Sustainable Energy, Grids and Networks 39 (2024) 101471

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

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

Renewable energy communities and mitigation of energy poverty: Instruments for policymakers and community managers

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ARTICLE INFO

Keywords:
Energy communities
Energy poverty
Shapley value
Renewables
Energy policy
Sharing mechanisms

ABSTRACT

Energy poverty has been increasing since the early 2020s because of rising energy prices. This is attributed to geopolitical crises and the inclusion of the energy cost of CO_2 pricing, which was historically an externality. Policymakers and citizens need new tools to address this issue, and energy communities are recognized as a valuable tool for mitigation. This study proposes two complementary approaches that relate to energy poverty and Renewable Energy Communities (RECs). The first aims to define and map energy poverty to support the policy in targeting measures and incentives. Using publicly available data, a new methodology is proposed for mapping energy poverty risk over a large territory with a fine granularity. The second approach taken sees REC managers at the center, who are tasked with sharing the economic benefits appropriately and equitably. A series of multi-criteria sharing mechanisms were developed and compared with the existing ones (e.g., based on Shapley value), including the energy poverty mitigation among them and the assessment of the impact of RECs on it. The results show that sharing methods can be one of the viable pathways for mitigating energy poverty through RECs without compromising the economy of non-vulnerable REC members.

1. Introduction

The energy price trends in 2021–2022, linked to various geopolitical crises [1], strengthened the social drive for energy poverty mitigation measures [2,3]. Even if there is no unique definition, energy poverty is defined by the European Commission (EC) as a situation where “energy bills represent a high percentage of consumers’ income, or when they must reduce their household’s energy consumption to a degree that negatively impacts their health and well-being” [4]. Additionally, the proposed recast of the Energy Performance for Building Directive adds the concept of vulnerable households, describing “households in energy poverty or households, including lower middle-income ones, that are particularly exposed to high energy costs and lack the means to renovate the building they occupy” [5]. These definitions include both sides of the coin: energy poverty is visible when bills are expensive, however, hidden energy poverty occurs when residents lower their use (thus their bills) to levels that reduce their well-being because they cannot afford the energy costs [6]. Three major factors attributing to the rising risk of households’ (hidden) energy poverty include the low income of the inhabitants, poor energy efficiency of buildings, and high energy prices [4]. Since 2021, energy prices have risen, especially in Europe [7], thus worsening one of the previously cited causes.

The EC is also at the forefront of defining a regulatory framework that addresses the policymakers in fighting the risk of energy poverty. The Energy Poverty Observatory (EPOV) commenced in December 2016, and it aimed to collect resources and develop indicators helpful for assessing energy poverty at the national level. It then evolved into the Energy Poverty Advisory Hub, which now holds a set of energy poverty indicators that national governments should directly use as input for social climate plans [8].

Exploring the issue of energy poverty at EU level returns a multifaceted panorama. Energy poverty could affect from 1.5 to 35.6% of national populations, with Bulgaria, Greece, Lithuania and Croatia reporting the highest values, widely varying based on the adopted indicator [4]. A valid measure for energy poverty is fundamental, and three main approaches are recognized in the literature: (i) the expenditure approach examines the energy costs faced by the household against absolute or relative thresholds; (ii) the consensual approach considers self-reported assessments of indoor housing conditions and ability to attain basic energy needs that are “consensually” perceived as necessary; and (iii) direct measurements of the energy use and/or of the indoor conditions can be performed and checked against a standard [9,10]. Clearly, the use of direct measurements is subject to their availability or collection and, in general, applies only to groups or samples of a population. Expenditure and consensual approaches can instead benefit from databases available at a regional/national

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https://doi.org/10.1016/j.segan.2024.101471
Received 31 January 2024; Received in revised form 28 May 2024; Accepted 1 July 2024

level. The expenditure approach relies on objective variables, such as energy bills, the income of the household, and other expenses. Whereas a consensual approach is instead based on self-assessed and often subjective data: this can increase the uncertainty in reading the results of a consensual-based analysis. Conversely, expenditure approaches can be limited in detecting hidden energy poverty [2]. To overcome this issue, energy expenditures can be modeled to detect if low expenditures could be due to hidden energy poverty or other causes (e.g., high energy efficiency). While requesting many input data (building type, heating type, floor area, number of people, etc.), this approach allowed to spot that 56% of underconsuming households in Spain are affected by hidden energy poverty [11].

A set of three indicators recurs in recent analyses based on a consensual approach as they are included in the EU Survey on Income and Living Conditions [10,12]. These indicators are the inability to keep the house warm, the arrears on the bills, and the presence of leaks or dampness in the building. As said before, the subsistence of one or more of the mentioned conditions is generally perceived as evidence of energy poverty risk.

Focusing on the economic approaches, some widespread indicators are based on the incidence of energy expenses on the households' income. A binary indicator is based on whether the ratio of energy expenses over income is greater than twice the average value of the considered population (2M). The indicator is true if the condition is verified, null elsewhere. This is useful to spot energy inequality but fails to consider the absolute expenses; therefore, it can include the supposed vulnerable households that show unjustified high expenses for energy. In addition, it is unable to highlight the hidden energy poverty. For doing so, another binary indicator (M/2) is true if the energy expenses in absolute terms are lower than half the median value of the population. M/2 indicator can not only recognize hidden energy poverty but also generate false positive values; the energy costs either can be included in the rent of the dwelling or can be low because of the high energy class of the building. In this case, the considered household is not necessarily in energy poverty. A more comprehensive index that builds up on the previous ones is the Low Income High Cost (LIHC) indicator. It is a binary indicator that considers the simultaneous presence of an absolute value of the energy expenses larger than the median and an income net of the energy expenses lower than the poverty line [13]. An improved version of the LIHC, which also considers the hidden energy poverty, has been proposed in Italy and used for the Italian National Energy and Climate Plan (PNIEC) development [14].

The discussion is open on which is the better indicator for energy poverty. In [10], an approach based on multiple indicators was proposed. Indeed, this would help recognize vulnerable people by using alternative factors and avoiding part of the population being left out of support schemes.

In this work, we propose tools for using Renewable Energy Community (REC) to fight energy poverty by adopting two perspectives: the policymaker's and the REC manager's.

1.1. The policymaker perspective: mapping the energy poverty risk

Policymakers can benefit from mapping the energy poverty risk for prioritizing support schemes where there is a larger need. This has been done in different areas for Portugal [15], using economic indexes and household interviews. The results supported defining possible measures, such as the renovation of buildings. Considering the literature, maps emerged as one of the most effective ways to represent energy poverty, allowing the opportunity to catch the spatial inhomogeneity characterizing it. This is addressed in [16], in which the authors highlight the strong spatial variability of the multiple factors causing energy poverty by performing a study fitted on the Santiago de Chile metropolitan area; furthermore, in this study, it is also underlined that it is challenging to obtain a satisfactory amount of data to support studies on this topic, especially for large areas. Also, [17] enhances this idea of the spatial variable nature of the factors which define a household's vulnerability and its likelihood of experiencing energy poverty, proposing maps to support the outcomes. Analyzing the literature, it can be observed that most studies focus on a limited area, usually neighborhoods, for which a large amount of data is available because of sufficiently detailed local databases. For example, in [18], the energy poverty in the different neighborhoods of Barcelona was determined, opening the field for interventions by local policymakers in limiting the issue of energy poverty. Similar approaches have been adopted in Italy: in [19], the city of Bologna was mapped considering income data and the energy performance of buildings; another methodology based on energy performance certificates (EPCs) has been extended from municipal to provincial basis in [20], in which, for the Italian province of Treviso, fuel poverty was estimated at a municipal level using a multi-source statistical approach, which is necessary if a single database containing both information on incomes and building's energy performances are not available. Few studies present a study on a whole country with fine granularity (e.g., the municipality), they focus on the Iberian peninsula [21,22]. This fact raises and stresses that estimating energy poverty is complicated not only because of the variety of the issue but also because of the difficulty in finding a comprehensive data set containing the required information for the desired spatial resolution. An additional consideration on socioeconomic studies in general is the increasing gap between the first and the last deciles inside populations [23], that demanded for metrics such as the Palma ratio, able to highlight the tails of the distribution [24] instead of an average value. Failing in coherently valorizing the risky tails (e.g., concerning building performances and economic indicators) could return misleading results when identifying energy poors [25]. Furthermore, in these last examples, it has been shown that the complementary presence of economic vulnerabilities and below-standard energy performance increases the risk of energy poverty, hence defining priorities for building renovation requiring policies and dedicated incentives.

1.2. The REC perspective: energy communities as a tool for counteracting energy poverty

Recently, RECs have been introduced in the EU legislation for implementation in each Member State. In general, the Clean Energy Package illustrates two types of energy community frameworks: Citizen Energy Communities, better addressed in EU Directive 2019/944 [26], and Renewable Energy Communities, described in EU Directive 2018/2001 (REDII) [27]. Given their social attitude, community energy initiatives can represent a viable support scheme for supporting vulnerable electric customers via Renewable Energy Sources (RESs) production [28]. Indeed, RECs can socialize the RES investments and related economic benefits to lower the bills of all the REC members in general and users at risk of energy poverty in particular. In 2018, REDII introduced the RECs as configurations of collective self-consumption with a local nature to be implemented and promoted in each Member State. In Italy, the implementation was done with Decree 199/2021 in December 2021 [29], then the scheme was developed by the Italian Regulatory Authority [30]. This scheme would allow the REC members located under the same primary substation (PS), i.e., the medium to high voltage substation, to share energy from RES plants up to 1 MW. In RECs, households, small and medium enterprises (SMEs), and institutions can participate as either producers, consumers, or prosumers. The shared energy is the minimum between the sum of the injection and the sum of the withdrawals by REC members each hour. The shared energy is remunerated (in €/kWh) with an incentive defined by the Ministry [31] and a proxy of the saved grid costs because of local use of energy defined by the Italian National Regulatory Authority (ARERA) [32]. The shared energy does not lead to direct discounts on individual members' bills, who continue to be billed for their total energy withdrawal. Instead, the remuneration is directly given to the REC manager, which is then distributed among the members.

The internal redistribution of the economic benefit among the REC members is not defined by rules; instead, it is a matter of members defining the algorithm for redistribution in the REC's statute [33]. The definition of best sharing methods in REC has already been investigated. In [34], a game theory approach based on the Shapley value was proposed to assess the contribution of each member to the energy sharing in the REC, thus coherently defining the economic benefit of sharing. The Shapley value is also of interest as it shows that, in a REC, welcoming a new consumer (e.g., a vulnerable electric customer) can increase the REC benefit even in cases when it does not contribute to new RES investments (i.e., just sharing energy). Anyway, the Shapley value has a large computational effort in the case of a community with several users. Therefore, simpler sharing methods approximating it were developed and compared in [35]. Several methods were compared and checked in a case study in [36], where the economic benefit of members with different levels of RES plant ownership and energy sharing was tested under different sharing algorithms. None of these works consider energy poverty. However, it was considered in [37], where the advantages of RECs for vulnerable end-users in a popular neighborhood council estate were assessed. By considering an energy poverty indicator based on energy expenses both in cases of no RES plants and in cases of REC presence, the potential for energy poverty mitigation in an energy community was recognized. The evaluation of the best sharing methods for enhancing this potential was not within the scope of that study.

