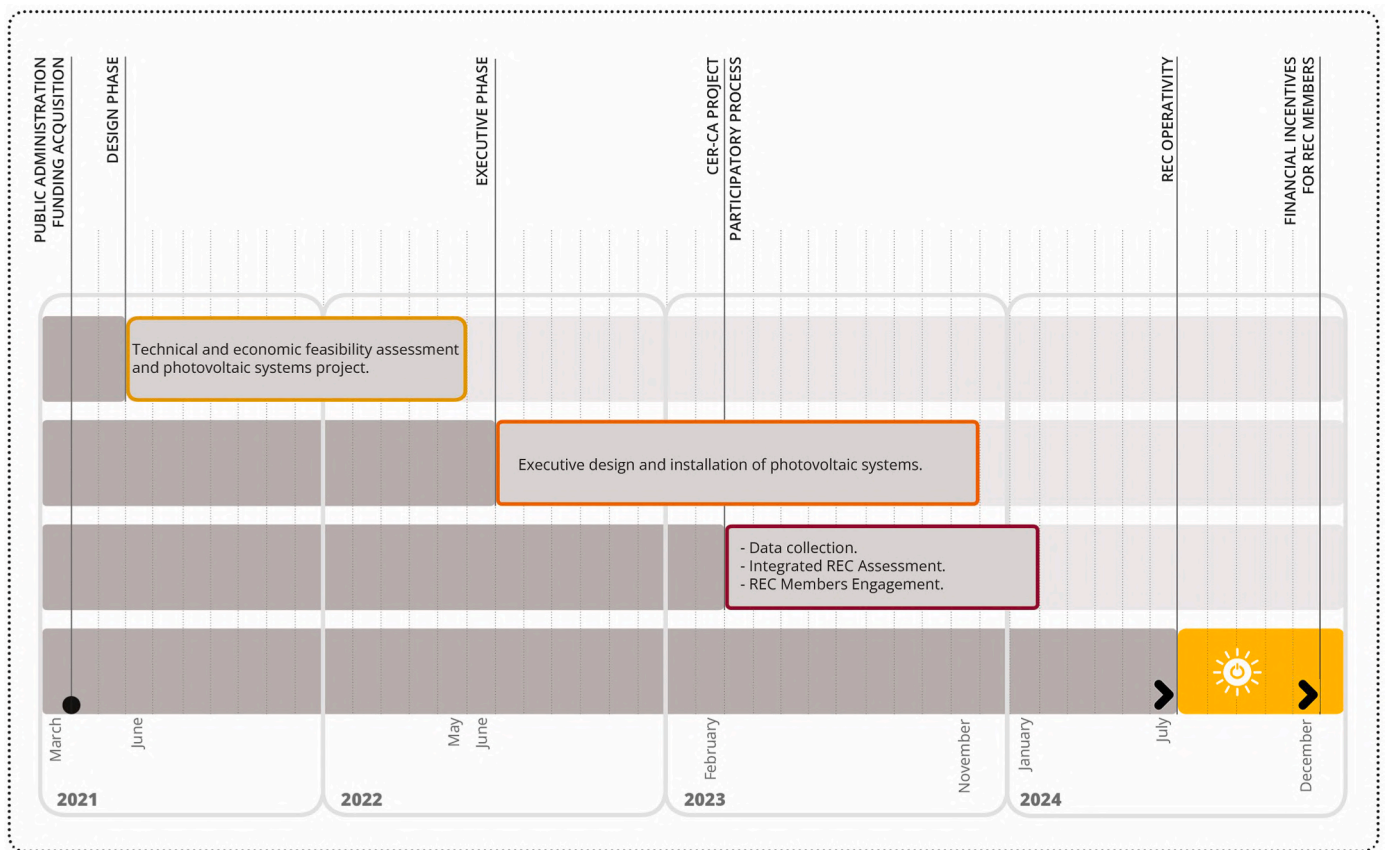


Fig. 1. REC establishment pathway schedule.

Personal Interview (CAPI) method, an approach widely adopted in renewable energy research (Ahmed et al., 2022; Roberto Moraes et al., 2021; Achnicht and Madlener, 2014). The survey was conducted using a self-build stand, co-designed and built in collaboration with community members.

The stand was strategically located within the housing complex to maximize visibility, ensure ease of access, and seamlessly integrate into residents' daily routines. Four researchers team the stand at agreed-upon times each week, based on consultation with the community, over a period of eleven weeks. This setup fostered an open and welcoming environment where residents could receive clear information about the technical and administrative aspects of the REC, express their concerns or scepticism, and register their interest in participating. Addressing the initial, widespread mistrust toward the project was crucial for encouraging residents to share their data and take an active role in the process.

The data collected included information on energy consumption, household size, apartment dimensions, and the presence of specific electrical appliances in their apartments, such as heat pumps for heating and cooling, electric water heaters, and dishwashers. The questionnaire was designed to capture varying levels of data granularity, categorizing responses into six groups: 1) Complete annual consumption data; 2) Aggregated monthly data; 3) Annual data segmented by time slots; 4) Partial monthly data; 5) Detailed monthly data including time slots; 6) Monthly data with only daily time-slot. Responses in the fifth category were classified as "sample users". This subset enabled the calculation of average monthly energy consumption by time slot, forming the basis for a "standard profile" used in simulations to extrapolate representative consumption patterns beyond the available dataset.

## 2.2. Technical-economic analysis: multiple scenario simulator

Performing technical-economic analysis is a fundamental step in the establishment of a new REC, as it allows for a preliminary assessment of the project's profitability based on an accurate evaluation of the expected environmental, economic, and social benefits for the community. In this regard, it is important to highlight that energy communities are not static elements; rather, they may undergo relevant changes in their original configuration during their lifecycle, since members can freely join or leave the community at any moment. In accordance with the latest Italian regulations (MASE, 2023), new Renewable Energy Communities are entitled to receive an annual cashback incentive from the Italian Energy Services Manager (*i.e.* the so-called GSE), proportional to the so-called "shared energy" for a period of 20 years. This is granted without prejudice to the right of *producers* and *prosumers* to sell any surplus energy to the GSE.

All this considered, an accurate simulator can serve as a powerful decision support tool, enabling hourly calculation of REC energy flows, associated cash flows, and environmental benefits. From this perspective, an Excel-based simulator has been developed to perform multi-scenario simulations, considering various potential REC configurations (see Fig. 2).

The proposed simulator requires the following input data:

- Number of potential members of the energy community, distinguished by category (*producers*, *prosumers*, *consumers*).
- Energy demand of potential members of the REC (estimated or user-provided).
- Technical data concerning new photovoltaic (PV) systems to be installed (*e.g.* peak power, Balance Of System - BOS, location and related solar irradiance, tilt, azimuth and number of solar panels).

