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Methods to mitigate energy poverty in a Renewable Energy Community

TESI DI LAUREA MAGISTRALE IN
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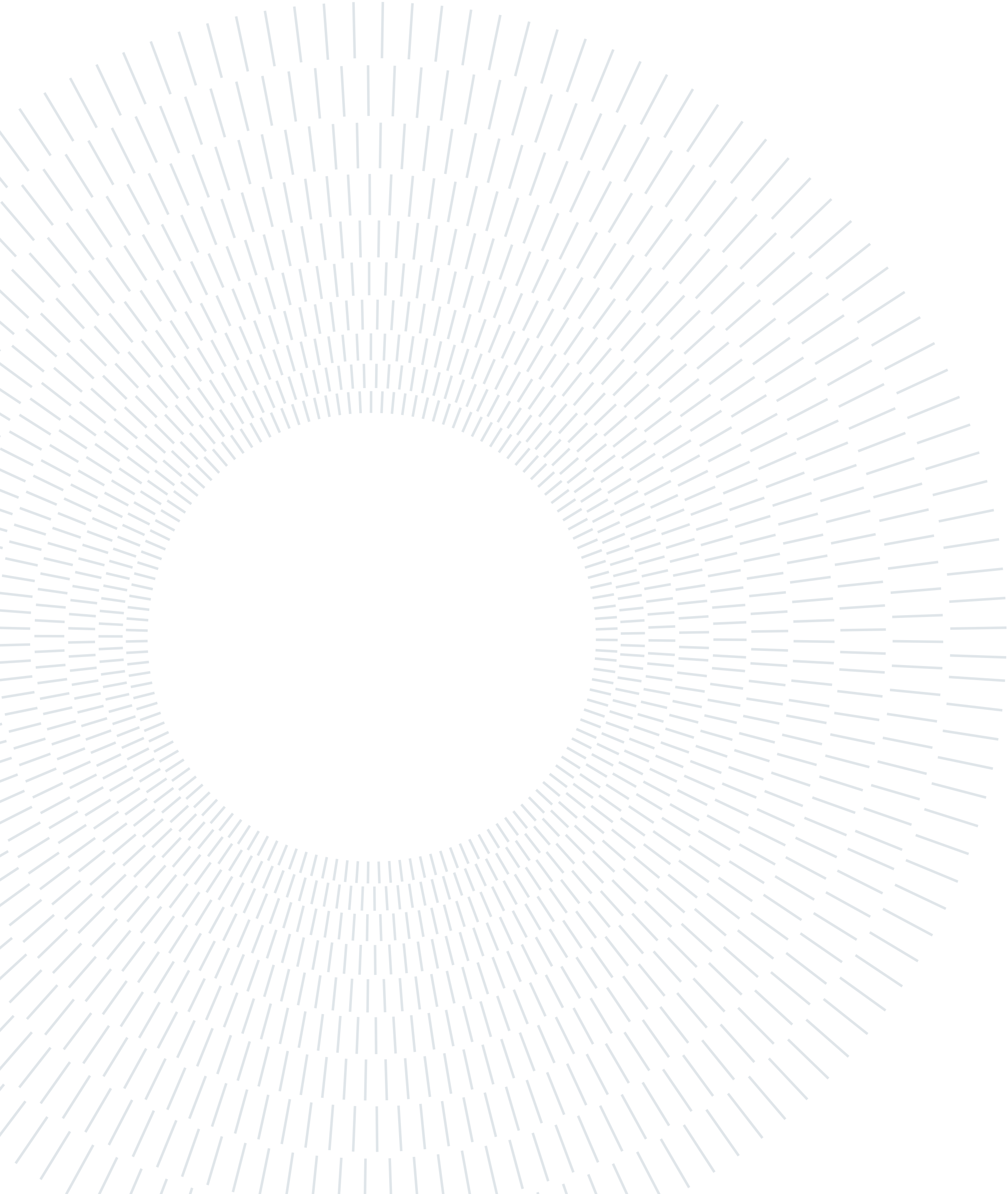


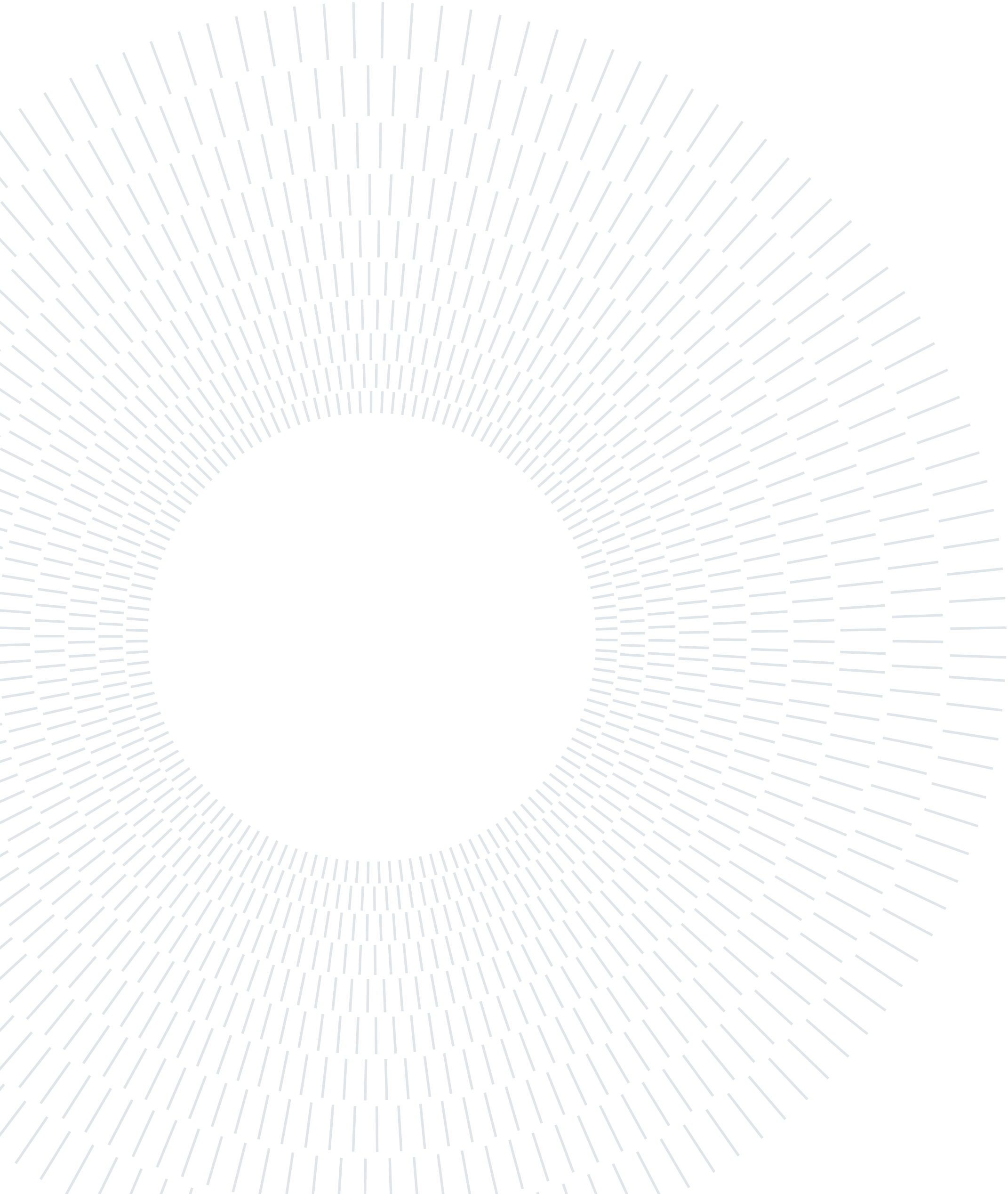
Abstract

The COVID-19 crisis and the war in Ukraine have put upward pressure on energy prices, contributing to the worsening of energy poverty in Europe. At the same time, strong environmental policies request an increasing involvement of citizens in the fight against climate change. Born out of this process are the Renewable Energy Communities, a new tool created by the European Commission in 2018 that allows citizens to form a community that self-produces and self-consumes energy from renewable sources, bringing social, environmental, and even economic benefits to its participants. However, the European and Italian documentation does not give guidelines on the criteria to be adopted to distribute the incentives among the members of the community.

This thesis, therefore, proposes various algorithms that can be adapted to allocate incentives, taking into account the different configurations that a community can assume and the various aspects that characterize it. In particular, the economic, energy, and social aspects have been considered. More attention was paid to the social aspect, so an energy poverty index was selected to assess the economic condition of the members and then implemented and integrated into the algorithms.

The methods created were then applied to a real case study, the emerging Energy Community of Teglio, in Valtellina. The results in terms of bill gain and savings of the different members were calculated and compared. The economic implications that each algorithm brings were also assessed and a sensitivity analysis was carried out on how the community's balance changes as the number of energy-poor users increases. The results show that the Energy Community can indeed bring great benefits to the most fragile households, in particular to communities promoted by local authorities such as the municipality.