As observed in [38], having a basic sharing technique capable of addressing a set of criteria and distributing income can benefit REC management during the implementation phase. A gap in the literature is recognized when considering more than one of the following fundamental criteria in a single-sharing method: the ownership of the RES plants, the contribution of each member to energy sharing, and the situation of energy poverty of a REC member.

1.3. *Contributions of the paper*

In this paper, we propose tools to assess REC's potential in energy poverty mitigation. In doing so, we investigate the two aforementioned perspectives. On the one hand, we consider the policymaker perspective, which aims to highlight the risk of energy poverty in particular contexts to direct sound public investment to cope with the issue. On the other hand, the REC manager perspective is of interest as the statute of the REC can define the benefit-sharing (BS) method and therefore consider the best algorithm for mitigating energy poverty among REC members. The first perspective can benefit from mapping a whole country, considering economic indicators for households and energy performance indicators of buildings (available nationwide) to propose a multicriteria indicator describing the level of risk of energy poverty for each city in the country. In the literature, no papers have been found that report large-scale mapping with this granularity, only with higher granularity for large areas or lower granularity for small areas, therefore a comparison is not possible.

The second perspective is analyzed by comparing BS methods for RECs, adopting existing or developing new ones. In this case, the methods consider multiple criteria, selecting one or more of the following: ownership of the plants, the contribution to energy sharing, and the condition of vulnerability of each member. The methods are then compared and checked against a game theory method based on the Shapley value, adopted as a reference. The energy poverty indicator used is based on the LIHC. As said before, it does not identify hidden energy poverty. This is considered acceptable as the estimation of hidden energy poverty in Italy has already been enforced [39] and shows that this issue involves a limited amount of citizens concerning the whole energy poverty [4].

The novelties of the paper are the following: (i) it presents a new methodology based on public data for mapping a whole country with an energy poverty risk indicator, considering both economic and building-related aspect and highlighting the tail of the distribution for both quantities; (ii) it defines sharing methods in RECs based on energy poverty. An additional improvement brought by the work is developing a non-binary yet continuous version of the LIHC for defining the depth of the energy poverty condition.

The adopted case study for the mapping procedure is the country of Italy, specifically the Teglio city in Lombardy, for the sharing methods assessment. The latter has been selected given its mountainous location, and consequently a high energy demand during winter. In the Community, the objective is to share the revenues obtained to use them for the reduction of its members' bills and a return on investment of the facilities.

The layout of the remainder of the paper is as follows: Chapter 2 illustrates the proposed methodology, both focusing on mapping and sharing mechanisms. Chapter 3 presents the map of Italy and the case study of Teglio city. Chapter 4 describes visually and quantitatively the obtained results. Chapter 5 summarizes the conclusions.

2. Proposed methodology

As previously introduced, this work aims to elaborate tools useful in social REC projects from both the perspective of the policymaker and the REC manager (see Fig. 1). In 2.1, a procedure for mapping the risk of energy poverty in a wide area (e.g., a country) is presented. It elaborates on existing literature, developing a risk index based on the energy performance of buildings and on local conditions of income vs life costs, considering a wide territory and focusing on highlighting the tails of the distribution, i.e., considering only families with low income and families with low-performance buildings, instead than average (or weighted) values. This is possible by adopting publicly available data that offer a good trade-off between accuracy, availability in different geographical areas, and generalization of the results. Results are proposed in terms of the risk index value for each municipality in the territory and of a national map to visualize the relative results. The goal of this first analysis is to offer the policymaker a way to understand in detail the map of the issue and act consequently: for instance, prioritizing actions where it is more necessary and/or distributing incentives for initiatives against energy poverty over the country based on the energy poverty risk index of each municipality. A powerful initiative to contrast energy poverty (besides energy efficiency) is developing social REC projects. Hence, the second part of the study, whose methodology is described in 2.2, is dedicated to a comparative analysis of BS methods in RECs, as said before the considered EC share among the members all the revenues. The revenues of a REC can be shared based on different criteria: we elaborate on the literature comparing some existing BS methods or developing new ones. We assess how each method values members based on the three following criteria: (i) who made the investment in a REC; (ii) who is sharing energy the most; (iii) who are experiencing energy poverty. The results are given on a case study regarding bill reduction of different members, including vulnerable users. The case study is in a municipality selected based on the results of the energy poverty risk index. The tool can be useful for REC managers and social REC initiatives.

2.1. *Developing municipal energy poverty risk coefficient*

The growing interest in energy communities raises several issues that must be addressed in the future to permit not only their spread on the territory but also the full utilization of all the benefits they may provide to their members. Indeed, as already depicted in the introduction, the REC goals are not just environmental, attributed to emission reduction, but also economical and social. These positive effects justified the introduction of incentive schemes, opening the field for one of the aims of this paper: the creation of an instrument to help the political stakeholders allocate incentives to different RECs and,

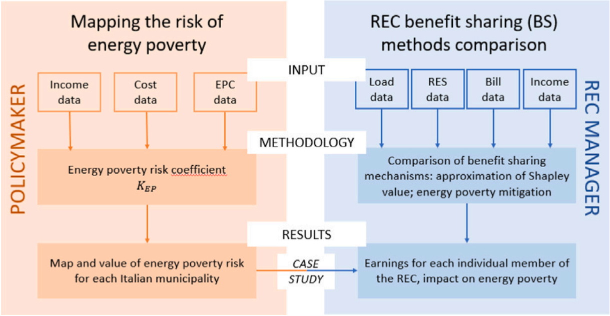


Fig. 1. Methodology flowchart.

Table 1
Data sources.

Data	Source	Reference
Income distribution statistics	Irpef	[41]
Poverty condition threshold for Italy	Eurostat	[42]
Household expenditure statistics	Osservatorio Findomestic	[43]
Energy certificates statistics	Siape - ENEA	[44]
Residential buildings age classes	Istat	[45]

more precisely, the use of the incentive to mitigate energy poverty risk. This brings socio-economic benefits to frail zones by adopting a “wider area” approach with respect to the REC manager, addressed in the next chapter. The developed tool involves the creation of an Energy Poverty Risk indicator and mapping the territory based on its local value. The approach proposed in this paper is applied to the whole country. Indeed, the user input comes from national databases with a municipal scale, granting a unique data source for all the territory while keeping municipal granularity.

The energy poverty coefficient is based on two factors: (i) an economic coefficient considering income vs cost of life and (ii) an energy performance coefficient of buildings in the municipality. Italy has been selected as a case study. This can be seen as a good benchmark for evaluating the methodology because of the considerable differences in economic, social, and geographical variables [40]. In the economic area, there is a certain ease in getting data, whereas, in the energy one, it is difficult to find national databases (e.g., there is not yet a unique open-access database containing the EPCs of the buildings in the Italian peninsula). A list of the datasets consulted in this work is shown in 1.

The developed equations are defined on a municipal basis, to ensure sufficient resolution and accuracy to the results. Indeed, the Italian territory is divided into more than 8000 municipalities, leading to a granular map. This implies that the equations have to be applied for each of these municipalities to produce a final map ready to be promptly used by the political stakeholder to support the eventual partitioning of an incentive among different RECs to tackle the energy poverty phenomenon. For example, allocating a larger amount of incentive to more vulnerable areas. As demonstrated in the literature, energy poverty can be caused by the concurrence of different factors (e.g., a low income where there is already an energy-inefficient residential building). This point precisely supports the definition of the coefficient proposed in this work to realize energy poverty risk maps. It is, in fact, articulated in two terms, as shown in Fig. 2: the first one is related to the economic situation of the municipality (k_{econ}), whereas the second tries to define the average energy performance of the residential buildings in that municipality (k_{ener}), which is directly related to the energy expenditure of a household.

The following reports the equations necessary to calculate the energy poverty risk index (K_{EP}) for each ith municipality.

As seen in (1), the K_{EP} combines the economic and the energy term in an additive manner.

$$K_{EP} = w_{econ} * k_{econ} + w_{ener} * k_{ener} \tag{1}$$

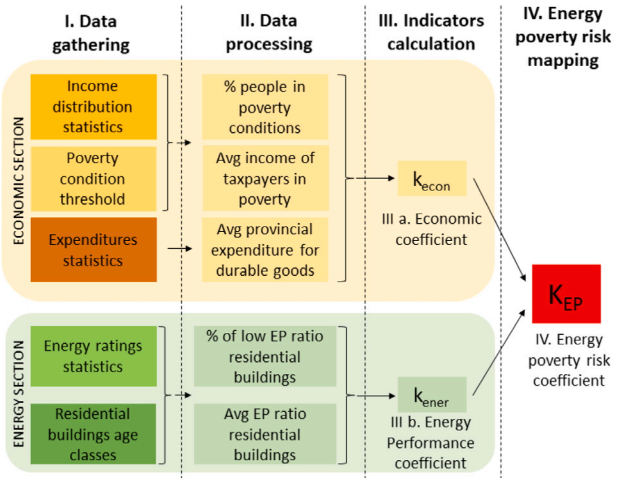


Fig. 2. Methodology flowchart for the energy poverty risk coefficient.

Two weighting coefficients (w_{econ} and w_{ener}) have been considered to introduce the possibility for a public stakeholder to increase or decrease the importance of one term with respect to the other. Based on the scope of the study, higher w_{econ} can be used to focus on the costs and incomes with respect to building situation, and vice versa. In this work, they are both equal to 1 to be neutral. The economic term is estimated as follows.

$$k_{econ,i} = \frac{\%\ taxpayers\ in\ poverty_i * average\ provincial\ expense\ for\ durable\ goods_i}{average\ income\ taxpayers\ in\ poverty_i} \tag{2}$$

In (2), the expenses are at the numerator, and the incomes are at the denominator; the share of taxpayers in poverty is adopted to highlight the tail of the income distribution, thus lowering the weight added by the income of the population. The tail is more likely to experience an energy poverty condition. During the development of the economic coefficient, it has been observed how the averaging of the incomes of the taxpayers of a municipality without excluding the wealthier population segment leads to a shading effect with the tendency to underestimate the economic poverty risk. This affects towns and province capitals because of the larger social and economic gap affecting their population. Without entering into the details of the literature on the topic, the adopted approach is considered coherent with the last trends for inequality analysis: both the middle and the tails of income distribution should be considered; however, the tails (and in particular the relative weight of the lower tail) have a specific relevance [24,46]. To reason in terms of poverty, it is implicitly necessary to define a poverty condition threshold; as a municipally based poverty threshold is not available, the Eurostat one has been selected, which is unique for Italy [42], according to which an individual is in poverty if his income is lower than the 60% of the national equalized disposable income. Thus, the threshold for poverty in Italy is 10,052 €/year/taxpayer. This implies that, for each municipality, the share of taxpayers with an income lower than this value has been calculated crossing [41,42] to identify the portion of taxpayers in poverty conditions. This share is then multiplied by the ratio of the average provincial expense for durable goods per capita and the average income of the taxpayers in poverty. This approximates the ratio between the cost of life and income and thus allows us to consider the differences in costs in different parts of Italy. For example, by considering two individuals with the same income living in the North and in the South of Italy, the first will be more economically vulnerable because of the higher cost of living in the northern area of the peninsula. The use of a provincial indicator in the numerator represents an approximation; however, unfortunately, more granular information related to the cost of life is not available, highlighting the difficulty in collecting data on a municipal and national scales.