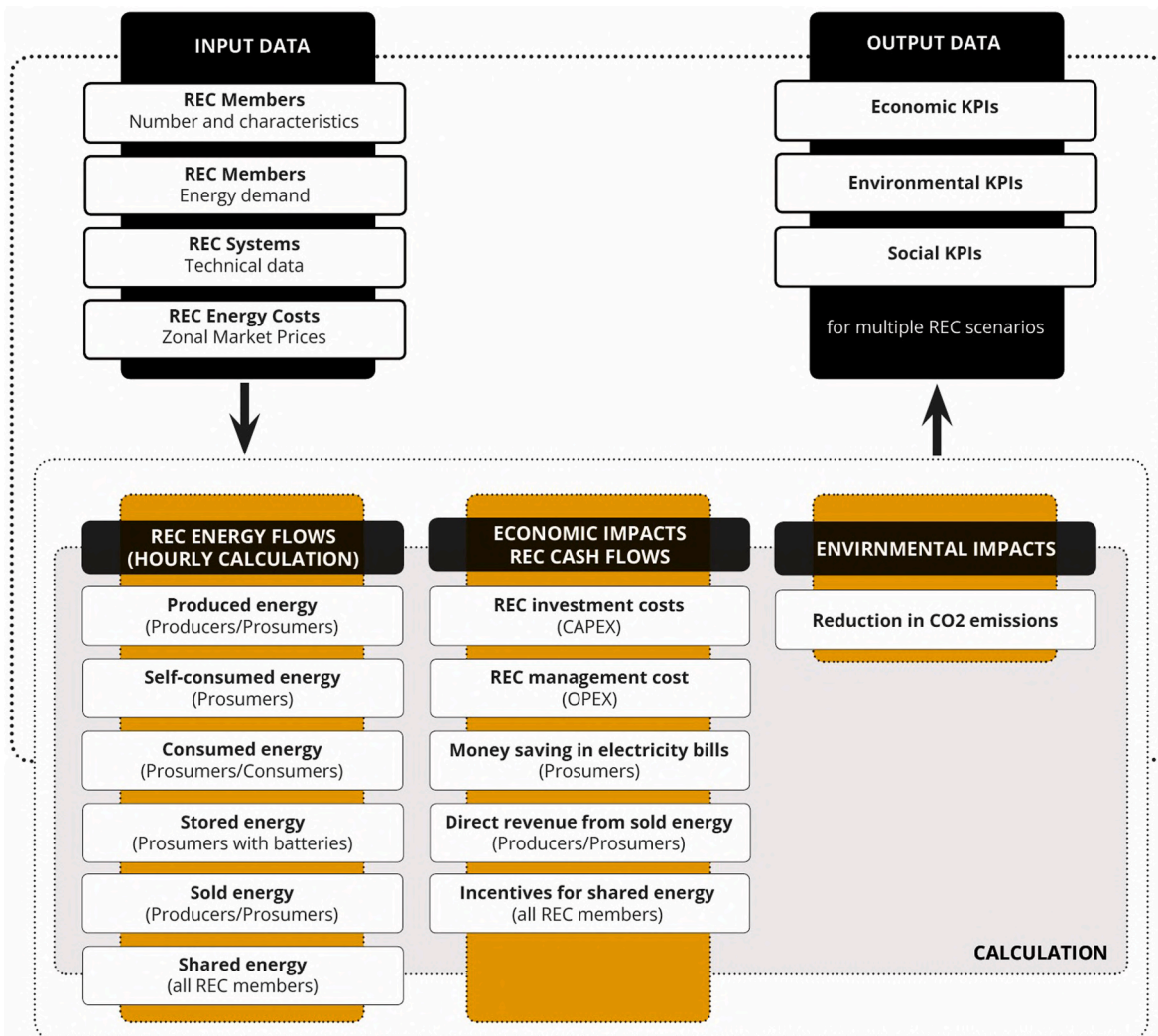


Fig. 2. REC simulator framework.

- Technical data concerning battery energy storage systems (BESS) to be installed (e.g. storage capacity, battery efficiency, depth of discharge, hourly charging and discharging rates).

Based on input data mentioned above, the presented simulator returns the hourly-calculated values of the following energy flows:

- The clean energy produced by the PV systems owned by *producers* and *prosumers* of the REC
- The energy directly self-consumed by *prosumers* when the related PV systems are actively operating
- The energy consumed by *consumers* and *prosumers* (when PV system is not fully supplying *prosumers* loads)
- The energy stored in BESS (by accurately simulating charging and discharging cycles of batteries)
- The surplus produced energy to be sold to the GSE by *producers* and *prosumers*
- The total amount of energy hourly withdrawn from the electricity distribution network by all REC members
- The so-called *shared energy* (i.e. the energy virtually shared between REC members, which is hourly calculated as the minimum value between the surplus produced energy injected into the power grid by *producers* and *prosumers*, and the energy simultaneously withdrawn from the electricity distribution network by the energy community).

Special attention must be given to the estimation method adopted for calculating the energy produced by PV systems. The proposed simulator estimates hourly energy production by multiplying the peak power of PV systems by the panels efficiency and the global solar irradiance. The global solar irradiance on the tilted and oriented surfaces of the PV panels is analytically calculated in accordance with the Italian standard on climatic data for building cooling and heating (UNI, 2016), using hourly data from Photovoltaic Geographical Information System PVGIS (Photovoltaics Geographical Information System (PVGIS) of the European Commission, n.d.) on global and diffuse solar irradiance on a horizontal plane. It is worth noting that PVGIS provides solar radiation data for any geographical location where a PV system might be installed, based on a Typical Meteorological Year (TMY) dataset derived from the 2005–2020 period.

Regarding the estimation of energy consumption by *consumers* and *prosumers* within the energy community, consumptions data can be derived either from standard load profiles or from user-provided electricity bills. However, since electricity bills generally present data aggregated by months and time slots, to make energy flows calculation more accurate, hourly coefficients have been first extracted from 12 residential load curves (i.e. three per season, one for working days, the second for days before holidays and the third one for non-working days, made available by (Gallanti et al., 2012), and then applied to hourly values of residential consumptions. For non-residential users, simulations were based on real monthly electricity consumption data provided

by users, broken down by time slot and then evenly distributed hourly. This accurate hourly calculation of expected energy flows allows for an equally precise estimation of expected cash flows. The economic feasibility of potential REC scenarios can thus be assessed based on detailed estimates of the following costs and revenues:

- The initial investment costs (CAPEX) for the installation of new PV systems and BESS
- The operation and maintenance costs (OPEX)
- The money saving in electricity bills deriving from the directly self-consumed and BESS withdrawn energy by *prosumers*
- The revenues from the surplus produced energy, sold by *producers* and *prosumers*
- The revenues from incentives granted for the *shared energy*.

It is important to note that the proposed simulator assumes a market electricity price of 0.25 €/kWh for estimating the monetary savings on electricity bills. Regarding revenues from the sale of surplus energy, the energy produced by *prosumers* and *producers* and injected into the power grid is valued according to the hourly energy zonal price ( $ZP_h$ ) made available by the Italian Energy Services Manager (GSE). Specifically, the proposed simulator estimates yearly revenues from sold energy by using a Design Reference Year (DRY) composed of hourly zonal price values ( $ZP_h$ ) for the Sardinia region (i.e. the so-called SARD), selected from a multi-year dataset (2013–2022) publicly available on the GSE portal.

In accordance with the Italian regulations concerning RECs (MASE, 2023), the *energy* virtually *shared* between energy community members is subject to a reward tariff ( $SE_{rt,h}$ ) defined by the following formulas:

$$SE_{rt,h} = 60 \frac{\text{€}}{\text{MWh}} + (\min(\max(0; 180 - ZP_h); 40)) \frac{\text{€}}{\text{MWh}} \quad (1)$$

$$SE_{rt,h} = 70 \frac{\text{€}}{\text{MWh}} + (\min(\max(0; 180 - ZP_h); 40)) \frac{\text{€}}{\text{MWh}} \quad (2)$$

$$SE_{rt,h} = 80 \frac{\text{€}}{\text{MWh}} + (\min(\max(0; 180 - ZP_h); 40)) \frac{\text{€}}{\text{MWh}} \quad (3)$$

Where equation (1) is used for PV systems with a peak power greater than 600 kW, while formula (2) applies to systems with a peak power between 200 kW and 600 kW. Expression (3) is adopted for PV systems with a total power less than or equal to 200 kW.

Based on a precise calculation of the expected cash flows, the proposed simulator enables an accurate estimation of several Key Performance Indicators (KPIs), widely used to assess investment profitability. In this context, the assessment of KPIs is aimed at providing useful parameters for estimating and easily comparing individual and collective economic benefits across different REC scenarios. The following economic KPIs are estimated:

- The Present Value (PV) of future cash flows, estimated as follows:

$$PV_n = \sum_{t=1}^n \frac{CF_t}{(1+r)^t} \quad (4)$$

- The Payback Period (PBP) of the initial investment (CAPEX), obtained by solving the following equation to find:

$$-I_0 + \sum_{t=1}^n \frac{CF_t}{(1+r)^t} = 0 \quad (5)$$

- The Profitability Index (PI), estimated as follows:

$$PI = \frac{PV_n}{I_0} \quad (6)$$

Where:

- $n$  is the number of years considered in the calculation of the time value of money
- $t$  is the time slot varying from 1 to  $n$
- $r$  represents the discount rate considered
- $CF_t$  is the actualized yearly cash inflow
- $I_0$  corresponds to the total initial investment (CAPEX), thus including not only the simple cost for the PV system installation ( $C_{PV}$ ) but also the related design cost, safety obligations and other expenditure on additional services.