Keywords: Renewable Energy Comunity, energy poverty, sharing methods



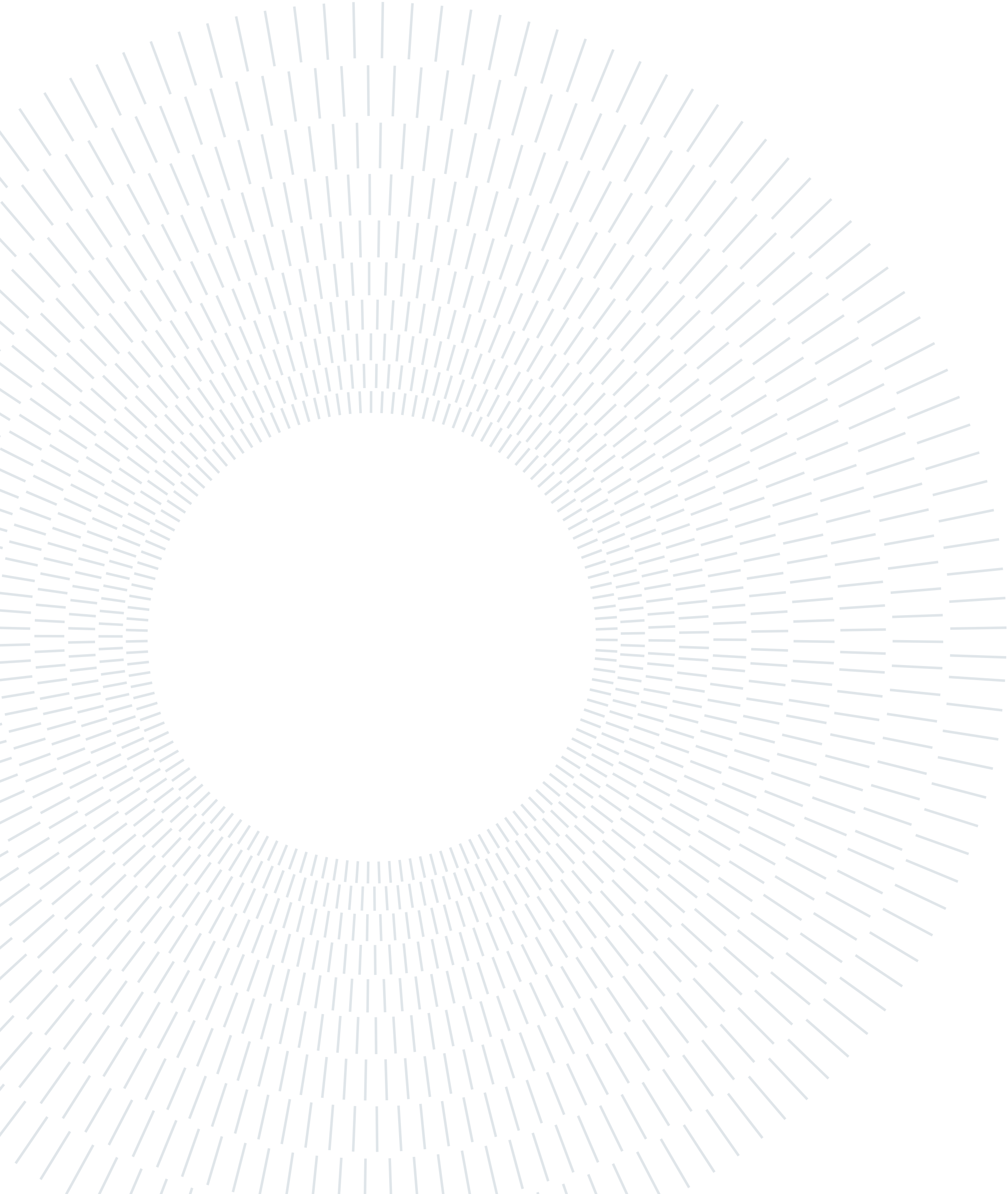
Abstract in lingua italiana

La crisi dovuta al COVID-19 e la guerra in Ucraina hanno esercitato una pressione al rialzo sui prezzi dell'energia, contribuendo al peggioramento della povertà in Europa, in particolare il fenomeno della povertà energetica. Contemporaneamente le forti politiche ambientali richiedono un sempre maggior coinvolgimento dei cittadini nella lotta contro il cambiamento climatico. Figlie di questo processo sono le Comunità Energetiche Rinnovabili, un nuovo strumento creato dalla Commissione Europea nel 2018 che permette ai cittadini di formare una comunità che autoproduce e autoconsuma energia da fonti rinnovabili, apportando benefici sociali, ambientali e anche economici ai suoi partecipanti. La documentazione europea e italiana non dà però linee guida sul criterio da adottare per ripartire gli incentivi tra i membri della comunità.

In questa tesi si propongono quindi diversi algoritmi che possono essere adottati per ripartire gli incentivi tenendo conto delle diverse configurazioni che una comunità puo assumere e i vari aspetti che la caratterizzano. In particolare, l'aspetto economico, l'aspetto energetico e l'aspetto sociale sono stati considerati. Maggior attenzione è stata posta al tema sociale, si è quindi selezionato un indice di povertà energetica che valutasse la condizione economica dei membri per poi implementarlo e integrarlo all'interno degli algoritmi.

I metodi creati sono stati successivamente applicati a un caso studio reale, la Comunità Energetica emergente di Teglio, in Valtellina. I risultati in termini di guadagno e risparmio in bolletta dei diversi membri sono stati quindi calcolati e comparati. Sono state inoltre valutate le implicazioni economiche che ogni algoritmo porta e si è svolta un'analisi sensitiva su come cambiano gli equilibri della comunità all'aumentare degli utenti in povertà energetica. I risultai ottenuti mostrano come la Comunità Energetica possa effettivamente apportare grandi benefici alle famiglie piu fragili, in particolare per le comunità promosse da enti locali come il Comune.

Parole chiave: Comunità Energetiche Rinnovabili, povertà energetica, sistemi di ripartizione



Contents

Introduction

The last few years have been characterized by challenges that Europe has never faced before. The present climate emergency has increasingly led to the need to define more challenging environmental policies. However, these actions not only require large investments but e.g. in the 'FIT for 55' resolution also to involve citizens through active participation. At the same time, the Covid-19 pandemic and the gas crisis caused by the outbreak of war between Russia and Ukraine have placed many European households in difficulty, drastically increasing the phenomenon of energy poverty. The Member States therefore have to work on two fronts, on one hand to achieve the 2030 and 2050 targets to contain climate change, and on the other one to protect the most vulnerable citizens.

One of the instruments identified by the European Union in 2018 to address this challenge is the Energy Communities and in particular Renewable Energy Communities. RECs are groups of people, companies, cooperatives, local authorities, associations, and religious organizations that come together to self-produce and self-consume electricity from renewable sources: photovoltaic, wind, hydroelectric, and biomass. They are not the solution to the problem, but they can be a great help in tackling the energy transition. By sharing the energy produced by renewable energy plants, all citizens, even the most economically fragile, will have access to clean energy. They also enable citizens to save money on their energy bills, reduce pollution and emissions, and increase the country's energy security and independence.

In recent months the Italian Ministry for the Environment and Energy Security presented a draft decree to the EU. It provides for proportional incentives on collectively consumed energy and an allocation of 2.2 billion from the PNRR (Piano Nazionale Ripresa e Resilienza). This allocation will be used for non-repayable financing of up to 40% of the costs of setting up a new plant or upgrading an existing one in municipalities of up to 5 thousand inhabitants. The latter measure aims to provide economic support for more economically disadvantaged territories that would otherwise find it difficult to establish Energy Communities.

This type of support, by the legislator, is not, however, the only instrument that can be used to mitigate the phenomenon of energy poverty. Individual communities can act internally through the distribution of incentives. In this thesis, the aim is, based on the information available in the literature, to develop several algorithms that can be effective in the distributing the economic benefits obtained among the members of the Energy Community. The algorithms will take into account three fundamental aspects of the REC: the economic aspect, that is, plant ownership, the energy aspect, that is, the match between demand and production, and the social aspect, i.e. the energy poverty. The latter one will be studied and measured by an indicator specifically designed.

The thesis is structured in the following way:

- in Chapter 1 is presented a literature review of both the energy communities and the energy poverty phenomenon, describing the main features and focusing both on the European and Italian frameworks.
- In Chapter 2 is presented how the calculations of the energy and economic variables of the REC were carried out, the index used to establish the households at risk of energy poverty is developed, and finally, the algorithms developed to distribute the economic benefits among the members of the REC are presented.
- In Chapter 3 is presented the case study used to validate and investigate the algorithms developed in the previous section. In particular, the emerging Energy Community of Teglio will be analyzed, characterizing it from both the production and load side.
- In Chapter 4 the results of the simulations conducted are presented. In particular, the current scenario of Teglio will be analyzed, an optimum in terms of power installed will be found, and all the algorithms developed will be applied and compared. A sensitivity analysis of the number of energy-poor users belonging to the Energy Community is also conducted in order to assess how the community's balance changes.
- In Chapter 6 the conclusions of this work and its possible future developments are presented.