The most complicated coefficient in data gathering is the k_{ener}. Indeed, many factors can influence the energy bills, such as the climate, the building energy efficiency, and one of the appliances, the price of energy vectors. The energy performance (EP, or more properly $EP_{gl,nren}$) indicator is adopted as it represents the geographic differences between cities well. The Italian law defines it as the overall EP index of a building [47], measured in primary non-renewable energy demand in $\mathrm{kWh/m^2/y}$ of the building. It can be determined as the sum of all the thermal consumption of a building; thus, it includes both heating and cooling services, water heating, and ventilation. In Italy, for each new, renovated, or sold building, an EPC has to be issued, where the EP coefficient is used to assign an energy rating, going from A4 (best energy performance) to G (worse energy performance). To calculate it, the already mentioned EP is divided with the EP of a reference building ($EP_{gl,nren,rif,standard}$), having the same shape as the real building but standardized components as envelope, thermal units, etc.: the ratio between the two EPs (EP ratio) returns the performance of the analyzed building. As per the recent evolution of Italian EP computation methodology [47], following the EU Directive [48], the reference standardized components are specific for each climatic zone. Italy is indeed classified with respect to 6 climatic zones (A to F). A municipality in a lower climate zone (e.g., Lampedusa in zone A) needs for a shorter heating period and consequently its heating needs are low. If, on the other hand, a Municipality is in a higher climate zone (e.g., Belluno in zone F), the heating demand is much higher. This is considered by EP since the energy performance for the reference building is higher in Belluno than in Lampedusa. Therefore, an EP ratio equal to 2 in Belluno identifies larger building performance than the same value in Lampedusa. k_{ener} value incorporates this information, thus a better average energy performance of building for a Municipality in a mountain area will have the same k_{ener} as a lower energy performance in a Municipality in the flatlands, returning climate-aware risk. The formula for the energy term of the ith municipality is given in (3).

$$k_{ener,i} = share_{\text{buildings }<1991,\text{i}} * \left(\frac{EP_{gl,nren}}{EP_{\text{gl,nren,rif,standard}}}\right)_{\text{i}} \tag{3}$$

where the average EP ratio of the municipality ($EP_{gl,nren}/EP_{gl,nren,rif,standard}$) and the share of buildings built before 1991 ($share_{\text{buildings }<1991,\text{i}}$) are considered. A detailed explanation of these choices is given in the following. The most appropriate choice to address the energy term would be the average energy bills for each municipality as it is the value that directly influences energy poverty; however, no complete database is available [47]. For this reason, shifting the attention from this economic parameter to a purely energy-driven one is more convenient. The idea has been then to use this EP ratio to qualify the energy performance of the buildings in each municipality, or more precisely, the average difference in energy performance between the actual buildings and the corresponding reference ones.

To obtain the average EP ratio for buildings in Italy, it would be necessary to access the regional data sets containing the EPCs. Unfortunately, these databases are not yet open-access. In this study, coefficients were developed that could be easily obtained from a national database to ensure a uniform comparison, even in different regions, because of standardized and reliable data processing procedures. For the k_{ener} calculation, thus, the two main datasets which have been used are the Istat Population and Residential Buildings Census [45], dividing for each municipality the residential buildings according to their construction age and the Siape database by ENEA [44], which reports statistics regarding the EPCs in Italy. In particular, it is possible to correlate the buildings' age classes with a statistical distribution of energy ratings (cf. "classi energetiche"), to obtain an average municipal EP ratio ($EP_{gl,nren}/EP_{gl,nren,rif,standard}$) via a weighted averaging procedure. The starting point is the statistics in Fig. 3 from the Italian EPC database [44]. Each age class is characterized by a share of energy ratings from available EPCs.

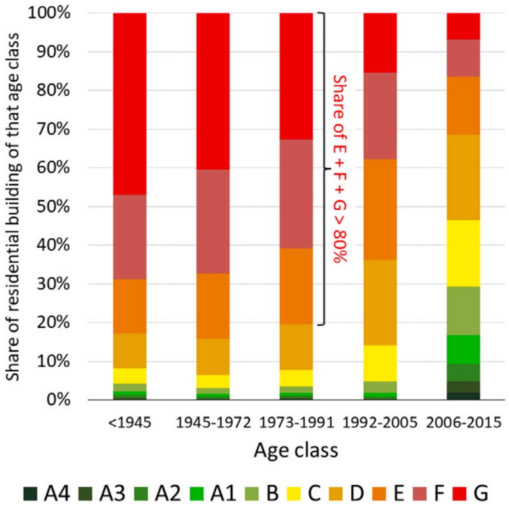


Fig. 3. National EPCs statistics—age class vs energy rating.

The procedure aims to pass from energy rating to an EP ratio range (as seen in Fig. 2); the average EP ratio for each age class is the weighted average of energy ratings' EP ratio according to its share in the considered age class, as shown in Eq. (4).

$$\left(\frac{EP_{gl,nren}}{EP_{gl,nren,rif,standard}}\right)_{\text{k}} = \sum_{j=1}^{energy\ \ rating\ \ levels} share_j * \left(\frac{EP_{gl,nren}}{EP_{gl,nren,rif,standard}}\right)_{\text{average,j}} \tag{4}$$

Once the average EP ratio of each age class is known, it is possible to calculate the average EP ratio for each municipality by considering the age class distribution of its residential buildings. To use a coefficient conceptually similar to the k_{econ} (which considers just the lower tail of the taxpayer's distribution, identifying the share of taxpayers with a low income instead of the average income of all the taxpayers), a k_{ener} is adopted, considering just the buildings built before 1991, i.e., the ones with a higher EP ratio, where the three lowest energy ratings (i.e., E, F, G) have a share of 80%. The resulting equation is the (5):

$$\left(\frac{EP_{gl,nren}}{EP_{gl,nren,rif,standard}}\right)_{<1991,\text{i}} = \sum_{k=1}^{age\ \ classes\ \ <1991} share_k * \left(\frac{EP_{gl,nren}}{EP_{gl,nren,rif,standard}}\right)_{\text{k}} \tag{5}$$

In previous equations, i denotes the ith municipality, whereas k indicates the kth age class and j the jth energy rating level. It is then possible to finalize the k_{ener} calculation for the ith municipality, which is calculated as the product between the share of buildings older than 1991 and the previously calculated average EP ratio of the same buildings, as in Eq. (3).

Before the K_{EP} calculation, both the k_{econ} and the k_{ener} were subjected to a statistical normalization procedure to ensure that both of them assume values between 0 and 1. The rescaling allows the reworking of data to obtain clearer maps, if necessary. During this normalization procedure, in the case of both coefficients, some outliers were excluded from the K_{EP} calculation because of evident errors in the raw data that led to unrealistic results.

At this point, it is possible to simplify the calculation of K_{EP}, as reported in Eq. (1):

The calculation of the K_{EP} for each municipality is followed by the energy poverty risk map creation; the results are primarily shown as maps in this work.

The energy poverty risk of a municipality should be more properly intended as the reasonable risk of finding individuals in an energy poverty situation inside that municipality. This is the final consideration in this study. Furthermore, the indicator represented in the maps has a relative value rather than an absolute one. Indeed, the instrument aims to help the stakeholder understand which municipalities are more likely to host energy poverty phenomena concerning the others and not to quantify the energy poverty level precisely. This is coherent with a view of preferential incentives for higher-risk situations. This approach is justified by another observation—during the development of the instrument; it has been realized how hard it is to catch the energy poverty risk definition as the parameter selection strongly impacts it. This implies that the claim of producing an absolute measure of the energy poverty for each municipality in such a large-scale context is not supported by data availability and the lack of standardized criteria to calculate energy poverty for that domain size. Once the map of the issue has been developed, it can be used to prioritize and incentivize initiatives fighting energy poverty. Besides energy efficiency, a new tool for this goal is social RECs. Social RECs can be developed first where the energy poverty risk is higher. The following paragraph illustrates how the effectiveness of a social REC is assessed by comparing BS mechanisms.

2.2. Multicriteria BS mechanisms for REC

To estimate and share the benefits among the REC members, it is necessary to (i) calculate the overall energy and economic flows of the community and (ii) define the BS method to be adopted. For the former, the proposed approach is described in Section 2.2.1, whereas for the latter, several methods are developed and presented in Section 2.2.2. It is worth noting that this study concentrated solely on PV-based RECs; however, the approach utilized is broad enough that it may be applied to other systems.

2.2.1. Estimation of energy and cash flows of the REC

An analytic procedure is proposed in order to estimate the energy and cash flows of the community, receiving data for consumption and production, elaborating them to return the yearly outcomes. The estimated energy flows are self-consumption (Esc), energy injected (Ei), energy withdrawn (Ew) from the grid, and shared energy (Esh). They are computed for each user i, for each day d in each hour h.

$$Esc_{i,d,h} = \min\left(Ec_{i,d,h}; Ep_{i,d,h}\right) + Ebess_{i,d,h} \tag{6}$$

$$Ei_{i,d,h} = \max\left(0, Ep_{i,d,h} - Esc_{i,d,h}\right) \tag{7}$$

$$Ew_{i,d,h} = \max\left(0, Ec_{i,d,h} - Esc_{i,d,h}\right) \tag{8}$$

$$Esh_{i,d,h} = \min\left(\sum_{i}^{N} Ei_{i,d,h}, \sum_{i}^{N} Ew_{i,d,h}\right) \tag{9}$$

where Ec is consumed energy, Ep is produced energy, $Ebess$ is energy from the battery energy storage system (BESS), and N is the number of REC members. (6) indicates that BESS influences self-consumption; it absorbs energy when Ep is larger than Ec and vice versa. Instead, (7) to (9) indicates that the shared energy is the minimum between the summation of the injected energy and the summation of the withdrawn energy by the whole community. Indeed, what is injected and simultaneously withdrawn (in the same hour h) within the REC is considered shared as per the Italian regulation.