The yearly cash flow  $CF_t$  is assessed by adding up revenues from the sold and shared energy with the estimated money saving in electricity bills, net of yearly operation, maintenance and monitoring costs. In this regard, yearly O&M costs are estimated as follows:

$$C_{O\&M,y} = 1500 \left[ \frac{\text{€}}{\text{year}} \right] + 0.01 * C_{PV} \quad (7)$$

Where  $C_{PV}$  corresponds to the initial cost for the installation of PV systems.

The yearly costs for the monitoring system ( $C_{Mon,y}$ ) are instead appraised based on the number of REC members ( $n_{memb}$ ) according to the following formula:

$$C_{Mon,y} = 50 \left[ \frac{\text{€}}{\text{year}} \right] * n_{memb} \quad (8)$$

Furthermore, the proposed simulator - whose framework is summarized in Fig. 2 - includes a basic estimation of the potential environmental benefits generated by RECs. Specifically, it calculates the potentially avoided  $CO_2$  emissions by multiplying the total amount of the produced clean energy by a conversion coefficient of 0.702 t  $CO_2$ /MWh (Naitana et al., 2023). Finally, to assess the potential social benefits for REC members, the simulator incorporates an Electrical Energy Poverty Index (EEPI), which is estimated as follows:

$$EEPI = EE_{exp} / NAI \quad (9)$$

Where:

- $EE_{exp}$  corresponds to the average energy expenditure for electricity.
- $NAI$  is the Net Annual Income.

It is worth remarking that the introduced EEPI has been conceived to be assessed for different REC scenarios and, moreover, to be compared with the corresponding statistical values obtained from data provided by the Italian Institute of Statistics (ISTAT), specifically for the Italian and Sardinian contexts (ISTAT, n.d.).

### 3. Case study: the first energy community in Cagliari (Italy)

The first REC pilot project in the city of Cagliari (CER-CA project) was implemented in *San Michele*, a public housing neighbourhood characterized by social and economic vulnerability (see Fig. 3). The selection of this area was a strategic decision by the municipality to tackle energy poverty through a comprehensive and integrated approach. A distinctive feature of this urban context is its ring-shaped arrangement of public housing buildings encircling *Piazza Medaglia Miracolosa*. Despite the area's state of decay, the presence of a kindergarten at the heart of the square has kept this public space vital for the local community (Blečić et al., 2023, 2024a).

The CER-CA project included a variety of activities, focusing not only

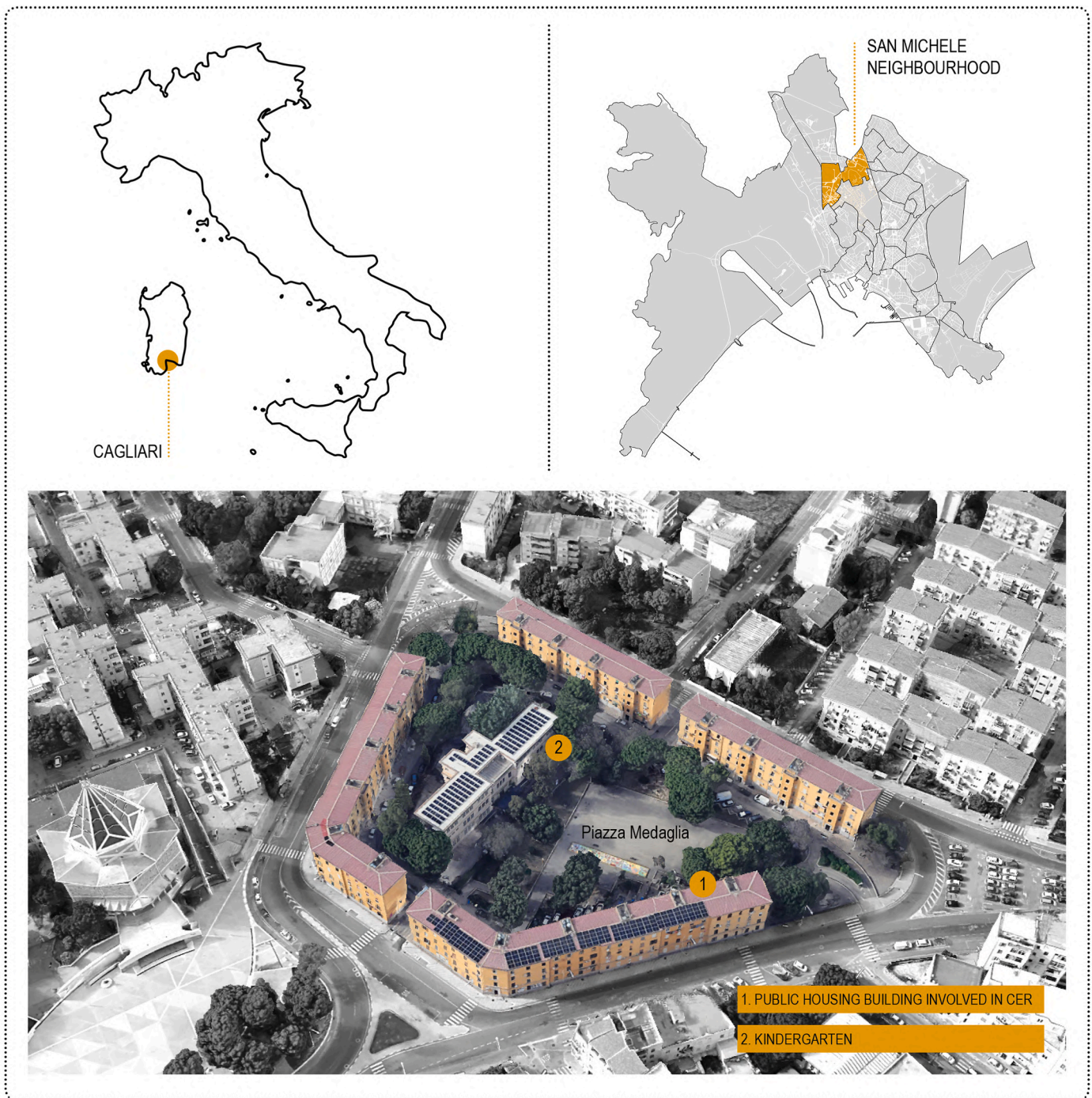


Fig. 3. The REC pilot project in the San Michele neighbourhood (Cagliari): public housing buildings and the kindergarten involved in the REC.

on improving energy efficiency through the installation of photovoltaic systems on the roofs of residential buildings and the kindergarten, but also on using this opportunity to pursue broader social and economic objectives. Among these was the promotion of active participation by residents, further enhancing the long-term impact of the project. The herein described pilot project envisaged the establishment of a REC through the installation of a PV system, composed of three different lots, respectively two on the best oriented residential blocks and one installed on the kindergarten roof. The municipality envisages that through the co-operation of most of the 80 households and the electricity consumption of the kindergarten, the electricity produced by the PV would have been almost completely (physically or virtually) self-consumed by the REC members.

## 4. Results and discussion

### 4.1. Citizen engagement activities and data collection

To encourage participation in the REC, engagement activities were organized for the residents. In the initial phase, kindergarten children were involved in the redevelopment of an abandoned bocce court within the square. This initiative fostered a sense of belonging among the residents towards the space and increased their willingness to take care of it, thereby connecting them more closely to the CER project. In the following months, data collection and membership activities for the REC took place. During the citizen engagement phase, energy consumption data were collected from 14 potential members residing in the project

area who were interested in joining the REC (called in this paper “REC users”), of which:

- 1 user provided only aggregated monthly energy consumption data.
- 1 user provided only an annual summary of energy consumption by time slots.
- 3 users provided only partial monthly energy consumption data.
- 6 residential users and 1 commercial user provided complete data for all months and time slots of energy consumption.
- 3 users provided monthly data with only the indication of the F1 time slot for energy consumption.

Notwithstanding 37 local people had agreed to be interviewed, a quite low number of potential REC members supplied personal data related to their electricity consumption, reflecting the initial widespread mistrust in institutions, which inevitably extended to the REC project despite the concerted efforts made through the engagement activities. As shown in Table 1, only the data from the 6 residential users who provided complete data for all months and time bands of energy consumption were assumed as “sample users” and used to define a “standard profile” starting from the related average consumption values.