1 | State of art and literature review

1.1. Renewables Energy Communities

Over the past 50 years, the world has been experiencing dramatic climate change, and one of the main causes is an increase in greenhouse gas emissions, many of which are human-produced. The latest report from the IEA (International Energy Agency) shows a further increase in emissions in 2022 of 321 Mt of CO_2 more than the previous year, 60 Mt attributable to cooling and heating demand in extreme climate zones, and 55 Mt to the shutdown of nuclear power plants. To decelerate and possibly reverse this trend, strong environmental policies have been implemented in many countries [28].

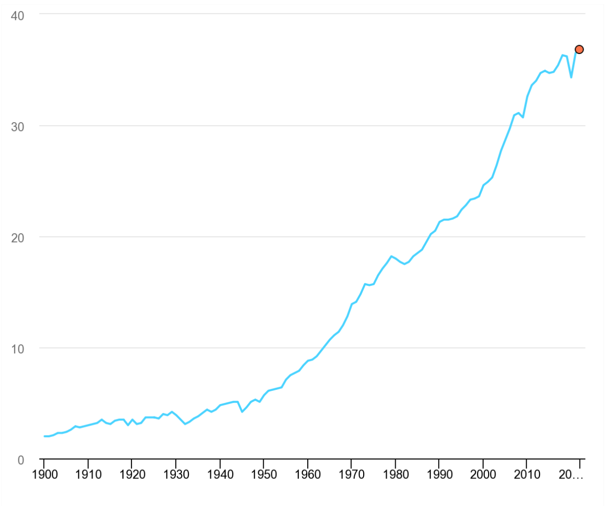


Figure 1.1: Global CO2 emissions in Gigatons from energy combustion and industrial processes, 1900-2022 [28].

The Conference of the Parties (COP) consisting of 196 countries on December 12, 2015, signed the Paris Agreement. The agreement requires that all signatory countries commit to containing global warming to within 2°C from the pre-industrial level and at least 1.5°C through zero greenhouse gas emission to be achieved by 2050.

The European Union has always been very attentive to environmental issues, especially in the energy sector; in fact, it was in 2001 that the first renewable energy directive, 2001/77/EC, was issued. After the Paris Agreement, Europe has chosen independently to develop its environmental policies in order to reach the 2050 target, setting intermediate steps that are increasingly challenging.

With the European Green Deal, Europe is committed to achieving at least a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 and has put in place a series of legislative proposals through the "FIT for 55" climate package. Included among the proposals there is a focus on the energy sector and more specifically a proposal to revise the Renewable Energy Directive (RED II). The proposal calls for an increase in the energy contribution from renewable sources from 32% to 40%, with mandatory minimum targets in Member State's gross final consumption.

Italy like other countries will play its role and through the National Climate and Environment Plan (PNIEC) it plans to cover 30% of total consumption from renewable sources. The target is very ambitious as it should result in a high average annual installation of wind and photovoltaic power of 3200 MW and 3800 MW respectively. From Figure 1.2, it can be seen that more than 70% of the capacity (75 GW) will be represented by solar, 53 GW attributable to utility-scale installations and 21.5 GW come from distributed PV installations [42].

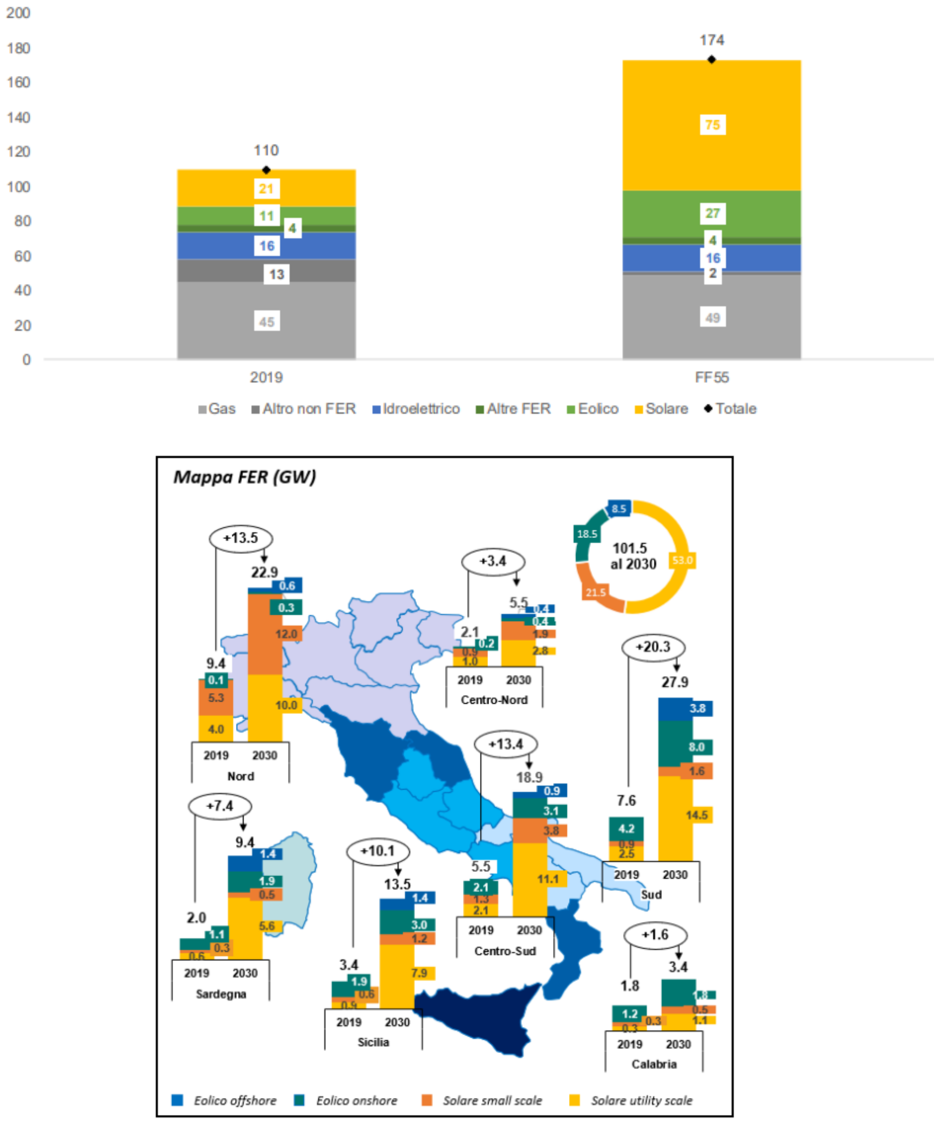


Figure 1.2: Evolution of installed capacity: current state and predictions for 2030.

Distributed installations thus constitute a not negligible percentage of the solar power to be achieved, so the contribution that individual citizens will make is also very important. To support and direct this process, the European Commission has created a new instrument: the Energy Communities

1.1.1. The European framework

The term Energy Community appears for the first time within the Clean Energy Package (CEP). The CEP was launched in 2019 and consists of eight Directives governing energy issues, including energy performance of buildings, energy efficiency, renewable energy, electricity market framework, security of electricity supply, and governance rules for the Energy Union. The Directives are reported in Figure 1.3.

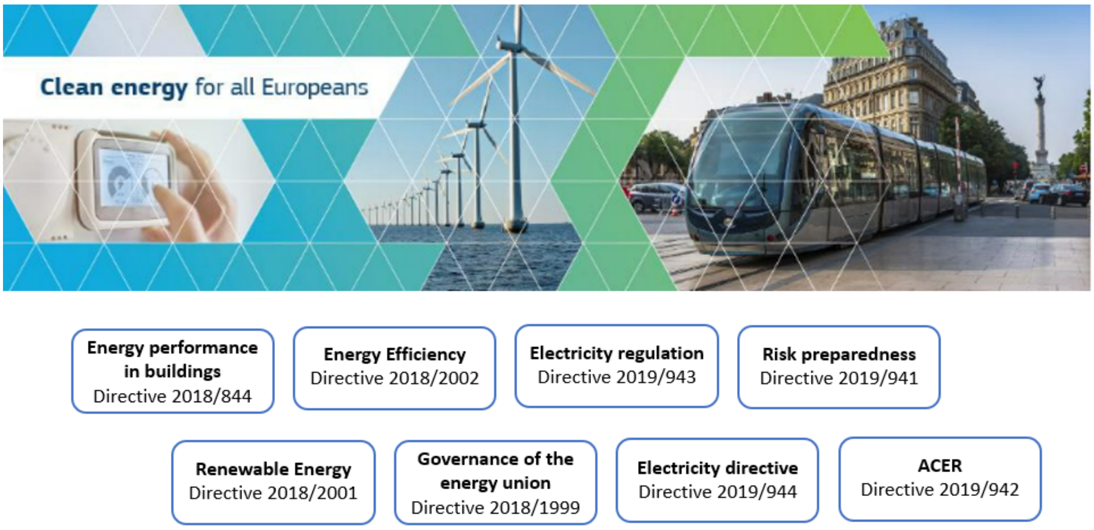


Figure 1.3: Clean Energy Package and the new 8 laws.