As per the Italian transposition, three main revenue streams are associated with the energy flows in a REC.

1. The first revenue streams are avoided cost in the electricity bill. They are obtained by multiplying the bill cost by the Esc.
2. The second revenue stream is the market remuneration for injected energy. This is computed by multiplying the zonal price (P_z) seen on Day-ahead Market (DAM) by the Ei.
3. The third revenue is associated with shared energy. Two revenues are considered in the Italian framework: (i) a reimbursement by the Italian National Regulatory Authority (ARERA) for the avoided costs and losses on the transmission grid given by local use of energy [32] and (ii) an incentive by the Ministry that works as a premium tariff. As of Q2 2023, the incentive values in €/MWh are published in a draft version [49] and are inversely proportional to P_z and to RES plant size (see Table 2).

Once the revenue streams in a REC are estimated, all or some can be shared among the members, considering the nature, the goals, and the promoters of the project.

- Most of REC will share at least the incentive on shared energy as it depends on the contribution of each member.
- The DAM remuneration for injected energy can be kept by the prosumer with the installed PV plant; especially if the prosumer financed the plant construction or shared, in the case of a collectively financed plant or a social REC. In this case, the revenues are redirected from the prosumer to the REC and are split considering a sharing method.
- Instead, in a real implementation, sharing the avoided bill costs is difficult as these should be estimated from hourly measurements using (6).

As this study is focused on RECs with social intents, the shared benefits are both related to shared and injected energy. Hence, the sharing methods described in the following will be applied to the sum of revenues related to Esh and Ei.

2.2.2. BS methods

Once the total revenue streams are computed, they are shared among members. This work compares existing and newly developed BS methods for RECs. For such a task, it is important to point out that an energy community is a collective project involving several, often very different, actors. Within it, both the production and load sides are fundamental and contribute to the economic benefits of the community itself. However, being such a complex and varied entity, it is difficult to understand the importance that each actor has within the community and especially to translate this concept into economic terms. Ideally, those who contribute the most to the economic returns of the community should gain the most. The three main goals of this analysis are listed in the following. (i) It aims to assess the possibility of approximating the reference BS method (i.e., the Shapley value) with simpler ones, requiring less computational effort. (ii) It aims to evaluate the impact of considering member's energy poverty in BS concerning the savings of all members, including both vulnerable and non-vulnerable ones, to check the social acceptability of these RECs. (iii) It proposes options for REC managers aiming to evaluate multiple criteria in BS (see the list here below). Specifically, this work considers three main criteria for BS.

1. The ownership share remunerates REC's RES plants investors. This implies that it pays back who paid for the system, disregarding where the system is located.
2. The relative amount of energy each member shares is considered to reward members whose consumption is aligned with production.
3. The vulnerable condition of each household is considered to mitigate energy poverty distributing RECs' revenues.

A set of BS mechanisms has been gathered from the literature, considering one or more BS criteria, as presented in Table 3. Four single-criterion and four multicriteria methods were compared. The

Table 2
Proposed premium tariff for shared energy [49].

	Large plants	Medium plants	Small plants
Installed power	P≥600 kW	200kW<P<600 kW	P<200 kW
Incentive (€/MWh)	$min(100; 60 + max(0; 180 - P_z))$	$min(110; 70 + max(0; 180 - P_z))$	$min(120; 80 + max(0; 180 - P_z))$

Table 3
Benefit-Sharing mechanisms summary.

	Ownership	Energy sharing	Energy poverty	Source
Shapley value-based		✓		[34]
Ownership-based	✓			[36]
Proportional		✓		Own elaboration
Packets-based		✓		[36]
Own.-based + Proportional	✓	✓		Own elaboration
Own.-based + Energy Poverty	✓		✓	Own elaboration
Proportional + Energy Poverty		✓	✓	Own elaboration
Own.-based + Proportional + Energy Poverty	✓	✓	✓	Own elaboration

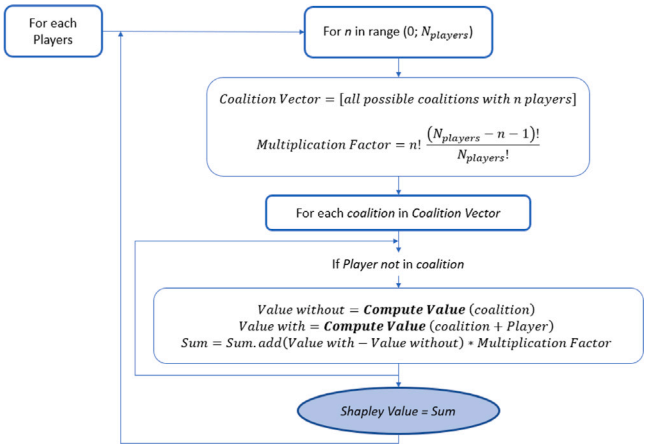


Fig. 4. Block diagram for Shapley value algorithm.

first algorithm was based on the Shapley value and was used as a benchmark of the fair revenue distribution [34]. A better description is given in the following sections.

Shapley value criteria. Game theory could be an effective tool for tackling the interactive nature of energy sharing [34,38].

The game theory originated with Von Neumann to mathematical define how individuals behave when they are in a situation that may lead to sharing or winning and making decisions that affect each other's welfare. It is typically divided into two different classes, cooperative and non-cooperative games, depending on the level of constraint established on the agreements made by the players. The cooperative game is characterized by a situation where binding agreements are in place, and players can interact with each other by forming coalitions. In the non-cooperative game, individuals are independent and require no constraints. Therefore, each player will try to maximize their benefits and minimize their costs by not communicating with the others, and there will be no coalition formation.

The energy community can be seen as a grand coalition. Hence, the created dynamics can be represented via a cooperative game where the players are all the participants: producers, consumers, and prosumers. They cooperate and communicate with each other to improve their earnings. The set of actors in the community or players is therefore called N, and $v(S)$ is the value of the coalition, where $S \in N$. The payoff of each player xi, with $i \in S$, is determined by a fair allocation criterion that disadvantages no one. The Shapley value is used to allocate the value of the coalition among the players according to their contribution. This index is calculated according to the definition in Eq. (10) and considers the added value that each player brings to the coalition, i.e., their marginal contribution.

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n - |S| - 1)!}{n!} (v(S \cup \{i\}) - v(S)) \tag{10}$$

in which the marginal contribution of the player i in the coalition S is $(v(S \cup \{i\}) - v(S))$, the value of the coalition with and without the player. The marginal contribution is weighted on the factor $\frac{|S|!\,(n-|S|-1)!}{n!}$ that takes into account the possible orders in which player i can join the coalition S. For the calculation of the Shapley value, all possible combinations that can be obtained with a set of players N and all its possible subgroups are considered. The computational cost of this calculation is, therefore, very high. When the number of players increases, the complexity increases according to a factorial function; therefore, a maximum limit of players can be considered. This problem makes this algorithm difficult to apply to a context such as an energy community where the members may be hundreds. One possible solution is clustering similar players. For example, clustering all passive consumers and distributing the payoff received among the players in the subgroup proportionally. A limitation of this method is that it assumes that those with a plant under their POD also own it. To overcome this, two different users should be created, one virtual and one physical.

The block diagram describing the algorithm is shown in Fig. 4. For each participant in the energy community and each value from 0 to the total number of members, all possible coalitions formed with N players and the multiplication factor expressed in Eq. (10) were calculated. For each coalition, the revenues that the REC would obtain with and without the considered user are then calculated using the Compute Value function. This function calculates the gains of the REC by taking any coalition as input.

As previously introduced, the Shapley-based method is used as a reference case. This method is a benchmark against all other algorithms created because it is the fairest way to distribute earnings. In any case, because of its complexity, its implementation in real applications is not easy. The following simpler methods are compared to assess similarities and extend to evaluating different criteria.

Ownership-based criteria. The "Ownership-based" method Refs. [36] and distributes the economic benefits only among the members who contributed to the investment, proportional to the invested money. This method can be easily applied where the PV plants are collectively financed as it requires no additional data flows or elaboration. In case most of the users did not contribute to the investment, it can be unacceptable as these users bring benefit to the REC (increasing shared energy) and receive 0.

Proportional. The "Proportional" method is designed to have an easy method to remunerate the effort of each member sharing energy. It

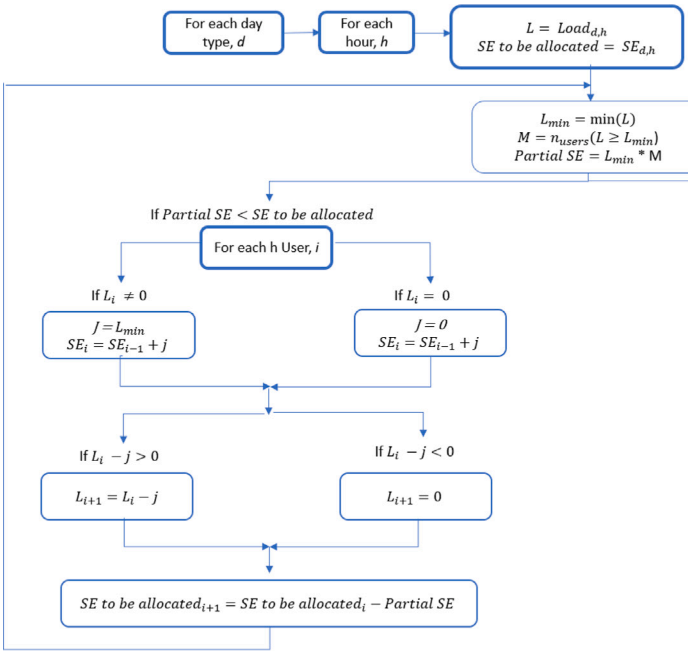


Fig. 5. Block diagram for Packet-based algorithm.

estimates the hourly load of each member i relative to the total REC hourly load for each hour h of each day d. The hour-by-hour REC revenues ($Rev_{CER,d,h}$) are distributed according to this proportional index to each member ($Rev_{i,d,h}$) as per (11).

$$Rev_{i,d,h} = \frac{Ec_{i,d,h}}{Ec_{REC,d,h}} * Rev_{CER,d,h} \tag{11}$$

This method considers the effort for energy sharing by each member while disregarding who made the investments. It requests data on the hourly value of consumed energy, withdrawn energy, and injected energy by each REC member. This is acceptable if the plant costs have been equally split between members or if no one has contributed (e.g., the plant is financed by a non-repayable grant). Sub-metering in the REC is possibly needed to get these data from each user.