In Fig. 4 the overall percentage of energy consumption for each time slot (F1, F2 and F3) is reported for the most relevant consumer profiles, in order to bring to light that except for the most virtuous consumer profile, most of energy consumption of potential consumers of the REC are concentrated in time slots F2 (from Monday to Friday h. 07:00–8:00 and h. 19:00–22:00, on Saturday h. 07:00–22:00) and F3 (from Monday to Saturday h. 00:00–07:00 and h. 22:00–24:00, on Sunday the whole day) whereas only a marginal part resulted to be referred to the F1 time band (from Monday to Friday h. 08:00–19:00). As it will be shown in the next section, the time distribution of members’ energy consumption has strongly impacted on the simulations results.

The engagement activities addressed technical and bureaucratic challenges while integrating social considerations into the REC design, aligning with the community’s needs, preferences, and priorities. This methodological approach (Blečić et al., 2023, 2024a), designed for the specific socio-economic conditions of the housing complex, provides a replicable framework applicable to other contexts, including within the ‘Energy Efficiency in 40 Schools Support Communities – EE(40)Sco’ program led by the Municipality of Cagliari. The experience gained through this process has refined the methodology, paving the way for broader applications. Conducting this pilot test allows for the collection of comparable data across different socio-economic environments, validating and enhancing the approach for other contexts.

The dynamics of inclusion observed in this REC project have the potential to shape a spatial, social, cultural, and economic frameworks capable of adapting to evolving circumstances, capacity demands, and

demographic, economic, and social trends. Such initiatives are instrumental in fostering programmatic, participatory, and democratic strategic planning, where the development and management pathways of an energy community are collectively defined. Although the engagement activities did not attract a large number of potential REC members, this approach has demonstrated its capacity to ensure valuable outcomes in terms of the quality of participants, creating a foundation for participation in the energy system, promoting virtuous behaviours, encouraging a degree of self-sufficiency in management practices (Blečić et al., 2023, 2024a).

#### 4.2. Multiple scenarios for different REC configurations

In this section, the results deriving from multiple-scenarios simulations will be discussed. In order to preliminarily predict potential economic, environmental and social benefits deriving from different realistic configurations of the REC project, different simulations have been first carried out by considering three different REC configurations in terms of members composition, which are:

- 1 prosumer, 20 residential consumers and 1 commercial consumer.
- 1 prosumer, 40 residential consumers and 1 commercial consumer.
- 1 prosumer, 60 residential consumers and 1 commercial consumer.

It is worth specifying that only variations in consumers composition (within a realistic range between 20 and 60 consumers considering the real size of the Piazza Medaglia community) have been preliminarily considered as the Municipality of Cagliari wholly provided the PV systems to the REC, by only allowing the municipal kindergarten to directly self-consume the produced solar energy. All this considered, the Municipality of Cagliari may be considered as the only prosumer of the REC. Some relevant parameter values used as input data in performed simulations are summarized in Table 2.

Additionally, to provide a more comprehensive analysis of the REC potential, further theoretical scenarios have been simulated by also considering a potential expansion of the REC in terms of members, as well as by varying the PV size and the BESS capacity keeping the initial investment (CAPEX) fixed. In this regard, all realistic and theoretical simulated scenarios are summarized in Table 3. Note that each scenario is doubled by simulating both, realistic load profiles of members and optimized load profiles, the latter obtained by rising 50 % the percentage of the energy consumed by residential consumers in monthly F1 time slots to increase the REC shared energy. The numbers of 260 and 120 residential consumers resulted from a basic sensitivity analysis which led to an identification of the optimum number of 260 consumers required to maximize the shared energy and to the optimum number of 120 consumers which maximize the overall economic revenues.

**Table 1**  
Energy consumption data and REC members characterization.

| N. | ID             | User category | User Type             | Consumptions [kWh/Year] | Sample User |
|----|----------------|---------------|-----------------------|-------------------------|-------------|
| 1  | CONSUMER_01    | Consumer      | Residential           | 2098                    | Yes         |
| 2  | CONSUMER_02    | Consumer      | Residential           | 930                     | Yes         |
| 3  | CONSUMER_03    | Consumer      | Residential           | 1445                    | Yes         |
| 4  | CONSUMER_04    | Consumer      | Residential           | 2615                    | No          |
| 5  | CONSUMER_05    | Consumer      | Condominium Staircase | 80                      | No          |
| 6  | CONSUMER_06    | Consumer      | Residential           | 2869                    | Yes         |
| 7  | CONSUMER_07    | Consumer      | Residential           | 2623                    | Yes         |
| 8  | CONSUMER_08    | Consumer      | Residential           | 3428                    | No          |
| 9  | CONSUMER_09    | Consumer      | Residential           | 1258                    | No          |
| 10 | CONSUMER_10    | Consumer      | Residential           | 2393                    | No          |
| 11 | CONSUMER_11    | Consumer      | Residential           | 4305                    | No          |
| 12 | CONSUMER_12    | Consumer      | Residential           | 3993                    | No          |
| 13 | CONSUMER_13    | Consumer      | Residential           | 3626                    | Yes         |
| 14 | CONSUMER_14    | Consumer      | Commercial            | 9180                    | –           |
| 15 | PROSUMER_01    | Prosumer      | Kindergarten          | 33915                   | No          |
| n  | STANDARD USER* | Consumer      | Residential           | 2532                    | –           |

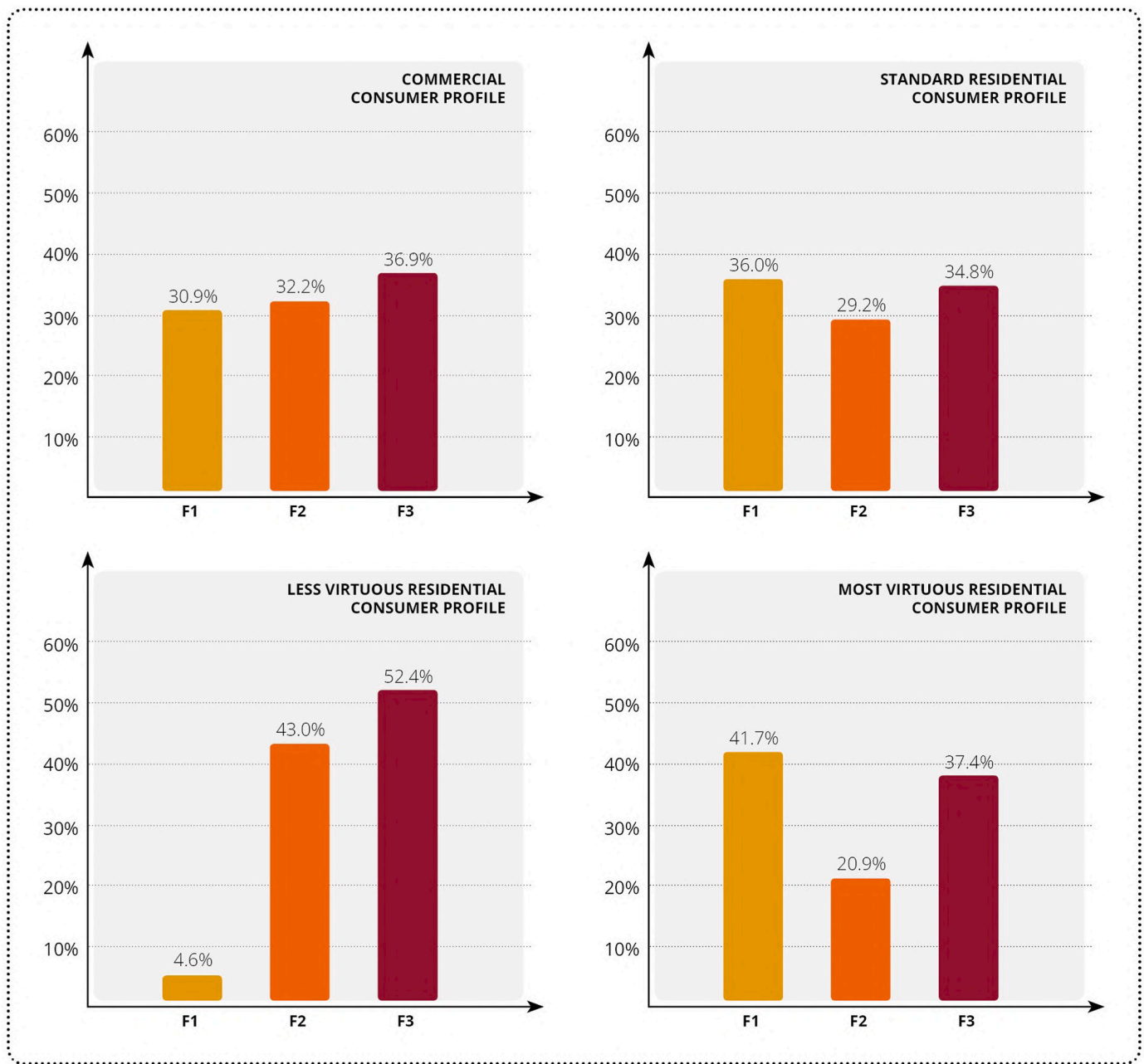


Fig. 4. Consumers' consumption profiles (from user-provided bills data).