There are two legislative acts dealing with the topic of Energy Communities:

- the Renewable Energy Directive 2018/2001, which entered into force on December 24, 2018, and transposed into national law by the Member States by June 30, 2021[14];
- the Electricity Directive 2019/944, which entered into force on June 5, 2019, and transposed into national law by member states by December 31, 2020[19].

Directive 2018/2001 is also known as RED II, and in addition to setting the target on the percentage of generation from renewable energy (32% by 2030), it gives us three important definitions of self-consumption:

- "**Renewables self-consumer** means a final customer operating within its premises located within confined boundaries who generate renewable electricity for its consumption, and who may store or sell self-generated renewable electricity, provided that, for a nonhousehold renewables self-consumer, those activities do not constitute its primary commercial or professional activity".
- "**Jointly acting renewables self-consumers** means a group of at least two jointly acting renewables self-consumers located in the same building or multi-apartment block".

- "**Renewable energy community (REC)** means a legal entity that is based on open and voluntary participation. It is autonomous and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity. The shareholders or members of which are natural persons, SMEs, or local authorities, including municipalities. The primary purpose of which is to provide environmental, economic, or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits" [14].

Energy Communities are thus a new innovation, a new way to increase the use of renewable energy. Central to the EU's definition is the fact that energy communities are accessible to all consumers, including those on low incomes or living in vulnerable housing. All citizens have the opportunity to use clean energy, even if they do not own their plant or live in a building that has a facility. It is important to underline that final customers, in particular household customers, are entitled to participate in a renewable energy community while maintaining their rights or obligations as final customers.

Instead, in Directive 2019/944, EMD II, there is the definition of the citizens energy community (CEC):

- "**Citizen energy community** means a legal entity that is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises. Its primary purpose is to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits. It may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders" [19].

The two types of communities seem very similar, they describe a form of collective organization dealing with the energy sector, whose primary goal is to provide environmental, economic, or social benefits for its members, and finally both allow open and voluntary participation. However, there are some differences between the two communities. In CECs there is no restriction on electricity production to renewable sources only and they do not have geographical limitations. In addition, CECs can own or lease distribution networks and operate them independently.

1.1.2. The Italian framework

The EMD and RED II must be transposed and incorporated into their national laws by all Member States by the established dates. For Italy, this process can be divided into two different stages, the experimental phase where there is a partial transposition of RED II, and the "official" phase where there is a full transposition, which is still ongoing at this time. Figure 1.4 shows a summary diagram of the entire process.

Figure 1.4: Italian transposition scheme.

The early Italian transposition

Renewable Energy Communities are currently regulated by Article 42-bis of the "Milleproroghe" Decree 162/2019, converted by Law 8/2020, and by the following implementing measures: ARERA's Resolution 318/2020/R/eel and the Ministerial Decree of September 16, 2020, of the Ministry of Economic Development. This set of regulations constitutes the first phase, the experimental one, which gave rise to the first pilot energy communities.

Within Decree 162/2019 [24] we have the introduction to two new consumption-production schemes, Collective Self-Consumption (CSC) and Energy Communities (RECs). The goal is the investigation of the impact of these two new schemes from a regulatory, financial and social point of view. Collective self-consumption is defined as a group composed of different individuals located in the same condominium or building who self-consume renewable energy. RECs, on the other hand, are composed of individuals ,small or medium-sized enterprises, authorities and/or local authorities including municipal governments, subtended, however, by the same secondary substation. In both cases one is therefore within the low voltage.

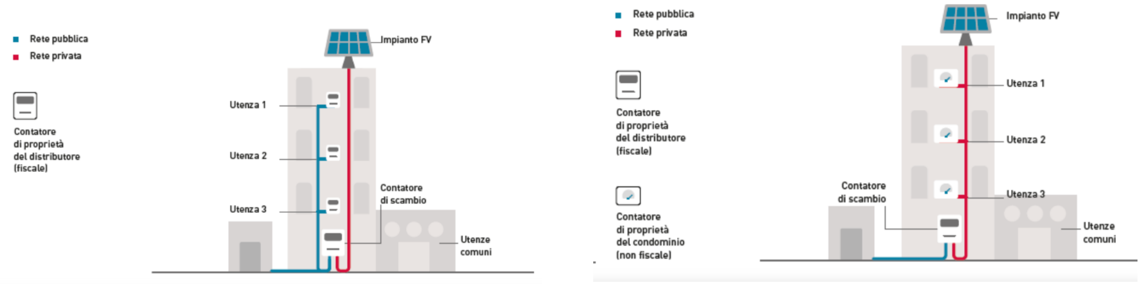
In addition to the geographic boundaries, which thus go to limit the entities that can join

CSCs and RECs, there is another limitation on the power of the plants. In fact, plants powered by renewable sources cannot exceed a total capacity of 200 kW and must have come into operation after March 1, 2020.

In both cases, moreover, the use of the existing distribution grid for energy sharing is included and the use of storage systems (BESS) is possible. Shared energy is defined on an hourly basis as the minimum between the total energy fed into the grid produced by renewable source plants and the total energy withdrawn from the grid. Thus, storage systems can be used but do not give benefits in increasing shared energy but only physical self-consumption, this is because they are not considered renewable source plants. The law also assigns ARERA and the Ministry of Economic Development (MISE) to define the regulatory model to be applied and shared energy incentive schemes, respectively.

On April 1, ARERA published Consultation Document 112/2020/R/eel [3] and subsequently Resolution 318/2020/R/eel [4] containing the transitional regulation model to be applied to CSC and REC schemes. Contained within the document there is an explanation of a new self-consumption scheme, called "virtual" to differentiate it from the "physical" one.

The virtual scheme, also known as the "extended perimeter" scheme, involves the use of the distribution grid for the exchange of energy between generating and consuming units. As we can see in Figure 1.5, there is no single POD for the entire apartment building, and the energy does not remain physically within the building's private grid, as is the physical self-consumption scheme. In this case, therefore, there is no need to make a single electricity supply contract; individual consumers retain their rights as final customers, including their choice of supplier.



(a) Virtual self-consumption scheme with connection on public grid between utilities and generation plant.

(b) Physical self-consumption scheme with private connection of utilities to the generation plant and single point of access to the public grid.

Figure 1.5: New Regulatory scheme.

ARERA also identifies a Shared Electricity Valuation Fee, consisting of two components:

1. a Monthly Self-Consumption Unit Charge (CU), given by the sum of the variable transmission components TRASe and the variable distribution component defined for utilities for other low-voltage uses BTAU, multiplied by the shared electricity to which must be added
2. a coefficient for avoided grid losses multiplied again by the shared electricity.

For Renewable Energy Communities, the subsidy takes into account only Unitary Charge and the components to be returned will be about 10 €/MWh for shared energy for collective self-consumption schemes and 8 €/MWh for shared energy of RECs.

To these components should be added the incentive provided by MISE in the September 16, 2020 decree [34]. The decree incentivizes shared energy by valuing it with two feed-in premium type incentives, which are then added to the market value of the energy:

- 100 €/MWh for Collective Self-Consumption schemes;
- 110 €/MWh for Renewable Energy Communities.

On December 22, 2020, GSE published the technical rules for the accreditation of RECs and CSCs systems.

Figure 1.6 shows the 15 pilot projects on collective self-consumption schemes and Energy Communities selected in collaboration with the RSE that emerged from these early regulations.

Figure 1.6: RSE pilot projects on collective self-consumption schemes and Renewable Energy Communities [41].

The final transposition

The final and complete transposition of both the two European Directives started in November 2021 with the issue of two Decree-Law: 199/21 and 210/21.

The two decree-law[37] introduce many changes regarding energy communities compared to the previous one:

- The enlargement of the perimeter by moving from MV/LV transformer substations to HV/MV, primary substations. This increase in the area allows for the construction of facilities of a larger size that can meet the energy needs of a community and not just a few households.
- Also in response to the expansion of the geographical area, renewable energy plants with a capacity of no more than 1 MW, instead of 200 kW, are eligible for the incentive. However, the incentive is only paid with reference to the share of energy shared by plants and consumer utilities connected under the same primary substation.
- There is the possibility of participation of existing plants, always of renewable electricity production, to an extent not exceeding 30% of the total power that belongs to the community.
- The REC can produce other forms of energy from renewable sources aimed at use by members and it can promote integrated home automation and energy efficiency interventions. It may also participate in generation, distribution, supply, consumption, aggregation, energy storage, energy efficiency services, or vehicle charging services.
- "Shared energy": in a renewable energy community or a group of self-consumers of renewable energy acting collectively, is equal to the minimum, in each hourly period, between the electricity produced and fed into the grid by renewable energy plants and the electricity withdrawn by all associated end customers located in the same market area. Only the renewable energy production of plants that are in the availability and under the control of the community is captured.

On December 15, 2021, Decree 199 came into force, and as a result, ARERA and MITE are required to update, respectively, the regulation and incentive mechanisms to be applied to CERs and Collective Self-Consumption schemes [25].

On December 27, 2022, ARERA approved the Integrated Text on Diffuse Self-Consumption (TIAD), which regulates the modalities for the valorisation of diffuse self-consumption for the configurations provided for in Decree-Laws 199/2021 and 210/2021.