Packet-based criteria. It exploits the method developed in [36] that distributes minimum packets of shared energy to each member. The REC members are sorted based on the ascending hourly load $Ec_{i,d,h}$: the lowest consumer in the REC for each hour is Ec_{min}, the second lowest is Ec_{2min}, etc. All the members equally share a packet of energy equal to the minimum consumption in that hour ($Ec_{i,d,h}(Ec_{min})$) times the REC members (N_c). Thereafter, the remaining members with $Ec_{I,d,h}$ larger than Ec_{min} share a packet of energy equal to the difference between the second last load $Ec_{i,d,h}(Ec_{2min})$ and $Ec_{i,d,h}(Ec_{min})$ times N_c minus 1. The iterative process continues until the minimum is reached between shared energy ($Esh_{REC,d,h}$) and consumed energy ($Ec_{REC,d,h}$) for that hour. Each member is then remunerated to share all the revenues proportionally to the energy packets attributed to each REC member. The block diagram of the method is presented in Fig. 5, whereas the splitting in an hour is exemplified in Fig. 6. The method does not consider who made the investment and needs hourly data by each member to be available. It is also important to underline that the algorithm is designed to distribute shared energy.

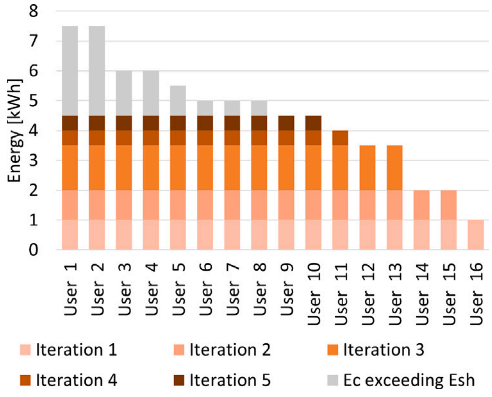


Fig. 6. Example of Packet-based benefit allocation to users.

Multicriteria BS mechanisms. The multicriteria BS methods developed in this work are based on more than one of the previously illustrated methods to avoid polarization on a single observed criterion. In addition, considering the energy poverty situation, most of these methods present a part of the revenues shared to add further revenue for vulnerable REC members. A premise for the energy poverty estimation within the REC is needed. The LIHC indicator was chosen [14] as the indicator of energy poverty used in multicriteria BS mechanisms. This indicator categorizes households at risk of energy poverty if they simultaneously have an energy expenditure above the national median value $P50(s_{e,i})$ and family income net of energy expenditure ($y_i - s_{e,i}$), divided by the income recipients in the household (N_{inc}) below a threshold value (y^*).

$$LIHC = I\left\{\left[s_{e,i} > P50(s_{e,i})\right] \cup \left[\frac{(y_i - s_{e,i})}{N_{inc}} < y^*\right]\right\} \tag{12}$$

$P50(s_{e,i})$ was obtained by summing the expenditure for electricity and gas, using Italian Regulatory Authority's estimates of consumption and costs for the standard user [50]. In (12), y^* is the income threshold that identifies a family at risk of poverty, if the income is 60% of the median equivalent income (as defined by EUROSTAT [42]), the same value used in 2.1. The input data required are the household's energy expenditure, its annual income, and the number of recipients. The formula returns a value of 1 if the household meets both conditions; otherwise 0.

In addition to a "Boolean" result, a "continuous" version of the index ($LIHC_{cont}$) has also been developed in this study to recognize the depth of poverty. Through (13), $LIHC_{cont}$ returns a value between

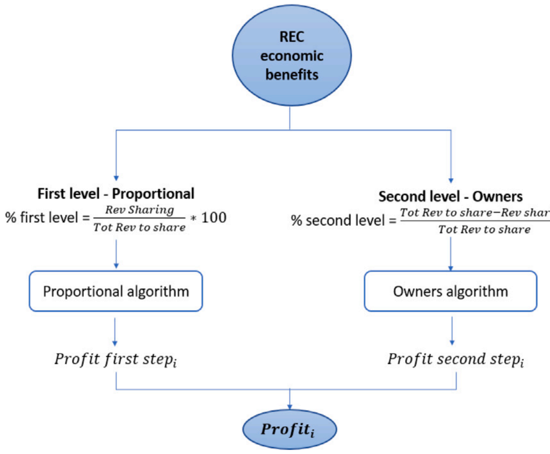


Fig. 7. Block diagram for the bi-level algorithm, “Proportional + Ownership-based” method.

0 and 1; 1 if there is no risk of energy poverty, and the further lower than 1, the greater the risk.

$$LIHC_{cont} = Min\left(1; Mean\left\{\left[\frac{P50(s_{e,i})}{s_{e,i}}\right], \left[\frac{(y_i - s_{e,i})}{Nind_{income} \cdot y^*}\right]\right\}\right) \tag{13}$$

The main differences between the methods are the basic BS mechanisms considered and the weight of each mechanism on the total revenues.

- “Ownership-based + Proportional” method distributes with the Proportional method the fraction of the revenues obtained by sharing energy out of the total revenues the community has decided to share (in this study: REC shares both revenues for shared energy and for injected energy). The remaining portion is instead distributed by the “Own.-base” method, as shown in Fig. 7. This is to coherently match the benefit that each member’s effort provided to the community to what it receives back. Indeed, the “Proportional” method (which remunerates those who shared energy) redistributes the portion of revenues related to sharing. In contrast, the “Own.-base” method (which remunerates those who invested in RES plants) redistributes the revenues coming from energy selling.
- “Ownership-based + Energy Poverty” method simply attributes a share ($n_{\%}$) of REC revenues to each user in risk of energy poverty (based on LIHC). Therefore, the total share of revenues for energy poverty mitigation ($share_{EP}$) is $n_{\%}$ times the total number of vulnerable users in the REC (N_{vu}) up to a maximum of 50% as share. The remainder ($share_{rest}$) is shared following the previously illustrated “Own.-based” method.

$$share_{EP} = \min\left(50\%, n_{\%} \cdot N_{vu}\right) \tag{14}$$

$$share_{rest} = 1 - share_{EP} \tag{15}$$

  In this study, $n_{\%}$ was arbitrarily set to 2% as the outcome of a fine-tuning process. Improved approaches could use $LIHC_{cont}$ to associate a larger $n_{\%}$ to members in harsher poverty conditions.
- Similarly, in the “Proportional + Energy Poverty” method (Fig. 8), $n_{\%}$ of revenues is attributed to each vulnerable user, and the rest (see (15)) is shared based on the “Proportional” method.
- In the tri-level method “Own.-based + Proportional + Energy Poverty”, the $n_{\%}$ rule is adopted to define $share_{EP}$, but $n_{\%}$ is 1.32% (0.66 times 2, as it is a tri-level method) and the maximum share is 33%. The remainder ($share_{rest}$) is split similar to the “Own.-based + Proportional” method. Thus, the “Own.-base” method redistributes the selling income, and the “Proportional” method sells that of sharing.

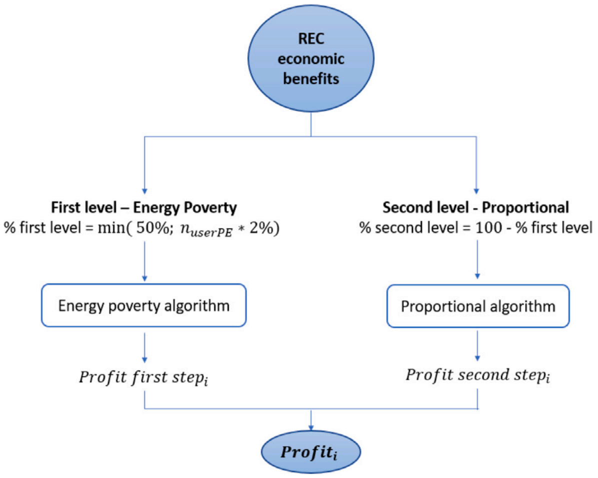


Fig. 8. Block diagram for the bi-level algorithm, “Proportional + Energy Poverty” method.

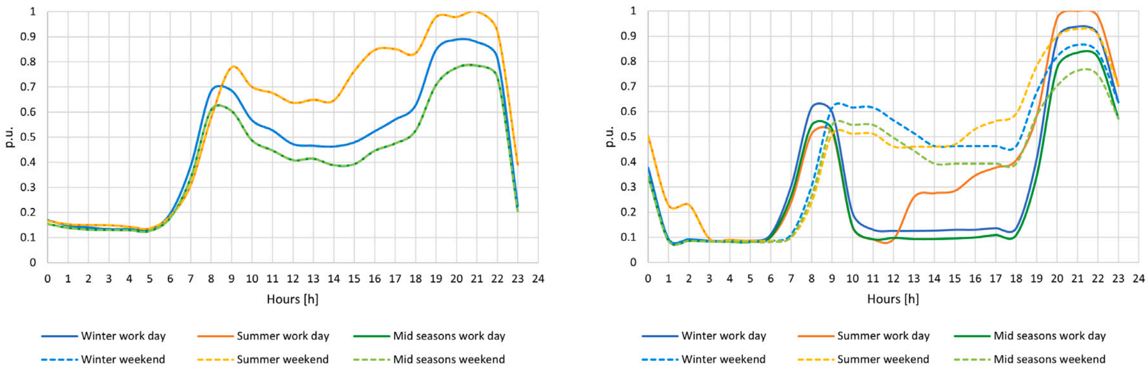
3. Case study and data processing

As described in the introduction, the interest is large-scale energy poverty mapping, at least corresponding to a country. Italy was selected because of the early implementation of RECs [49] as an energy poverty mitigation tool [51] and because of the inequality it presents within its demography and geographically [40,52]. It is worth noting that this study aims to accept a potentially larger degree of inaccuracy with respect to studies on a province (e.g., [20]) but extend the domain.

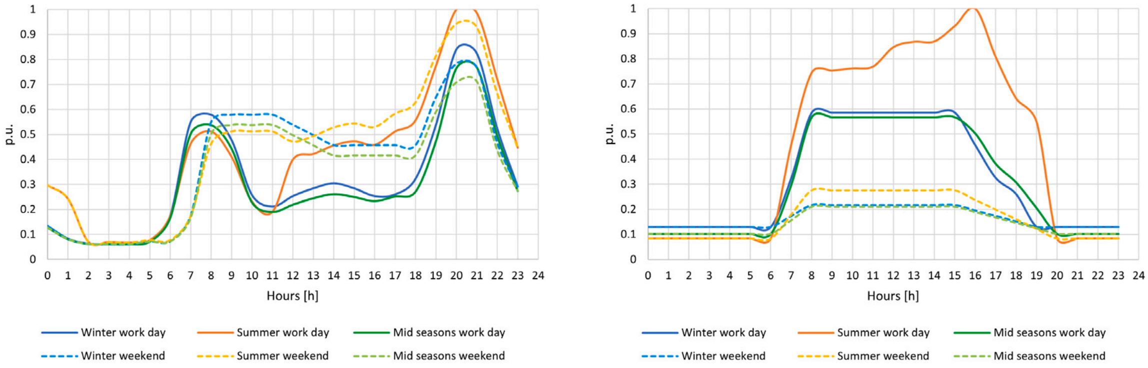
In terms of the BS methods, a social REC initiative (aimed to improve the social condition of its vulnerable members) should be considered for testing qualitatively and quantitatively the developed mechanisms in a suitable framework. The selected case study is a potential energy community in the municipality of Teglio in Valtellina. It is located in a mountainous area characterized by a harsh climate, especially in winter. Teglio’s households, therefore, have to bear large expenses for heating. This, together with the fact that the average salary is below the national value, places this municipality at medium-high risk of energy poverty (as will be better illustrated in the proposed energy poverty mapping). To generalize the approach to all the country, the users have been described with archetypes, and typical days are used for the yearly simulations. Six user archetypes were created, both residential and commercial, by making assumptions regarding the habits of its occupants. The categories are: $Old\ couple$, $Young\ couple$, $Family$, $Industrial$ and $Commercial\ SME$, $Office/School$, as can be seen in Fig. 9.