Table 2

Technical parameters used in simulations of realistic scenarios (i.e. considering the PV size and BESS capacity installed actually).

| Parameter                              | Value  |
|--|--------|
| Latitude [°]                           | 39.238 |
| Longitude [°]                          | 9.102  |
| PV field 1_1 - peak power [kWp]        | 16     |
| PV field 1_1 - North-based azimuth [°] | 218    |
| PV field 1_1 - tilt angle [°]          | 10     |
| PV field 1_2 - peak power [kWp]        | 48     |
| PV field 1_2 - North-based azimuth [°] | 164    |
| PV field 1_2 - tilt angle [°]          | 10     |
| PV field 2 - peak power [kWp]          | 43.2   |
| PV field 2 - North-based azimuth [°]   | 218    |
| PV field 2 - tilt angle [°]            | 13     |
| BOS of PV systems                      | 0.7    |
| BESS capacity [kWh]                    | 20     |

As anticipated in the methodological Section 2.2, the proposed simulation tool allowed for an hourly accurate evaluation of the solar energy produced by the PV systems, based on technical parameters in Table 2 for the realistic scenarios, and resulting in a total yearly amount of produced energy of 132705 kWh. Moreover, it has been estimated that the *prosumer* of the REC (i.e. the kindergarten) may directly consume only the 13 % of the produced energy, store into the BESS the 10 % of the yearly produced energy and feed into the power grid the exceeding 77 %, to make it available to all REC members to be virtually shared. In this regard, Fig. 5 provides the yearly trends of the most relevant energy flows, including the produced energy, the self-consumed energy, the BESS stored energy, the energy withdrawn from and fed into the power grid, as well as the virtually-shared energy. All those quantities have been estimated hourly for a typical meteorological year (TMY) and then aggregated by month for the considered REC scenarios.

**Table 3**  
Realistic and theoretical simulated scenarios.

| Scenario | Scenario code     | Residential consumers | PV size [kWp] | BESS capacity [kWh] | Load profiles | PV size [kWp] per consumer |
|----------|-------------------|-----------------------|---------------|---------------------|---------------|----------------------------|
| 1        | c20_pv107_b20_rc  | 20                    | 107.2         | 20                  | real          | 5.36                       |
| 2        | c20_pv107_b20_oc  | 20                    | 107.2         | 20                  | optimized     | 5.36                       |
| 3        | c40_pv107_b20_rc  | 40                    | 107.2         | 20                  | real          | 2.68                       |
| 4        | c40_pv107_b20_oc  | 40                    | 107.2         | 20                  | optimized     | 2.68                       |
| 5        | c60_pv107_b20_rc  | 60                    | 107.2         | 20                  | real          | 1.78                       |
| 6        | c60_pv107_b20_oc  | 60                    | 107.2         | 20                  | optimized     | 1.78                       |
| 7        | c260_pv107_b20_rc | 260                   | 107.2         | 20                  | real          | 0.41                       |
| 8        | c260_pv107_b20_oc | 260                   | 107.2         | 20                  | optimized     | 0.41                       |
| 9        | c120_pv107_b20_rc | 120                   | 107.2         | 20                  | real          | 0.89                       |
| 10       | c120_pv107_b20_oc | 120                   | 107.2         | 20                  | optimized     | 0.89                       |
| 11       | c120_pv97_b40_rc  | 120                   | 97.2          | 40                  | real          | 0.81                       |
| 12       | c120_pv97_b40_oc  | 120                   | 97.2          | 40                  | optimized     | 0.81                       |
| 13       | c120_pv79_b80_rc  | 120                   | 79.2          | 80                  | real          | 0.99                       |
| 14       | c120_pv79_b80_oc  | 120                   | 79.2          | 80                  | optimized     | 0.99                       |

Notwithstanding the performed simulations show an increase in the shared energy trends by increasing the number of potential consumers, basic calculations resulted in really low percentages of shared to produced energy for the realistic REC configurations, if compared to corresponding values reported in the literature (Cielo et al., 2021; Trevisan et al., 2024). More specifically, only 17.2 % of the yearly produced energy has been estimated to be virtually shared among the REC members in the **scenario 1** (20 residential consumers). Moreover, increasing the number of potential consumers to 40 (**scenario 3**) and to 60 (**scenario 5**), the shared to produced energy ratio only rose from 17.2 % to 29.7 % and to 40.5 % respectively. It is worth noting that the predicted low percentages of shared energy for all scenarios may provide negative indicators of the energy efficiency of the considered potential configurations of the REC project.

However, it should be also clarified that, at the same time, those predicted low values of shared to produced energy ratios mean that the potential of the REC is not fully exploited and its capacity in terms of users' number is not saturated yet. As matter of fact, the percentage of shared to produced energy percentage could not be analysed without considering the ratio between the PV systems peak power and the number of consumers, which especially for the realistic REC configurations (**scenarios 1–6**) assume high values (compared to the previously mentioned examples in the literature), ranging from 1.78 to 5.36 (as shown in Table 3). As further proof of that, it has been estimated that a total number of 260 residential consumers is required to maximize the virtually shared energy reaching the 100 % of the energy fed into the grid by the prosumer (corresponding to the 79.6 % of the produced energy).

Data reported in Fig. 6 prove the effectiveness of the proposed optimization strategy for the realistic scenarios, showing a considerable increase (ranging from 15 % to 17 %) in shared energy estimations when optimized load profiles are considered in simulations (i.e. the **scenario 2**, the **scenario 4** and the **scenario 6**).

According to the proposed integrated multi-dimensional approach (described in Section 2), the implemented decision support tool, based on the hourly estimation of the energy flows, also predicts equally accurately the corresponding yearly cash flows for all REC scenarios herein considered (see summarized data in Table 4) thus including the bill saving and the sold energy revenue for the prosumer, the rewarding incentives for the shared energy, the operational costs, the total incentives and the pro-capita revenue for consumers.

As far as the REC O&M yearly costs ( $C_{O\&M,y}$ ) reported on Table 4 are concerned, according to the economic plan produced by the Municipality of Cagliari, the estimated amount of 4153 € was calculated according to the (7) equation, based on a PV system installation cost ( $C_{PV}$ ) equal to 265319 €, thus resulting in a PV unit cost of 2480 €/kWp. However, it is worth specifying that the total initial investment ( $I_0$ ), made by the Municipality of Cagliari for the REC pioneering project was much higher than the  $C_{PV}$  cost item and equal to 389876 € (this amount

thus corresponds to the CAPEX) including design costs, safety obligations and other not negligible additional costs.

Lastly, the incentives from the shared energy reported on Table 4, were calculated according to the (3) equation as the total peak power of the installed PV plants was always assumed to be lower than 200 kW (see data on Table 2). The yearly total incentives (at the second to last column of Table 4) are simply obtained by adding up revenues from the energy sold with the bonus incentives recognized for the shared energy. In this regard, the pro-capita revenue resulted to be strongly affected by the variations in the number of potential REC members (Table 4) as the Municipality of Cagliari, acting as REC manager, for evident social purposes, decided to distribute equally among all REC members not only the incentives recognized for the shared energy, but also the revenues deriving from the sold energy.