There is a distinction of two different geographical perimeters in the document: the market zone and the zone underlying the same primary substation. The market zone identifies the area over which shared energy is measured on an hourly basis while the primary substation zone identifies the self-consumed energy subject to valorization. The latter is subject to higher valorization because it takes into account the electricity grid operating costs avoided as a result of geographical proximity producer - consumer.

Currently, a map of the Italian territory is already available on E-distribuzione's website, which identifies all conventional geographical areas corresponding to the primary areas under its responsibility, approximately 89% of the total, as shown in Figure 1.7.

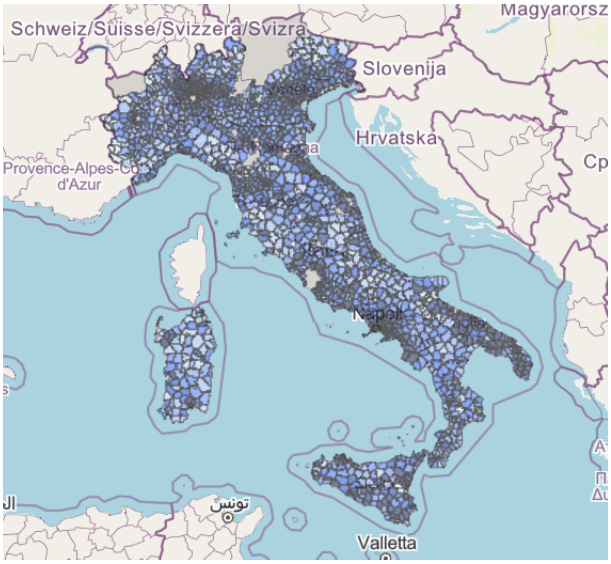


Figure 1.7: Conventional geographical area for primary substations.

A further change is also present for storage systems and the calculation of shared energy. In contrast to Resolution 318/2020/R/eel, which did not take into account self-consumed energy through storage, as the system was not considered a renewable energy system. The solution proposed by ARERA is to consider this energy with a conventional charge and discharge efficiency. The shared energy will then be calculated as a minimum, on an hourly basis, between the sum of the energy fed into the grid and produced by the renewable plants and the sum of the energy withdrawn by the end users with the absolute value of the energy withdrawn by the storage plant or the subsequent feed-in multiplied by its charge/discharge efficiency.

The Ministry of Environment and Energy Security (MASE) should publish a ministerial decree to establish the incentives and thus conclude the process. Currently only a draft of the decree is available [33], and the Tables 1.1 and 1.2 show the calculation of the premium tariff to be applied to the shared energy that can be incentivized.

	BIG PLANTS	MEDIUM PLANTS	SMALL PLANTS
Peak power	>600 kW	>200 kW and <600 kW	<200 kW
TIP	60+max(0; 180-Pz)	70+max(0; 180-Pz)	80+max(0; 180-Pz)
Maximum tariff	100 €/MWh	110 €/MWh	120 €/MWh

Table 1.1: Calculation of the premium tariff to be applied to incentivized shared energy.

Geographical Area	Correction factor
Central Regions (Lazio, Marche, Toscana, Umbria, Abruzzo)	+ 4 €/MWh
Northern Regions (Emilia-Romagna, Friuli-Venezia-Giulia, Liguria, Lombardia, Piemonte, Trentino-Alto Adige, Valle d'Aosta, Veneto)	+10 €/MWh

Table 1.2: Tariff correction for photovoltaic systems.

1.1.3. Key features of Energy Communities

In addition to renewable energy production facilities, the Energy Community can adopt new technologies to facilitate consumption monitoring and help community users save, in an efficient way. Among the most important technologies might be found storage systems and the "smart meter". Storage systems accumulate electricity when there is an excess of production over consumption and release it when production fails to fully cover the load. It is a benefit to both "prosumers" and the power grid, and they are very important when generation comes from non-programmable sources such as solar or wind. The use of batteries is therefore a recommended investment when you have large-scale renewable source installations as might be the case of Energy Communities and they also increase shared energy.

Instead, the "smart meter" is a meter that enables energy efficiency strategies to be implemented. In fact, smart metering and monitoring of consumption data are indispensable not only for utilities that distribute energy and gas, but also for consumers to be more aware of consumption and waste and, consequently, active in improving their efficiency and habits. In the case of the Energy Communities, it would help consumers align with plant production, plus the data collected can be sent via an energy box to an aggregation Cloud platform, which stores it in a database for later use for analysis and processing.

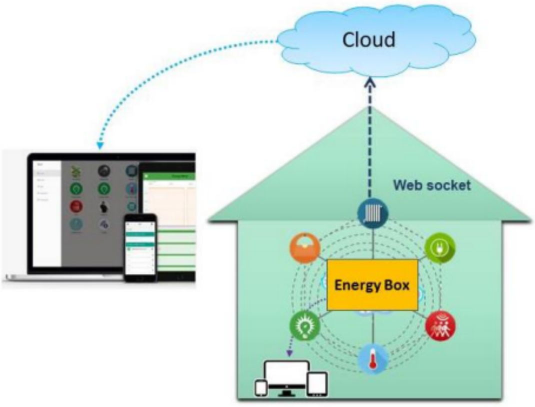


Figure 1.8: Scheme of energy box and cloud platform interaction [7].

Besides the opportunity to implement new technologies, there are many benefits associated with an energy community for both domestic and commercial, and industrial users. As it was analyzed in the previous paragraphs, 1.1.1 and 1.1.2, self-consumption is the ability to consume electricity produced by renewable source plants to cover domestic needs, this brings a number of economic and environmental benefits:

- Savings in utility bills, both through a reduction in variable components of the bill and the ministerial incentive on shared energy;
- Valorization of the energy produced, the energy produced in excess can be sold through the incentive mechanisms “Scambio sul Posto” and “Ritiro Dedicato”;
- Tax benefits, with the installation of a photovoltaic system it is possible, in fact, to deduct from IRPEF 50% of the construction costs;
- Reduced environmental impact since the energy produced is from a renewable source and therefore allows a large reduction in greenhouse gas emissions such as CO_2.

These benefits are related to physical self-consumption, however, it is not always possible to consume all the energy produced, which is precisely why collective self-consumption could be useful. With the Energy Community, excess production is pooled, allowing other users to use it while reducing transportation costs and energy lost on the grid. The prosumer benefits seen above would then be extended to users who do not have their own system, and this could be a great advantage for economically vulnerable individuals.

1.2. Demand-side management

In an Energy Community, there is both the load side and the production side, both of which are crucial for the success of the project. In particular, the match between demand and production is important. Consuming during production hours, the central hours in the case of photovoltaic systems leads to more self-consumption and more shared energy, which translates into higher earnings for the REC.

This concept was already known before RECs, when the figure of the prosumer, i.e. a user who is both producer and consumer, began to diffuse. Self-consumption not only benefits the prosumer but also the grid operator. The spread of so many distributed small-scale renewable resource plants means that production is intermittent and non-programmable, which can create problems for the grid in terms of frequency regulation, the ability to rapidly start and ramp the remaining electric power generation and exceed voltage limits. Such drawbacks can partly be solved by increased self-consumption of the distributed generation.

The definition given to self-consumption is important, in the study conducted by R. Hander et al. [27], two types of metrics are defined. Figure 1.9 shows the production profile of a photovoltaic system, area B, and the electricity demand profile, area A. The overlap of the two areas is called area C and is the energy directly consumed at the instant it is produced, or properly called absolute self-consumption. However, there are other ways of quantifying how 'virtuous' a user is, for example, two other indicators are defined:

$$Self - Consumption = \frac{C}{B + C} \tag{1.1}$$

$$Self - Sufficiency = \frac{C}{A + C} \tag{1.2}$$

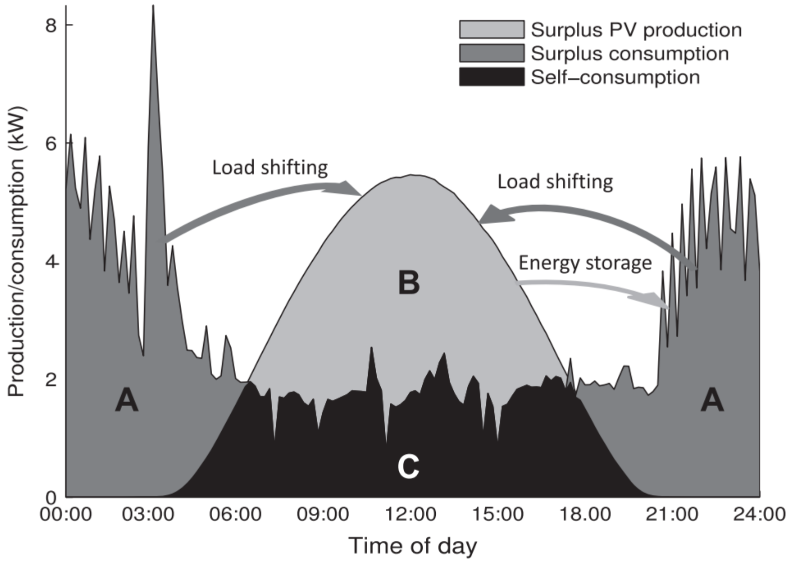


Figure 1.9: Schematic outline of daily net load (A + C), net generation (B + C) and absolute self-consumption (C) in a building with on-site PV [27].