Additional profiles that do not fit into any category can also be entered manually for peculiar case studies. In addition to the production and demand profiles, the specifications of each category (number of users and peak power) and each PV plant (peak power, presence of BESS, BESS capacity, BESS maximum power, and type of connection) were entered.

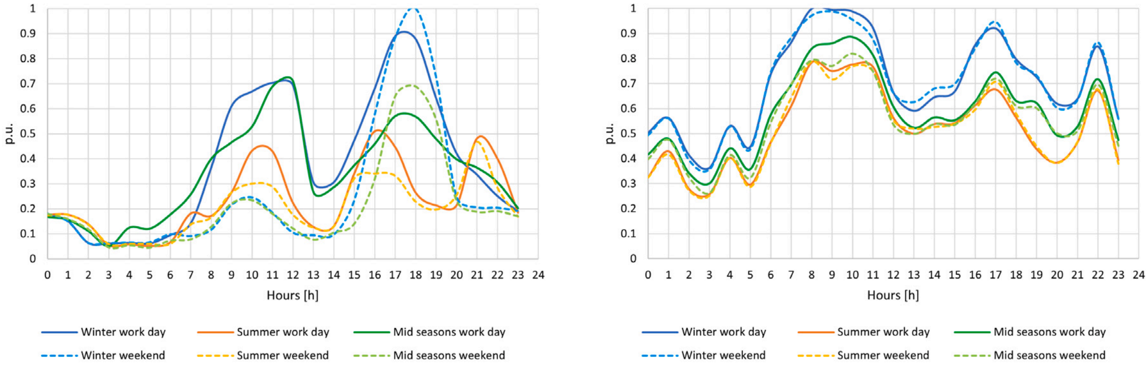
Six typical days have been identified, each with several occurrences during the year. They feature power profiles for consumption and production (not shown here) for two daily profiles, work and holiday, and for three seasonal periods, winter, summer, and mid-season. The per unit production profile is the same for each plant, and a correction factor was used according to the Italian geographical area in which the REC is located: north, central, or south, to obtain real values in annual production.



(a) Old couple (b) Young couple



(c) Family (d) Office and school



(e) Sports arena (f) Nursing home

Fig. 9. Load profiles for REC member archetypes.

The user's data, including electricity consumption and bills, are presented in Table 4. For residential users, it was also necessary to define the gas bill, the total energy costs, and the household income. In this simplification, gas represents the source of heating for all households. This is not unusual in Italy, where 70% of buildings have natural gas-based heating and only 8% have electric heating [53]. All data come from statistical analysis. The users were defined using Istat data on the population of Teglio according to age [54]. Electricity consumption and electricity bill costs were assumed using average data from Italian Authority regarding the number of members per household, while gas consumption is typical for mountain areas [50]. Regarding incomes, once again open data on tax declarations for Teglio were used [41]. To distribute incomes in age classes, national data were used [54]. Considering this data and assumptions, three community participants were identified to be at risk of energy poverty according to the LIHC index: $Old\ Couple$ 3, $Old\ Couple$ 4, and $Young\ Couple$ 2. This result is consistent with reports on energy poverty from the Italian observatory OIPE, based on Istat data [55].

Regarding RES production, in the district considered for the REC, there are already three photovoltaic systems owned by the municipality located on the school in Teglio (5.9 kW), the school in Tresenda (20.0 kW), and on the sports arena (20.0 kW). Each of them is connected behind the meter of the building, and they are integrated with lithium batteries, whose nominal power is 15 kWh for both schools and 40 kWh for the arena; this real case is taken as the reference case for this study (Ref case). A preliminary techno-economic analysis has been developed to assess the installed PV power: starting from the Ref case, the ratio of produced energy (Ep) over consumed energy (Ec) in the REC has been increased stepwise (from 25% to 150%). The proposed REC configuration is the one that maximizes the share of revenues from shared energy (Esh). This criterion is considered to investigate a case where the REC brings relevant economic boost to PV installation alone.

Table 4
Yearly data of REC members.

	Electricity consumption [kWh]	Electricity bill cost [€/kWh]	Natural gas consumption [m3]	Total energy expenditure [€/year]	Family income [€]
Old Couple 1	1490.16	0.35	1481	2446.86	25 934.7
Old Couple 2	1530.44	0.341	1481	2447.18	24 755.85
Old Couple 3	1570.71	0.32	1481	2427.93	22 398.15
Old Couple 4	1610.99	0.307	1481	2419.87	21 219.3
Young Couple 1	1533.97	0.331	1481	2433.04	28 636.3
Young Couple 2	1592.97	0.319	1481	2433.46	23 429.7
Family 1	2090.99	0.303	2058	3308.97	37 685.27
Family 2	2121.3	0.292	2058	3294.82	36 543.06
Family 3	2151.60	0.282	2058	3282.15	35 401.20
Family 4	2181.91	0.278	2058	3281.97	33 117.47
Family 5	2787.99	0.269	2635	4175.47	31 975.61
Family 6	2878.91	0.252	2635	4150.99	30 833.4
Teglio School	46 818.17	0.27	–	–	–
Tresenda School	42 831.47	0.262	–	–	–
Nursing Home	165 058.78	0.25	–	–	–
Sport arena	24 407.54	0.295	–	–	–

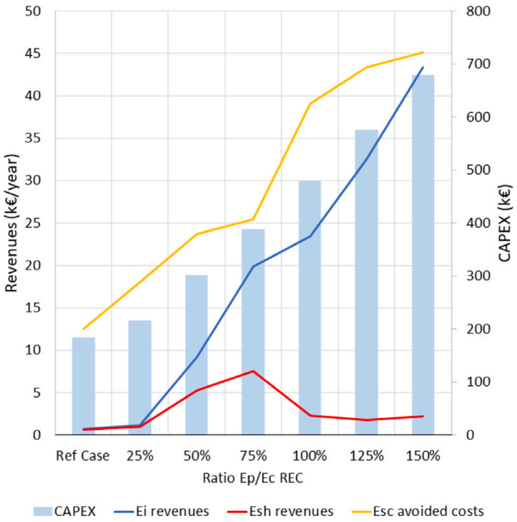


Fig. 10. Community economic benefits and CAPEX as a function of increased energy produced.

Ep/Ec of 75% is the selected value, as shown in Fig. 10. It corresponds to 29.7 kW installed at Teglio's school, 122.1 kW at Tresenda's school, and 40.2 kW at the sports arena. The PV sizes are coherent with the rooftop area limitations of these building.

For plants under 30 kW, CAPEX is 1600 €/kW and OPEX is 26 €/year; otherwise, they are 1400 €/kW and 21.5 €/year, respectively. Additionally, a battery cost of 1200 €/kWh was considered. Both the incentive for shared energy and the earnings from the sale of energy were considered economic benefits to be shared among all community members. This is coherent with the social purpose of the REC. Self-consumption is not shared because it represents an indirect economic flow and is, therefore, more complex to take into account; it largely decreases the bills of the public administration buildings, where plants are located.

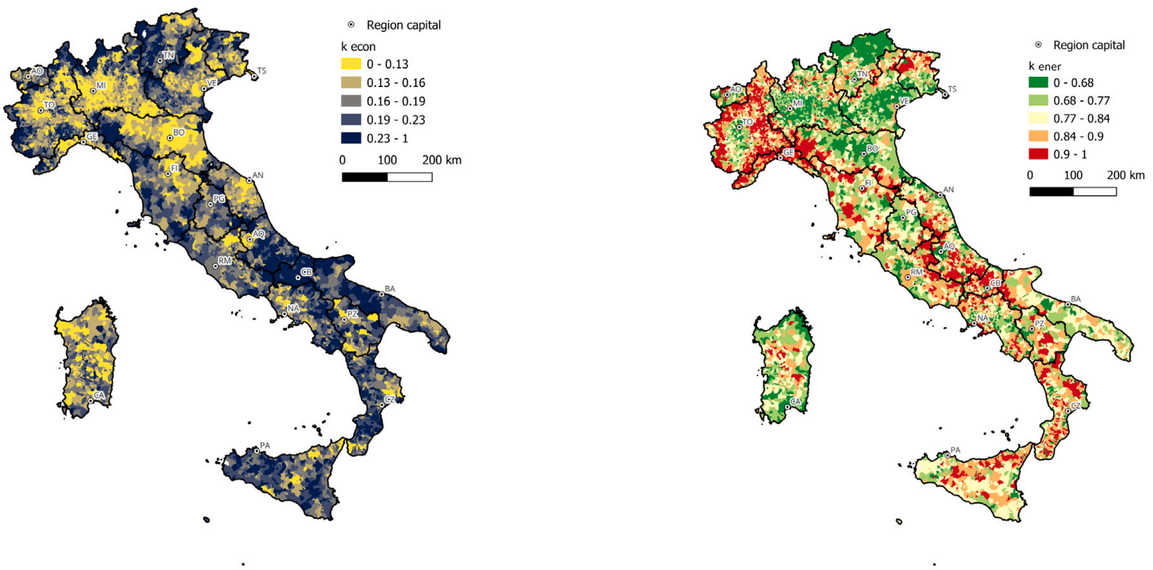
4. Results

4.1. Energy poverty risk map of Italy

In order to effectively manage the risk of energy poverty, political decision-makers can promote targeted incentive schemes. To facilitate this process, this paper proposes a tool capable of quantifying the issue across the entire country. The approach, detailed in Section 3, is based on an index that considers both the energy aspect (quantified by the k_{ener} index) and the economic aspect (quantified by the k_{econ} index). By conducting this analysis on the Italian region, the geographical maps presented in Figs. 11 and 12 are obtained. In particular, Fig. 11(a) shows that the economic vulnerability is more concentrated in mountain areas; indeed, high values of k_{econ} are found by following the two main mountain ranges of Italy: Alps (at the northern borders) and Apennines (which run all along the Italian peninsula from north to south). Also, the number of municipalities in wealthy economic conditions reduces moving from north to south. A strong economic vulnerability is encountered by Abruzzo, Molise, and northern Apulia regions, caused by low incomes when compared with the value of expenditures for durable goods, signaling high living costs. However, in terms of absolute values, the most pronounced risk of economic poverty is located in the municipalities close to the Swiss canton of Ticino, and is probably caused by the cross-border commuters phenomenon [56].