Based on the calculation of the expected energy and cash flows, the performed multi-scenario simulations finally led to the assessment of some relevant economic, environmental and social KPIs (Key Performance Indicators), to more easily analyse both, individual and collective, economic, environmental and social benefits for the considered REC configurations. To that end, the Present Value at a 20-years horizon ( $PV_{20}$ ) of the estimated future cash flows for all scenarios has been estimated, according to the (4) formula, considering two different potential discount rates (i.e.  $r_1 = 3\%$  and  $r_2 = 6\%$ ). Compared to the Net Present Value (NPV), the Present Value (PV) assess the future cash flows by neglecting the negative contribution of the CAPEX (i.e. the total initial investment  $I_0$ ). The latter is instead considered in estimating the overall Profitability Index (PI), which resulted to be always much lower than 1 (see Table 5).

Both the resulting  $PI_3\%$  and the  $PI_6\%$ , as well as the obtained values of the Payback Period (PBP) in Table 5, all assessed for all normal and optimized scenarios according with the (6) and the (5) formula respectively, prove that the project of this REC is not able to generate a positive economic value in 20 years for the investor, unless the number of REC members increases considerably. Data summarized in Table 5 confirm that, from an economic point of view, the **scenario 9** (c120\_pv107\_b20\_rc) turned out to be the most convenient in terms of profitability, even though the shared energy is not maximized (see Fig. 7) and the related PI values resulted to be lower than 1. Fortunately, in this specific case, the Municipality of Cagliari benefited from public funding. The negative values of the obtained economic KPIs are in line with the non-profit purposes of the project, which instead mainly aimed at generating environmental and social benefits for a fragile context. As far as the environmental benefits potentially generated are concerned, as the avoided CO<sub>2</sub> emissions have been simply assessed based on the clean produced energy, the obtained yearly amount of 93.16 tCO<sub>2</sub> only slightly decreases when the PV size is reduced. Lastly, the values of the Electrical Energy Poverty Index (EEPI), estimated according to the (9) formula, provide a basic quantitative indicator of the positive social impact of the considered REC scenarios. In this regard, Fig. 8 shows a

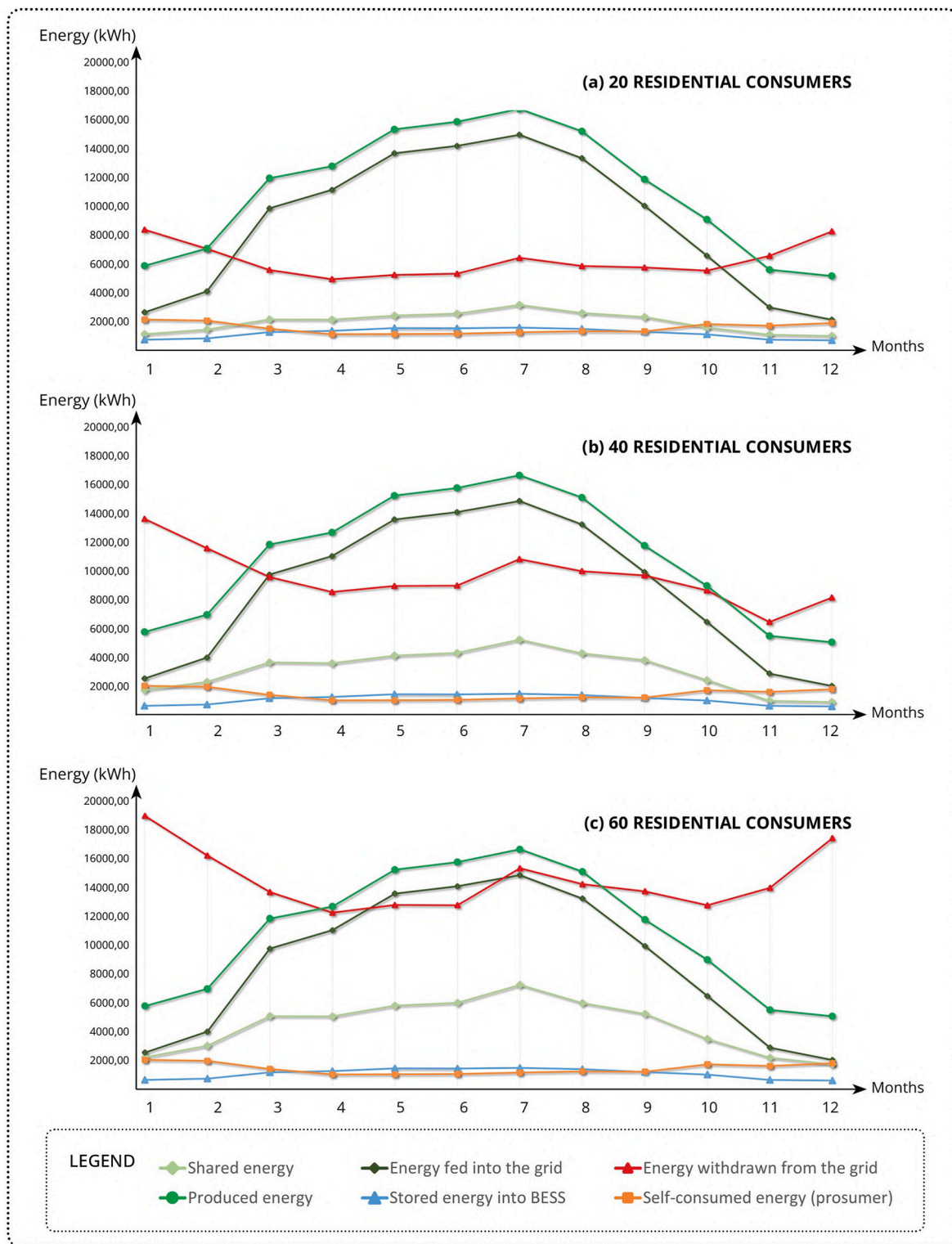


Fig. 5. Estimated energy flows for a Typical Meteorological Year (TMY): scenario simulation for three different realistic REC configurations including 1 *prosumer*, 1 *commercial consumer* and, respectively, 20, 40 or 60 residential *consumers*.

comparison between the EEPI values of the halfway realistic REC scenarios considering 40 residential consumers (with both real and optimized load profiles), the ideal scenarios 9 (c120\_pv107\_b20\_rc) and 10 (c120\_pv107\_b20\_oc), the ex-ante REC context, as well as the corresponding Italian and Sardinian average indicators.

As far as the EEPI values regarding the REC ex-ante and ex-post scenarios are concerned, the net annual income NAI in the (9)

equation was assumed to be equal to 14573 €, that corresponds to the income threshold requirement to be eligible for public housing allocation owned by the Municipality of Cagliari in 2023 (with reference to Article 21 of Law No. 457 of 5 August 1978 “Regulations for Residential Housing”). This assumption is due to the sensitivity of this kind of personal information, which is not freely available. Furthermore, the average electricity expenditure  $EE_{exp}$  of potential REC members (equal