Self-consumption is defined relative to total production, i.e. what percentage of the energy produced is consumed on-site. Self-sufficiency, on the other hand, is defined relative to load, indicating the degree to which the on-site generation is sufficient to fill the energy needs of the building.

To increase these two indicators, action can be taken on several fronts, the main ones being through the use of storage systems, which then allow the energy produced to be stored for use at a later date, or through demand side management(DSM). The two systems can also be coupled.

DMS is defined as the modification of energy demand by consumers, this can be done mainly either by reducing demand or by shifting part of the load during peak production hours, for example, washing machines and heating, ventilation, and air-conditioning (HVAC) systems. Load shifting can either be achieved manually, where persons switch on electric devices when the sun is shining, or automatically, which requires control algorithms and devices, and sometimes also weather forecasts of ambient temperature and solar irradiation.

The contribution and involvement of individual users is therefore very important, and can benefit both individuals in the case of prosumers and the entire group of people in the Energy Community.

1.3. Energy Poverty

As it has just been analyzed, Europe and Italy are moving toward a policy of decreasing emissions, lowering consumption, making energy efficient, and, above all, producing clean energy through the installation of renewable energy production facilities. This energy transition will put upward pressure on energy prices, especially that of electricity, which is considered the main energy carrier. The already ongoing COVID-19 crisis along with the Russian invasion of Ukraine in 2022 have also contributed to a general worsening of poverty for all European citizens. This together with rising energy prices will lead to a greater risk of energy poverty, especially in the most vulnerable portions of the population, and greater difficulty for lawmakers to implement environmental policies. In the following sections, the concept of energy poverty and the main policies adopted to combat it will be explored in more detail.

1.3.1. Definition and main indexes to measure the energy poverty

Household energy poverty (PE) is understood as the inability to purchase a minimum unit of energy goods and services [21]. The three main causes according to the Energy Poverty Advisory Hub (EPAH) [13] are: low income, low household energy efficiency and energy performance of buildings, and high energy prices. Therefore, in addition to a financially precarious situation, the type of building in which people live is also important, low energy class buildings impose very high energy expenses to heat them adequately, or to avoid this they force inhabitants to reduce their consumption by lowering, for example, the heating, with a consequent negative impact on people's health. This phenomenon is a specific case of energy poverty and many studies in literature call it “hidden energy poverty” [8]. However, the phenomenon is very complex and often the result of a combination of different factors, which is why in Europe and Italy there is still no official definition of energy poverty and an indicator to be able to measure it. The literature has several indices that try to quantify the phenomenon, each of them very different from the others. It should be emphasized that the choice of index greatly influences the result and statistics, this is because each of them focuses only on one or a few sides of the phenomenon.

The first distinction can be made between two macro families, indices based on subjective and objective measures. The last ones, in turn, can be divided into absolute measurements, when the criterion does not depend on the conditions of other families but for example on the identification of essential conditions, or relative, when instead the situation of one family is compared to others.

The most used subjective indices are:

1. the share of the population declaring the inability to heat the house adequately;
2. the share of the population declaring late payment of bills.

This type of index, as it is defined, also takes into account the individual preferences of households, so it is very easy for statistical campaign measurements to lead to results that are far from the actual situation.

Objective indices, on the other hand, are based on spending and income. One of the earliest indices, developed in the United Kingdom in 2001, compared the percentage of energy expenditure to total household income with a ceiling value. In particular, it identified in poverty households those who had energy expenditure that corresponded to more than 10% of total income [21]. The main shortcoming of this measurement was the fixed comparison value of 10%, a value found empirically for the United Kingdom data. The research, therefore, progressed on searching for indices that took into account a central tendency index, more easily generalizable to all the European countries.

The most important indices are:

1. incidence of energy expenditure on income greater than twice the average value (2M);
2. incidence of energy expenditure in absolute terms less than half the median value (2/M);
3. the coexistence of low-income and above-average energy expenditure, Low Income and High Cost (LIHC)

As mentioned earlier there isn't an approach better than the others one, all indicators have advantages and disadvantages under different characteristics.

The first indicator, 2M, takes into account the percentage of energy expenses in the household's income and is a relative indicator, as it varies as the situation of the reference population varies. Below there is a mathematical representation of it.

$$\frac{1}{n}\sum_{i=1}^{n} w_i I\left[\frac{s_{e,i}}{Y_i} > 2\left(\frac{\sum_{i=1}^{n} s_{e,i}}{\sum_{i=1}^{n} Y_i}\right)\right] \tag{1.3}$$

where n is the number of households in the sample, w_i is the weight of it (n of individuals per household), I is a function that returns the value 1 in case the condition is verified otherwise 0, $s_{e,i}$ is the energy expenses and Y_i is the total income of the household.

However, this statistic implies that the indicator is compared to a single national threshold value, not taking into account differences by climate zone, number of household members, or other factors. An advantage, however, is that the index is very simple to be understood and thus has high communicative effectiveness, income-based indicators also are easier to implement at the policy level, since declared income is often used for tax purposes or its reworkings (in Italy ISEE).

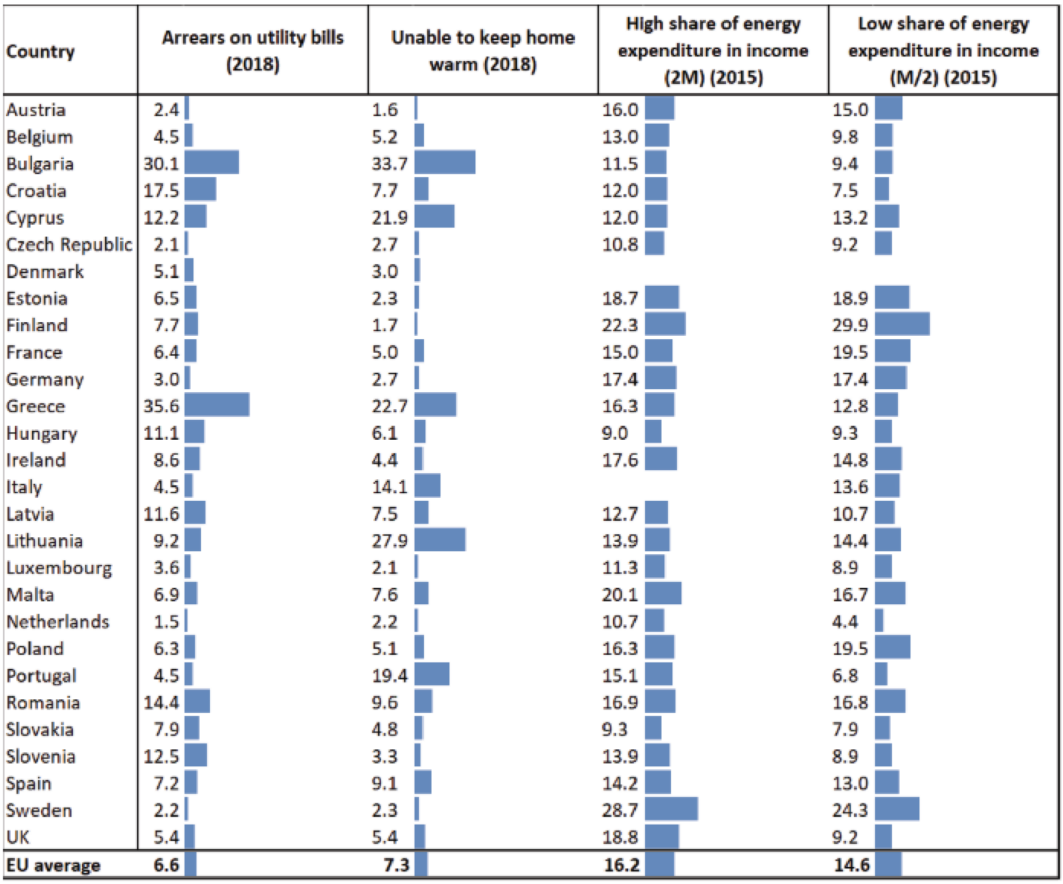
Using this index incurs the risk of neglecting households that decide to lower their energy expenses because they are unable to sustain them, and instead considering households with high incomes but who engage in non-virtuous energy-saving behavior. Because it is relative it does not take into account the actual hardship of households so comparisons between different countries are not simple, rich countries like Sweden might have a higher percentage in relative terms than poorer countries like Hungary [43].

The M/2 indicator is an absolute indicator, it uses the absolute energy expenditure of the household and compares it with the median national value ,$P50(s_{e,i}$, thus aiming to identify under-consumption.

$$\frac{1}{n}\sum_{i=1}^{n} w_i I\left(s_{e,i} < P50(s_{e,i})\right) \tag{1.4}$$

The results of the statistic may indicate a problematic situation, but there may be alternative explanations for low energy consumption. In many situations, for example, energy expenses are included in the rent of the dwelling and are not evalueted, moreover, energy consumption is low in buildings with a high energy class, in these two situations, the family is not necessarily in a state of energy poverty. The index, however, is simple and easy to implement and can be used to compare with other national estimates.