As already explained, the k_{ener} considers the average EP of the buildings in a municipality compared to the corresponding references. The resulting map showing k_{ener} is shown in Fig. 11(b). In this case, the north-west of Italy is the most penalized zone in terms of EPs, especially the Piedmont and Liguria regions. Also, the Apennines areas have considerably high k_{ener} values. It is worth noting that the k_{ener} incorporates the EPs that are relative values; the reference building in northern Italy has higher performances than the reference for southern Italy (to cope with the colder northern climate). Therefore, red areas in Piedmont and Liguria highlight lower building performances relative to the high standard for northern areas. In both the previous maps, the middle-eastern Pianura Padana flatlands (roughly delimited by an imaginary Milan–Bologna–Venice triangle) show low values, therefore associated with low risk of economic poverty and good building conditions.

Finally, the energy poverty risk (K_{EP}) map is presented, resulting in the summation of the previous two terms (Fig. 12). In the northern areas, the energy poverty risk is higher in the western part and the Alpine range, except in the Südtirol/Alto Adige province, which has very efficient buildings compared to other mountain municipalities. Because of a more flourishing economy and better housing conditions, the flatlands have lower K_{EP} values, except for central Piedmont, which shows poor average building energy performances and below-standard economics. Moving south, the red color becomes more spread, especially in Abruzzo and Molise regions, but also in Calabria and Sicily. It is important to notice that cities are not exempt from an energy poverty risk, showing very often a higher K_{EP} than the surrounding municipalities because of a larger share of taxpayers in economic poverty conditions.



(a) k_{econ}

(b) k_{ener}

Fig. 11. Economic coefficient and Energy Performance coefficient maps.

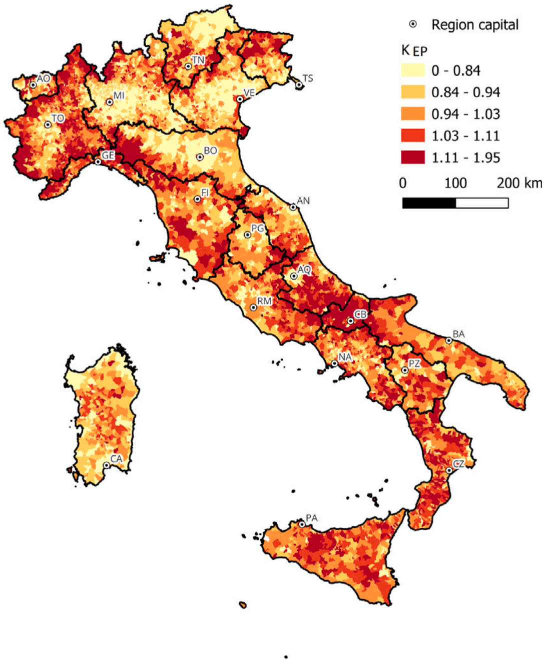


Fig. 12. Energy Poverty Risk map.

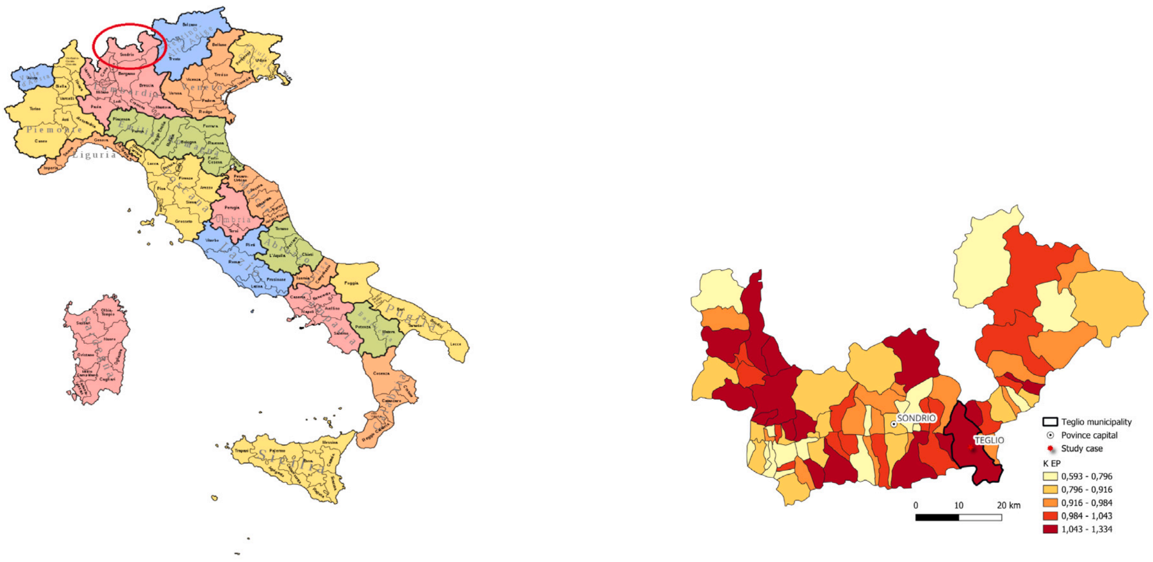
4.2. *Focus on the local case study*

To evaluate the different possible sharing methods of an incentive among the members of a REC and their effectiveness in facing energy poverty, these methods have been applied to a specific case study of an energy community in the municipality of Teglio. To contextualize the case study, K_{EP} map of Sondrio province, where Teglio is located, is reported in Fig. 13. Sondrio province is located in Northern Lombardy. The considered municipality is particularly vulnerable both from economic and EP perspectives. On the economic side, the deficit can be attributed to a large number of taxpayers in poverty (32.2%), considering that for Sondrio, it is 23.3%. Furthermore, Teglio includes a substantial share of buildings built before the nineties (93%), leading to a low estimated EP. The combination of these two characteristics makes Teglio one of the municipalities most at risk of energy poverty. Hence, it is a suitable case study to apply the above-mentioned methodology.

As already described, the REC has been modeled on the members' and RES production sides to obtain its total revenues. The comparison of BS methods gives different revenues and different bill reductions as output for each member.

4.3. *Different sharing mechanisms for different economic results*

Once the energy poverty risk index is defined for the entire Italian territory, political stakeholders could design effective incentive schemes to promote energy communities while also considering the risk of energy poverty. The definition of such incentives is beyond the scope of this paper. In a subsequent step, from the perspective of energy community members, as detailed in Section 2.2, it is necessary to identify criteria for sharing the economic benefits among the members. For such a goal, the Teglio study case has been investigated, in particular the algorithms described in Section 2.2.2 were applied to the energy community in Teglio to compare the revenue sharing. In Table 5, the earnings of the individual users are reported. The Shapley value-based algorithm is considered a reference; it represents how important each user is within the community. The results show that domestic users have a very limited yearly return of approximately 30 € for smaller loads and 50 € for larger families. The school in Tresenda (Off/Sch2) is the most important member because of its large plant. In fact, it has a return of approximately 67% of the total. The nursing home has a considerable gain despite being a passive load and not having photovoltaic installations. This is because it constitutes the main load in the community; the Shapley value rewards not only the installations but also captures the fundamental aspect of energy communities, which is the match between demand and production. The "Owners" method most resembled the results of Shapley. This is only because the installations are located on the building of the same members who invested (i.e., public administration); the results would be very different in a different set-up. Evidently, those who do not have a percentage of ownership on the plants receive nothing with this method; the likely consequence would be that household users and the nursing home would not participate in the community, therefore missing a large part of the energy demand and consequently the revenues for sharing. The "Proportional" and "Packets" methods



(a) Italian provinces

(b) Province of Sondrio

Fig. 13. Energy Poverty Risk map for Sondrio province.

are visibly different from the reference algorithm. The “Proportional” method weighs the load more and synchronism production vs load less. This is why energy-intensive consumers such as the nursing home get the most benefit. The “Packets” method differs in that it equalizes all results, and there are fewer differences between users. The two schools having approximately equal loads have the same payback; the production side is not considered. Notably, the avoided costs attributed to physical self-consumption (both the schools and the sports arena consume) are not considered.

To get closer to the results of the Shapley value and avoid null revenues for some members, the “Proportional” method and “Owners” were combined. The computational cost is relatively low, and weightage is assigned to both energy sharing and ownership based on the relative weight of sharing and injection earnings and, therefore, to both the consumption and production sides. The household revenues are extremely close to the reference “Shapley” method. Additionally, the difference between the two schools, in contrast to the “Proportional” method alone, is captured, even if the quantitative results differ slightly from the Shapley.

The results of the simulations with the algorithms involving the energy poverty index were analyzed. In these cases, the aim is to get close to the Shapley-based splitting yet add a social purpose to the REC. The bi-level algorithms yielded similar results upon implementing the algorithm without considering energy poverty, except for vulnerable users. Non-vulnerable users receive a slightly lower amount compared to the original algorithm. In contrast, there is a large increase for users in poverty, approximately 500 €/year. This amount is coherent with their annual electricity bill (approximately 100% reduction is obtained). This implies that, at the expense of a modest loss in the revenue of non-vulnerable users, there is a lot of help for the vulnerable.

The three-level method is the most complete of those analyzed; it considers all three aspects: ownership, energy, and social. The most important aspects of a social REC are taken into account; however, it deviates from the reference code in that the social aspect is considered, which was neglected in the Shapley value. Despite this, the results for users not in energy poverty are not substantially different. The result could be acceptable if the community has social purposes (the plant is financed by a grant).

In applying the algorithms, a further constraint was imposed on the revenue of each member: a maximum bill reduction of 100% and the coverage of investment mortgage, if any. It was considered unreasonable for the community to give additional income to a member concerning the complete reduction of the bill unless it contributed to the investment and they had to return on it. The unallocated money can be put into a common cash fund belonging to the community and managed by the operator. The cash fund could be very useful to balance any differences in members’ earnings between one year and the next because of changes in the price of electricity or the amount of energy produced. Should the fund be substantial, it could be used to improve the production facilities or to electrify the heating load. As a final remark of the comparison, it is worth noting that all the proposed BS methods required computational time approximately 100 times lower than the Shapley-based method used as a reference (i.e., less than 60 s considering Teglio’s case study). Thus, the simplifications with respect to the Shapley value make the proposed BS mechanisms suitable for a wide set of RECs, even when energy poverty is considered. To better check the impact of vulnerable users’ presence on the RECs economics, the following section proposes a sensitivity analysis.