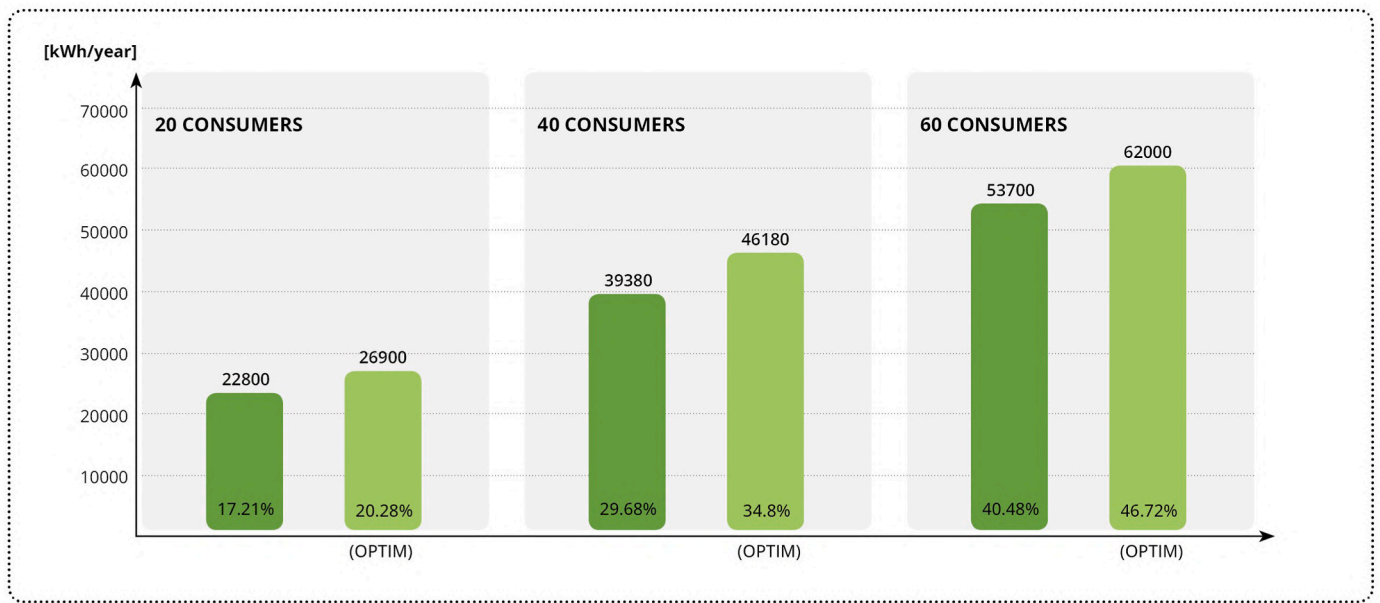


Fig. 6. Shared energy multi scenario trends including percentage values of the shared to produced energy ratios estimated for a TMY for realistic REC scenarios (with both real and optimized load profiles).

Table 4

Estimated cash flows for various REC scenarios.

| Scenario code     | Bill saving [€/year] | Sold energy revenue [€/year] | Shared energy incentives [€/year] | REC O&M Costs [€/year] | Monitoring system cost [€/year] | Total incentives [€/year] | Pro-capita revenue (consumers) [€/year] |
|-------------------|----------------------|------------------------------|-----------------------------------|------------------------|---------------------------------|---------------------------|---|
| c20_pv107_b20_rc  | 5942.16              | 5079.47                      | 2737.15                           | 4153.19                | 1050.00                         | 7816.62                   | 229.17                                  |
| c20_pv107_b20_oc  | 5942.16              | 5079.47                      | 3226.07                           | 4153.19                | 1050.00                         | 8305.54                   | 252.45                                  |
| c40_pv107_b20_rc  | 5942.16              | 5079.47                      | 4719.98                           | 4153.19                | 2050.00                         | 9799.44                   | 129.26                                  |
| c40_pv107_b20_oc  | 5942.16              | 5079.47                      | 5536.87                           | 4153.19                | 2050.00                         | 10616.34                  | 149.18                                  |
| c60_pv107_b20_rc  | 5942.16              | 5079.47                      | 6437.82                           | 4153.19                | 3050.00                         | 11517.29                  | 91.61                                   |
| c60_pv107_b20_oc  | 5942.16              | 5079.47                      | 7433.16                           | 4153.19                | 3050.00                         | 12512.63                  | 107.92                                  |
| c260_pv107_b20_rc | 5942.16              | 5079.47                      | 12652.31                          | 4153.19                | 13050.00                        | 17731.77                  | 0.95                                    |
| c260_pv107_b20_oc | 5942.16              | 5079.47                      | 12480.43                          | 4153.19                | 13050.00                        | 17559.89                  | 0.29                                    |
| c120_pv107_b20_rc | 5942.16              | 5079.47                      | 10179.31                          | 4153.19                | 6050.00                         | 15258.78                  | 44.58                                   |
| c120_pv107_b20_oc | 5942.16              | 5079.47                      | 10891.14                          | 4153.19                | 6050.00                         | 15970.60                  | 50.46                                   |
| c120_pv97_b40_rc  | 6805.86              | 4236.26                      | 9036.50                           | 4153.19                | 6050.00                         | 13272.76                  | 32.27                                   |
| c120_pv97_b40_oc  | 6805.86              | 4236.26                      | 9483.01                           | 4153.19                | 6050.00                         | 13719.28                  | 35.96                                   |
| c120_pv79_b80_rc  | 6943.02              | 3029.71                      | 7112.24                           | 4153.19                | 6050.00                         | 10141.95                  | 12.86                                   |
| c120_pv79_b80_oc  | 6943.02              | 3029.71                      | 7148.24                           | 4153.19                | 6050.00                         | 10177.94                  | 13.16                                   |

Table 5

Social, economic and environmental KPIs for various REC scenarios.

| Scenario code     | Yearly revenues (not discounted) [€] | Present Value (PV) at 20 years r = 3 % [€] | Present Value (PV) at 20 years r = 6 % [€] | Profitability Index (PI) r = 3 % | Profitability Index (PI) r = 6 % | Payback Period (PBP) [years] | Avoided CO <sub>2</sub> emissions [tCO <sub>2</sub> /year] |
|-------------------|--------------------------------------|--|--|----------------------------------|----------------------------------|------------------------------|--|
| c20_pv107_b20_rc  | 8555.59                              | 127285.53                                  | 77108.51                                   | 0.33                             | 0.20                             | >20                          | 93.16  |
| c20_pv107_b20_oc  | 9044.50                              | 134559.33                                  | 103739.71                                  | 0.35                             | 0.27                             | >20                          | 93.16  |
| c40_pv107_b20_rc  | 9538.41                              | 141907.46                                  | 85966.35                                   | 0.36                             | 0.22                             | >20                          | 93.16  |
| c40_pv107_b20_oc  | 10355.31                             | 154060.80                                  | 118774.54                                  | 0.40                             | 0.30                             | >20                          | 93.16  |
| c60_pv107_b20_rc  | 10256.25                             | 152587.12                                  | 92436.01                                   | 0.39                             | 0.24                             | >20                          | 93.16  |
| c60_pv107_b20_oc  | 11251.59                             | 167395.25                                  | 129054.86                                  | 0.43                             | 0.33                             | >20                          | 93.16  |
| c260_pv107_b20_rc | 6470.74                              | 96268.27                                   | 58318.51                                   | 0.25                             | 0.15                             | >20                          | 93.16  |
| c260_pv107_b20_oc | 6298.86                              | 93711.12                                   | 72247.42                                   | 0.24                             | 0.19                             | >20                          | 93.16  |
| c120_pv107_b20_rc | 10997.75                             | 163618.69                                  | 99118.84                                   | 0.42                             | 0.25                             | >20                          | 93.16  |
| c120_pv107_b20_oc | 11709.57                             | 174208.83                                  | 134307.84                                  | 0.45                             | 0.34                             | >20                          | 93.16  |
| c120_pv97_b40_rc  | 9875.43                              | 146921.40                                  | 89003.76                                   | 0.38                             | 0.23                             | >20                          | 84.50  |
| c120_pv97_b40_oc  | 10321.94                             | 153564.45                                  | 118391.87                                  | 0.39                             | 0.30                             | >20                          | 84.50  |
| c120_pv79_b80_rc  | 6881.77                              | 102383.43                                  | 62023.02                                   | 0.26                             | 0.16                             | >20                          | 68.91  |
| c120_pv79_b80_oc  | 6917.77                              | 102918.93                                  | 79346.27                                   | 0.26                             | 0.2                              | >20                          | 68.91  |

to 633 €/year) in simulated ex-post scenarios was decreased of the estimated pro-capita revenue owe to each household (see values in Table 4). As far as the Italian and Sardinian reference values of the EEPI

are concerned, they were roughly estimated assuming the ISTAT values of EE<sub>exp</sub> equal to 569 €/year for Italy and to 676 €/year for the Sardinian Region, as well as the ISTAT average values of the NAI equal to 32.812 €