The third report [9] of the European Energy Poverty Observatory (EPOV) compares these first four indicators, the two subjective and the two indices, through a table where the results are given in percentage values of the population at risk of energy poverty for each European country.



Country	Arrears on utility bills (2018)	Unable to keep home warm (2018)	High share of energy expenditure in income (2M) (2015)	Low share of energy expenditure in income (M/2) (2015)
Austria	2.4	1.6	16.0	15.0
Belgium	4.5	5.2	13.0	9.8
Bulgaria	30.1	33.7	11.5	9.4
Croatia	17.5	7.7	12.0	7.5
Cyprus	12.2	21.9	12.0	13.2
Czech Republic	2.1	2.7	10.8	9.2
Denmark	5.1	3.0		
Estonia	6.5	2.3	18.7	18.9
Finland	7.7	1.7	22.3	29.9
France	6.4	5.0	15.0	19.5
Germany	3.0	2.7	17.4	17.4
Greece	35.6	22.7	16.3	12.8
Hungary	11.1	6.1	9.0	9.3
Ireland	8.6	4.4	17.6	14.8
Italy	4.5	14.1		13.6
Latvia	11.6	7.5	12.7	10.7
Lithuania	9.2	27.9	13.9	14.4
Luxembourg	3.6	2.1	11.3	8.9
Malta	6.9	7.6	20.1	16.7
Netherlands	1.5	2.2	10.7	4.4
Poland	6.3	5.1	16.3	19.5
Portugal	4.5	19.4	15.1	6.8
Romania	14.4	9.6	16.9	16.8
Slovakia	7.9	4.8	9.3	7.9
Slovenia	12.5	3.3	13.9	8.9
Spain	7.2	9.1	14.2	13.0
Sweden	2.2	2.3	28.7	24.3
UK	5.4	5.4	18.8	9.2
EU average	**6.6**	**7.3**	**16.2**	**14.6**

Figure 1.10: National energy poverty indexes for EPOV [9].

The table shows that depending on which indicator is used, there is a more or less severe situation, thus highlighting the great difficulty in finding a single indicator that captures this complex phenomenon. In spatial terms, the two consensus indexes show a critical situation for Eastern, Central, and Southern Europe, particularly Bulgaria and Greece, which is not evidenced by the expenditure indexes. In contrast, the expenditure indexes indicate a more critical situation in Northern Europe and Scandinavian countries.

The last indicator is the LIHC, proposed by the United Kingdom in 2011 [21]. This indicator stems from the need to surpass the previous ones and thus not to make the mistake of including within the estimate households that do not have a situation of vulnerability. Therefore, a family in energy poverty is defined as a family with low income and high expenditure, thus there is the occurrence of two conditions simultaneously. The indicator is thus considered to be of better quality but with an additional degree of complexity and difficulty in obtaining the necessary data. The mathematical formula summarizing the index is given :

$$\frac{1}{n}\sum_{i=1}^{n} w_i \left\{ I\left[s_{e,i} > P50(s_{e,i})\right] * I\left[(Y_i - s_{e,i}) < y^*\right]\right\} \tag{1.5}$$

where y^* is a threshold value of a household at risk of poverty according to EUROSTAT, different for each Member State[21].

Building on this indicator, economists Faiella and Lavecchia have developed an even more comprehensive index that attempts to consider not only the phenomenon of energy poverty but also that of hidden energy poverty. The latter differs from the former because it is more complex to detect, vulnerable people voluntarily decide to decrease or zero their energy consumption to decrease the burden of expenses [8]. The energy expenses of these households will therefore be very low and for this reason, it will not be possible to identify them through the LIHC index. According to Faiella and Lavecchia [21], the LIHC index should be modified according to this new formula:

$$\frac{1}{n}\sum_{i=1}^{n} w_i I \left\{ I\left[\frac{s_{e,i}}{S_i} > 2\left(\frac{\sum_{i=1}^{n} s_{e,i}}{\sum_{i=1}^{n} S_i}\right)\right] * I\left[(S_i - s_{e,i}) < S^*\right] \cup \left[I\left(s_i^r = 0\right) * I\left(S_i < P50(S_i)\right)\right]\right\} \tag{1.6}$$

The index combines two different groups, the first requiring the simultaneous occurrence of two events:

- an incidence of energy expenditure about total household expenditures (S_i) greater than twice the average value of the sample;
- the subtraction of energy spending from total spending results below the threshold value S^* on which the official relative poverty measure is based.

The second group, on the other hand, requires the simultaneous occurrence of:

- zero energy expenditure on heating (s_i^*);
- and a total equivalent expenditure, which is then the sum of total household expenditures, below the national median value.

The proposed index is, among those analyzed, the most accurate, for this reason, it has been adopted by the Italian government as part of the national strategy of the PNIEC. It however requires numerous data to calculate it that are not always available if a high degree of discretization is required, e.g. a Municipal libel. It is also very complex to be formulated, and us has low communicative effectiveness.

1.3.2. Factors that influence energy poverty

It has been seen that different indices often give discordant results. The Italian situation does not show great differences as can be seen from the Figure 1.10 and the graph 1.11 that instead shows the results obtained using the Faiella-Lavecchia index. Energy poverty in 2020 in Italy ranges between 8% and 13% depending on the index that is considered.

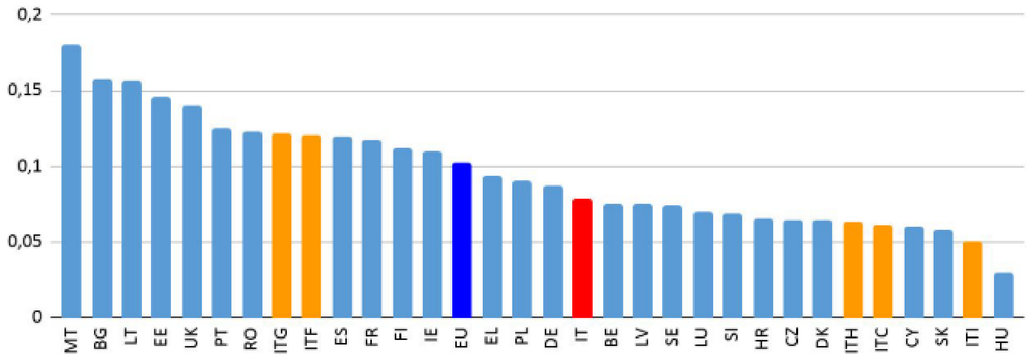
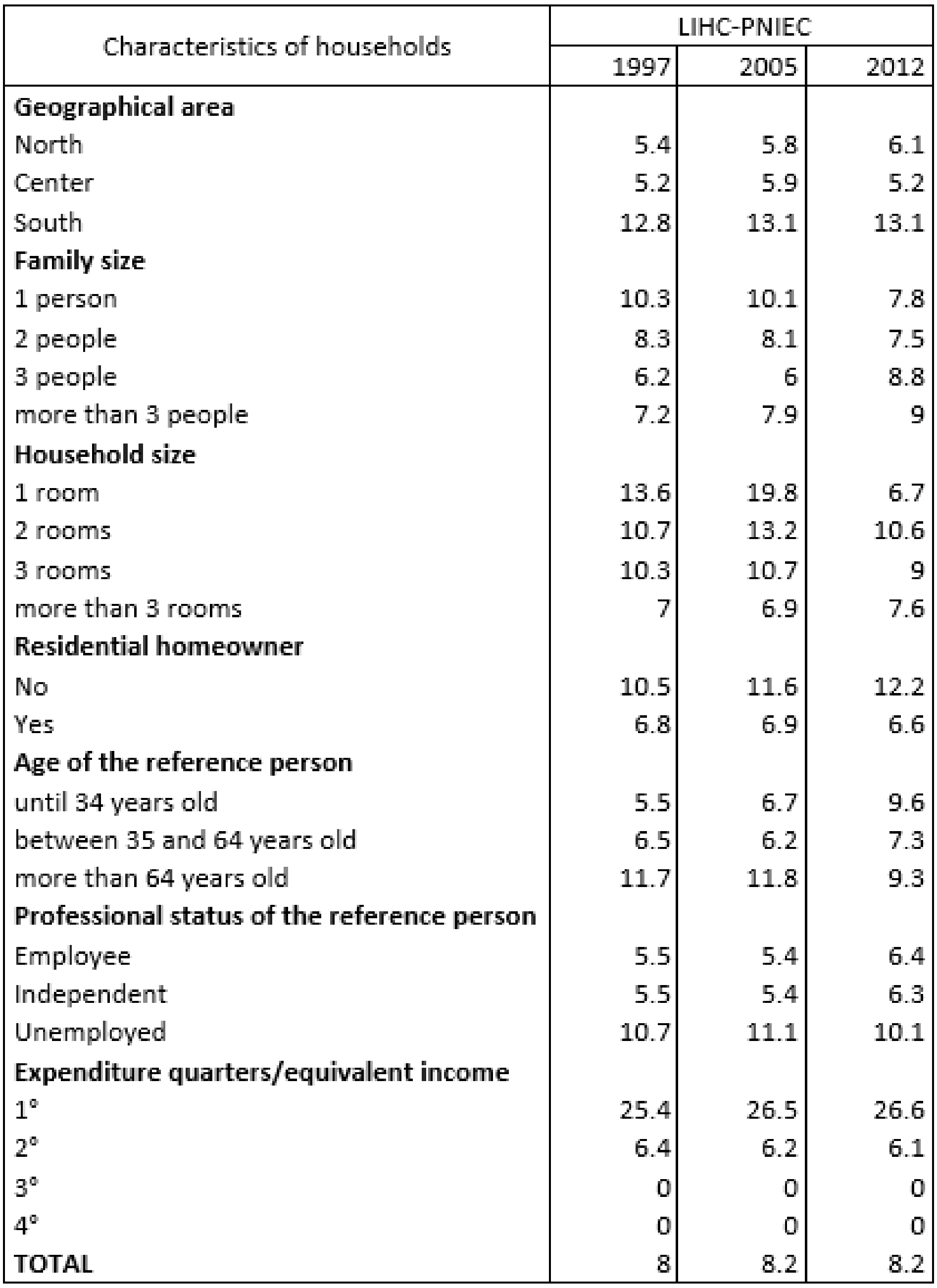