4.3.1. *Sensitivity analysis on the energy poverty situation*

The analyzed results and considerations are closely related to the case study, particularly the number and relative weight of users in energy poverty. For this reason, a sensitivity analysis was performed to analyze how much the distribution changes, increasing vulnerable users. This was done by changing the income of 6 and then 12 families out of 12 (100%). This aspect is more affected by fluctuations and differences between households (while the bills have less variability). The already analyzed case (base case) represents a REC project with members coming from a standard income distribution; now, two case studies are added, decreasing arbitrarily the incomes to design a REC with large penetration of users with a LIHC index lower than 1. The simulations were then repeated for the two additional case studies (featuring 50 and 100% of residential users in energy poverty) with the “PE + Proportional” method. The bill reduction for each REC member is reported in Table 6. The reference bill reduction obtained with the Shapley-based method is also reported.

Considering the base case and the case with 50% of users in energy poverty, in both cases all users with an energy poverty risk cover their electricity expenses. A slightly lower bill reduction can be seen for users not considered at risk when more vulnerable users are present. The reason is that the users at risk constitute a very small part of the

Table 5
Yearly revenues from sharing and sale of energy for each REC member with different sharing methods (in red users in energy poverty, in blue the municipality).

	$REFcase$: $Shapley$	Owners	Prop.	Packets	Prop. + Owners	EP + Prop.	EP + Owners	EP + Prop.+ Owners
Old1	34	0	128	161	35	120	0	34
Old2	35	0	131	165	36	124	0	35
Old3	36	0	135	170	37	503	503	401
Old4	37	0	138	174	38	495	495	389
Young1	25	0	103	120	28	97	0	27
Young2	26	0	107	125	30	508	508	405
Family1	44	0	171	204	47	160	0	45
Family2	44	0	173	207	48	163	0	46
Family3	45	0	176	209	48	165	0	46
Family4	46	0	178	212	49	167	0	47
Family5	58	0	227	267	62	214	0	60
Family6	60	0	235	275	64	221	0	62
Off/Sch1	851	4226	5563	6657	4593	5229	3972	4409
Off/Sch2	18079	17402	5089	6422	14021	4784	16358	13460
Nurs.Home	3680	0	13012	7786	3573	12232	0	3430
SportsArena	3680	0	13012	7786	3573	12232	0	3430

Table 6
Percentage saving on the electricity bill for each member of the REC in REF and in different scenarios, considering the "Energy Poverty + Proportional" method.

	@c@$REFcase$: $Shapley$	@c@Base Case (25%)	@c@50% of users in PE	@c@100% of users in PE
Old1	7%	23%	100%	100%
Old2	7%	24%	100%	100%
Old3	7%	100%	100%	100%
Old4	8%	100%	100%	100%
Young1	5%	19%	100%	100%
Young2	5%	100%	100%	100%
Family1	7%	25%	24%	100%
Family2	7%	26%	25%	100%
Family3	7%	27%	25%	100%
Family4	8%	28%	26%	100%
Family5	8%	29%	27%	86%
Family6	8%	30%	28%	89%
Off/Sch1	71%	106%	103%	98%
Off/Sch2	259%	140%	138%	132%
Nurs.Home	9%	30%	28%	24%
SportsArena	146%	110%	109%	106%

total load of the community: in the base case, they represent 2% with respect to the total REC load, whereas in second case, they are 3%. By increasing the vulnerable users to 100% of the residential users, more substantial changes can be seen; the percentage of consumption they constitute in relation to the total load has increased to 8%. In fact, it is no longer possible to completely cover the electricity expenditure of all impoverished users. The bill reduction for the energy poor comes at the disadvantage of substantially decreasing savings for the municipality and the nursing home. This sensitivity analysis offers a benchmark for sizing a social REC in terms of the share of vulnerable users. Clearly, different choices can be made by the community: changing the share of money dedicated to energy poverty mitigation ($n_{\%}$), varying the acceptable payback time for those who invested, and using the proposed continuous LIHC ($LIHC_{cont}$) instead of the standard, boolean LIHC, to have more impact where the condition of energy poverty is deeper. Does this effort work for mitigating energy poverty in different cases? The following section shows the impact on LIHC of the different REC designs.

4.3.2. Does REC mitigate energy poverty? computing the LIHC before and after

Finally, the energy poverty index was recalculated after applying the "PE + Proportional" sharing method to check if households' energy poverty situation has improved. "PE + Proportional" BS method has been selected since it seems a good candidate for a social REC, where plants are financed by the municipality. To better clarify the deepness of the energy poverty condition of users, the proposed $LIHC_{cont}$ is used in this section. Table 7 shows the results for all three scenarios analyzed in the previous section. The improvement is positive in all scenarios; the $LIHC_{cont}$ index increases, thus getting closer to the threshold value 1. In particular, the distance to the target is generally halved. In some cases (3 out of 21), the user gets out of the risk band owing to the energy community. Most users still remain below the value of 1; however, the number of users with $LIHC_{cont}$ below 0.8 (that returns a severe poverty condition) decrease from 21 to 5, indicating a relevant role of REC in mitigating energy poverty.

To better understand the outcomes, it is worth noting that for LIHC indexes, the factors influencing energy poverty are primarily three: household salary, heating expenditure, and electricity expenditure. The current nature of the Italian energy community only improves the latter. It is, therefore, a tool that can help mitigate energy poverty but not solve it by itself. It is also important to emphasize that these users would see their condition improve with just a signature: they did not participate in the investment of the installations, nor they had to change any habits in electricity consumption. The further impact of improving the energy consumption behavior and electrification on demand could be investigated.

5. Conclusions and policy implications

In recent years, there has been a surge in interest in initiatives to alleviate energy poverty in the context of the energy crisis. This study addresses the issue by offering tools to two main stakeholders.

The first tool is a methodology for mapping the energy poverty risk nationwide, primarily using public data available uniformly on a wide territory. The mapping procedure considered the income vs life

Table 7
LIHC index before and after application of the “Energy Poverty + Proportional” bi-level algorithm.

	25% users PE		50% users PE		100% users PE	
	before	after	before	after	before	after
Old1	1.00	1.00	0.78	0.87	0.78	0.87
Old2	1.00	1.00	0.75	0.84	0.75	0.84
Old3	0.77	0.85	0.77	0.85	0.77	0.85
Old4	0.74	0.83	0.74	0.83	0.74	0.83
Young1	1.00	1.00	0.78	0.87	0.76	0.85
Young2	0.79	1.00	0.79	1.00	0.75	0.84
Family1	1.00	1.00	1.00	1.00	0.71	1.00
Family2	1.00	1.00	1.00	1.00	0.69	0.76
Family3	1.00	1.00	1.00	1.00	0.68	0.75
Family4	1.00	1.00	1.00	1.00	0.68	0.75
Family5	1.00	1.00	1.00	1.00	0.61	0.65
Family6	1.00	1.00	1.00	1.00	0.61	0.66

cost-related aspect and the building’s energy performance aspect, to compute a value quantitatively describing the risk of energy poverty for each municipality in Italy. If, on the economic side, the Italian map returns the well-known gap between north and south (showing worse economic condition), the energy performance map highlights instead widespread vulnerabilities, with high values (low performances) in the northwest (Piedmont, Liguria) and in central Apennines area (Lazio, Abruzzo, Molise). This results in an energy poverty risk map that features: (i) larger risk in mountain areas, especially Apennines; (ii) moderate risk in big cities, with lower risk in the surroundings (the suburbs); (iii) a scattered mid-to-high risk area in the northwest, including Emilia and some inner areas of Tuscany; (iv) generalized high risk in southern peninsular area and Sicily. The obtained result was coherent with previous analyses and reached a wider territory while keeping a fine granularity (the municipal level). Policymakers can benefit from this knowledge in several ways. First, the index could be used to build a ranking to prioritize policies. For example, a system of priority bands can be developed selecting the municipalities from the most to the least critical and start the support campaign from the first band of municipalities. Second, policymaking can use the energy poverty risk index to split a State incentive for social energy initiatives. For instance, as sketched in the paper, the proposed methodology represents practical support to allocate an incentive among different RECs (or other initiatives, e.g., energy efficiency) to enhance the intrinsic capability of the REC model in facing the energy poverty phenomenon.

Indeed, the second tool supports RECs as one of the main instruments for bottom-up energy initiatives potentially mitigating energy poverty. Several BS mechanisms are developed and compared, addressing one or more of the aspects of REC: the ownership of RES plants, the virtuosity of the members in sharing energy, and the individual condition of energy poverty. The proposed mechanisms build on the existing literature to find easier methodologies for considering multiple criteria and approximate fair but computationally heavy algorithms (e.g., based on Shapley value). Within the criteria, the proposed methods include energy poverty, as of now just marginally addressed. The outcomes confirm that a simpler method can closely approximate the fair revenue distribution given by the Shapley value. In contrast, they highlight that RECs can help mitigate energy poverty by abating the harshest conditions and canceling the mild ones. Other initiatives (such as energy efficiency, electrification of load, and demand-side management) should join REC to increase their impact. Another important finding is that, under certain REC design assumptions, dedicating some part of REC revenues to energy poverty mitigation just slightly impacts the economics of non-vulnerable residential REC members (7% in the considered case studies): this increases the acceptability of social RECs. The impact on the energy poverty situation is instead significant: in the case studies, around 15% of users gets free from energy poverty, while 75% of them pass by a severe energy poverty condition to a milder one. RECs are, therefore, an effective tool for social energy policies.

The limitations of the study correlate to the aim of generalizing the approach: more precise data, for instance, the EPCs, were neglected in the study as they are unavailable on the whole territory (or not in the same format). Additionally, the energy poverty risk coefficient has a relative value instead of an absolute one. This is because of the relative nature of the EP index, which defines a reference building for each climatic zone (several reference buildings in Italy). Therefore, it does not return the purchasing power of each municipality but the relative risk for the municipality of presenting situations of energy poverty when compared to its climatic zone. When considering the REC case study, the limitations rely on the specific nature of this community: it is based on a few large photovoltaic plants financed and located on public administration buildings and a set of residential consumers. This has been selected as a widespread model for early REC initiatives in Italy but cannot represent each energy community. The findings have, therefore, mostly qualitative applicability to different designs.

Future works can expand on other REC designs or include other initiatives, such as gradual electrification of demand in a REC and implementation of demand-side management (by “smart loads” or “smart users”), to increase the impact of REC on energy poverty mitigation. Moreover, the application of this methodology to indicators that include hidden energy poverty could shed a further light on this rising issue.

CRediT authorship contribution statement

Laura Campagna: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Giuliano Rancilio:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Lucio Radaelli:** Writing – original draft, Methodology, Data curation. **Marco Merlo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, 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.

Acknowledgments

This study was partially carried out within the NEST - Network 4 Energy Sustainable Transition (D.D. n. 1561 dell’11.10.2022, PE0000021) and received funding under the Piano Nazionale di Ripresa e Resilienza (PNRR), Mission 4 Component 2 Investment 1.3, funded from the

European Union - NextGenerationEU. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.segan.2024.101471.

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