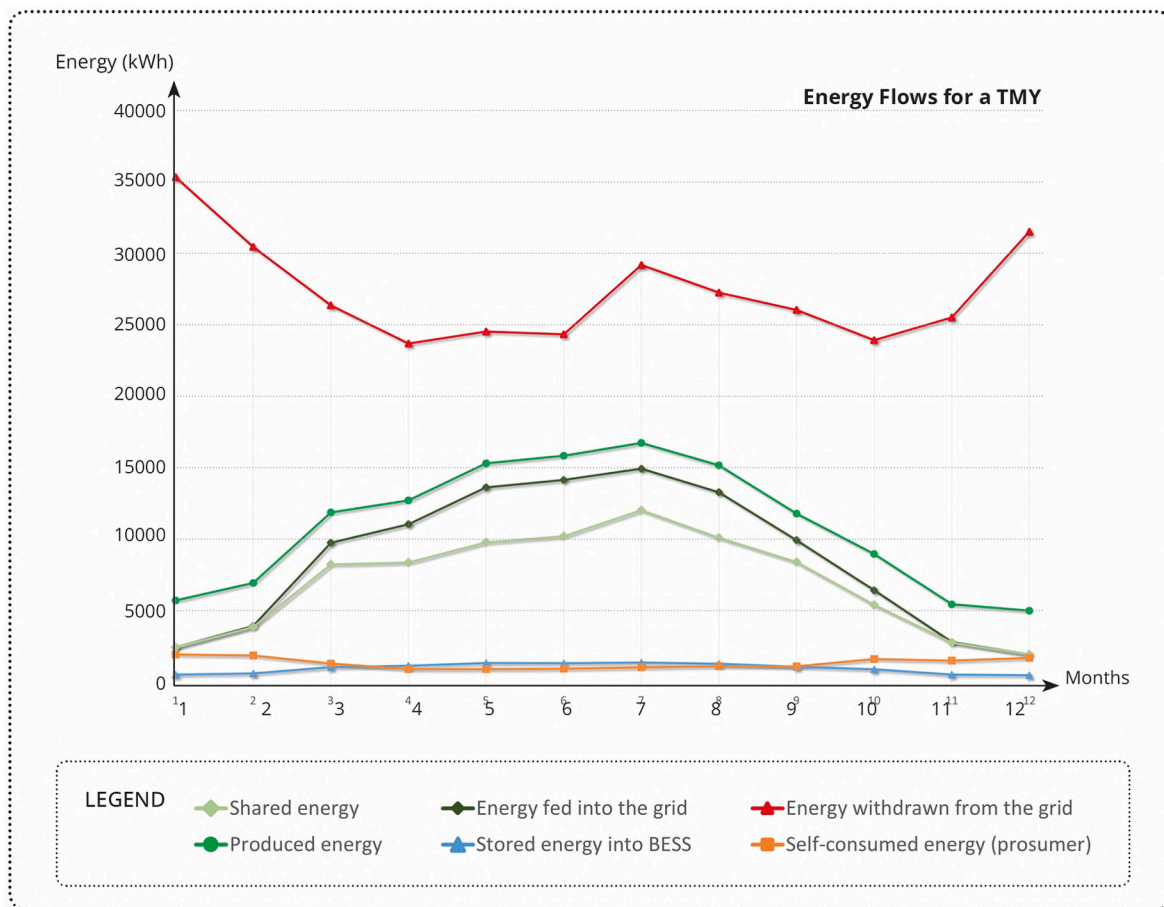


Fig. 7. Estimated energy flows for a Typical Meteorological Year (TMY): scenario simulation for an ideal REC configuration including 1 prosumer, 1 commercial consumer and 120 residential consumers (scenario 9 - c120\_pv107\_b20\_rc).

for Italian households and to 28.841 € for Sardinian households.

All this considered, the results in Fig. 8 clearly bring the energy vulnerability of the involved family units to light, as the values of the EEPI assessed for the REC scenarios turned out to be always significantly higher than the considered reference values for the Italian and Sardinian contexts.

These findings confirm that RECs present both opportunities and challenges that must be carefully examined, especially within the framework of public policies. Beyond the aspect of financial viability of the investment, it is also important to consider the indirect positive impacts of renewable energy installations, particularly in more vulnerable residential contexts such as public housing. Indirect social, health, environmental, and economic benefits are often overlooked when studying energy in buildings but represent an important lever for the promotion and dissemination of these technologies (Bahaj and James, 2007; Liddell and Guiney, 2015; Martini, 2023; Nesticò and Sica, 2017; Ntaintasis et al., 2019).

To maximize these indirect benefits, evaluations should include not only direct financial returns but also the broader impacts of the public investment. This comprehensive approach ensures a more accurate assessment of the value provided by renewable energy projects, helping policymakers in making informed decisions that maximize the positive outcomes, especially for vulnerable communities.

## 5. Conclusion

Given the limited research on renewable energy communities, which comprehensively addresses technical, economic, environmental and social dimensions, this manuscript presents a holistic approach with

providing an effective decision-support tool for RECs design. This integrated methodology was implemented in establishing the first REC in Cagliari, specifically within vulnerable social housing neighbourhoods. More specifically, starting from utilizing an accurate input dataset on potential REC members and renewable energy production systems, the tool enabled reliable multi-scenario simulations, estimating economic, environmental and social KPIs to guide decision-makers and identify potential improvements. However, the limited participation of potential REC members (12 out of 80 families), who provided personal electricity consumption data, affected the results, highlighting a prevailing distrust in public institutions. This occurred despite the University of Cagliari research team's significant efforts in dissemination, empowerment and engagement activities. This scepticism, especially in vulnerable contexts like public housing neighbourhoods, underscores the need to prioritize social aspects in REC design. Difficulties in making clear and simple some technical but fundamental working principles of RECs have emerged during meetings with citizens. This critical aspect also provided a major barrier to the acceptance of REC projects.

As far as the multi-scenario simulations outcomes are concerned, the negative values of the obtained economic KPIs bring the unexploited potential of the REC project to light. Those values should also be considered as in line with the non-profit purposes of the project, which instead mainly aimed at generating environmental and social benefits for such a fragile context. In this perspective, to roughly quantify the social impact of the project, an Electrical Energy Poverty Index (EEPI) has been defined and estimated for all ex-ante and ex-post REC scenarios, leading to values of pro-capita electricity expenditure to annual income ratios significantly higher than the considered reference values assessed for the Italian and the Sardinian context. This proved the



**Fig. 8.** Electrical Energy Poverty Index (EEPI) values: National Average, Sardinia Region Average, and values assessed for the Energy Community context, considering both the ex-ante situation and the ex-post halfway scenarios with 40 residential consumers (i.e. the scenarios **c40\_pv107\_b20\_rc** and **c40\_pv107\_b20\_oc**), as well as the simulated ideal scenario with 120 residential consumers (i.e. the scenarios **c120\_pv107\_b20\_rc** and **c120\_pv107\_b20\_oc**).

critical energy vulnerability condition affecting the specific community involved in this pioneering project.

However, this index does not account for the indirect impacts of these initiatives in affordable housing, highlighted in the previous section. Economically, enhancing energy efficiency can reduce residents' dependence on energy assistance programs, thereby decreasing their vulnerability to changes in program terms. Stabilizing utility bills through these measures facilitates the maintenance of operating budgets, retention of tenant services, and prevention of rent increases. This stability is crucial for the financial health of public housing projects and the well-being of their residents.

Socially, implementing renewable energy systems in public housing can improve community engagement, strengthen community cohesion. Improving energy efficiency and incorporating renewable energy can lead to improved indoor environmental quality, reducing health risks associated with inadequate housing conditions. Therefore, training, information, dissemination, and awareness-raising activities for individual residents and the collective public opinion must be adequately structured in the processes of construction and implementation of RECs.

These complex projects require integrated governance involving various stakeholders, including energy agencies, regional and local institutions, and citizens. A comprehensive understanding of the initial conditions is necessary, achieved through the measurement and mapping of building conditions and the assessment of families in energy poverty. This understanding is crucial for supporting decision-making in selecting appropriate energy efficiency interventions. Future research should focus on developing multicriteria evaluation systems that comprehensively address these diverse aspects, delving into the untapped potential of Renewable Energy Communities (RECs) in combating energy poverty and injustice, thereby fostering a just transition.

#### CRediT authorship contribution statement

**Ivan Blečić:** Supervision, Project administration, Funding acquisition, Conceptualization. **Alessandro Sebastiano Carrus:** Writing – original draft, Investigation. **Eleonora Congiu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Giuseppe Desogus:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Emanuel Muroi:** Writing – review & editing, Investigation. **Valeria Saiu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization, Investigation.

#### Declaration of competing interest

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

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## Data availability

The data that has been used is confidential.

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