Figure 1.11: LIHC modified by Faiella-Lavecchia in Europe [23], note: ITH (North-East of Italy), ITC(North-West of Italy), ITI (center of Italy), ITF (South of Italy), ITG (Islands of Italy).

It is important to emphasize that the national indication is often not the result of a homogeneous situation on the territory, the Italian case is very telling. Figure 1.11 shows how the situation is more severe in the islands and the south of the Italian territory and less in the northern area.

In addition to the geographical factor and thus the climatic zone, other factors put certain families and individuals in a more vulnerable condition to energy poverty. From the Istat data, OIPE says that the risk of poverty is greater in the case where the main earner is unemployed or where the number of household members is high. Other variables, such as educational qualification, age, source of income, and gender show results in line with expectations, with higher energy poverty rates in the case of heads of households with low educational qualifications, non-EU nationality, single-parent households headed by women, and income types other than employed. Numerical results on risk rates in Italy are shown in the Table 1.12.



Characteristics of households	LIHC-PNIEC		
	1997	2005	2012
Geographical area			
North	5.4	5.8	6.1
Center	5.2	5.9	5.2
South	12.8	13.1	13.1
Family size			
1 person	10.3	10.1	7.8
2 people	8.3	8.1	7.5
3 people	6.2	6	8.8
more than 3 people	7.2	7.9	9
Household size			
1 room	13.6	19.8	6.7
2 rooms	10.7	13.2	10.6
3 rooms	10.3	10.7	9
more than 3 rooms	7	6.9	7.6
Residential homeowner			
No	10.5	11.6	12.2
Yes	6.8	6.9	6.6
Age of the reference person			
until 34 years old	5.5	6.7	9.6
between 35 and 64 years old	6.5	6.2	7.3
more than 64 years old	11.7	11.8	9.3
Professional status of the reference person			
Employee	5.5	5.4	6.4
Independent	5.5	5.4	6.3
Unemployed	10.7	11.1	10.1
Expenditure quarters/equivalent income			
1°	25.4	26.5	26.6
2°	6.4	6.2	6.1
3°	0	0	0
4°	0	0	0
TOTAL	8	8.2	8.2

Figure 1.12: Characteristics of Italian households in PE[21]

Other key variables to characterize the risk of energy poverty are related to the building, in particular, the period of construction, materials used, type of dwelling (single-family, small villas, condominium), title of occupancy of the property (rental/ownership), and finally, the type of municipality of residence (metropolitan city, suburbs, municipalities under and over 50,000 inhabitants).

The factors that therefore most influence the risk to fuel poverty can be summarized the diagram below.

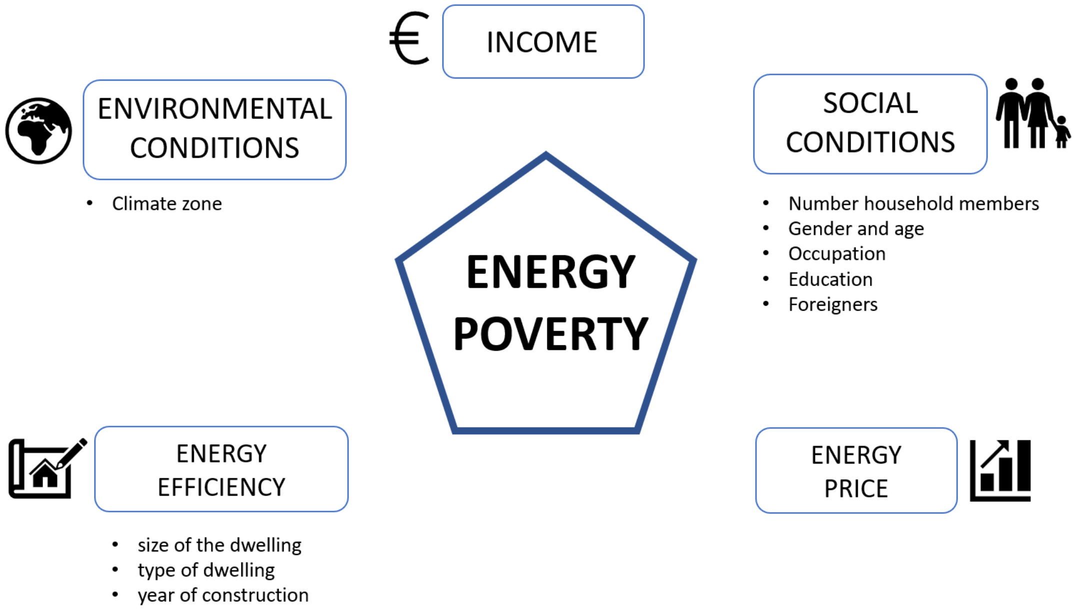


Figure 1.13: Main causes of Energy Poverty

1.3.3. The European context

In September 2015, the governments of 193 countries signed the 2030 Agenda for Sustainable Development, an action program consisting of 17 goals to be achieved by 2030 in the environmental, economic, social, and institutional spheres. These goals are developed in a larger program consisting of 169 targets, this section will look at what Europe is doing to achieve goal: T7.1 "ensure universal access to affordable, secure and modern energy services." [12]

To be able to achieve this goal, the European Union has made great efforts over the past decade to address energy poverty and protect the most vulnerable consumers, keeping the issue in mind in energy efficiency, decarbonization, and renewable energy policies aimed at the energy transition.

In 2020, the European Commission published a recommendation on energy poverty to support Member States. Within this document the importance of access to energy as an essential good is reiterated, therefore each State must evaluate the number of households in energy poverty and, in case the result is significant, adopt counteracting policies to be incorporated into their integrated climate and environment plan (NECPs). The appendix to the document provides some aggregate indicators developed by the Statistical Office of the European Union (EUROSTAT) and the European Energy Poverty Observatory that can be used to monitor the phenomenon, possibly supplemented with indicators developed by States. These include some of the indicators discussed in the previous section. The recommendation also promotes sharing best practices between EU countries and identifies the potential to access EU funding programs that prioritize measures targeting vulnerable groups [16].

Building on this document, specific measures are proposed in the "Fit for 55 packages" to identify the main risk factors of energy poverty. This European communication consists of a series of interconnected proposals, all geared toward the same goal: to ensure a fair, competitive, and green transition by 2030. Therefore, one of the central themes is a "socially equitable" transition, and for this reason, specific funding is provided for States to support those Europeans most affected or at risk of energy poverty such as the 72.2 billion Social Fund for the period 2025-2030. "Fit for 55 packages" also includes a proposal to revise the Energy Efficiency Directive to put more focus on reducing energy poverty and empowering consumers [17].

In October 2021 with the worsening COVID-19 crisis and rising energy prices, the European Commission published a new communication containing a package of intervention and support measures for Member States to mitigate the impact of recent events. In addition to short-term interventions, an overview is given of coordinated medium-term measures to ensure better preparation for gas price fluctuations and reduce the EU's dependence on fossil fuels. Immediate or short-term interventions include:

- "Provide time-limited compensation measures and direct support to energy-poor end-users including groups at risk, e.g., through vouchers or by covering parts of the energy bill, financed from the ETS revenues;
- put in place and/or maintain safeguards to avoid disconnections from the energy grid or defer payments temporarily;
- exchange best practices and coordinate measures through the Commission Energy poverty and vulnerable consumers coordination group;
- reduce taxation rates for vulnerable populations, in a time-limited and targeted way;
- consider shifting the financing of renewable support schemes away from levies to sources outside the electricity bill." [18]

Instead, long-term proposals to approach the problem include a focus on the need for a revision of the Energy Performance of Buildings Directive and support for the development of energy storage, adequate for both short- to medium-term future needs, such as batteries, and long-term needs, hydrogen [18].

Another initiative that is important to report is the Energy Poverty Advisory Hub (EPAH) which unlike EU Energy Poverty Observatory (EPOV) has a much more active role in targeting not just tracking the phenomenon. EPAH was formed in 2021, given the request of the European Parliament; it provides a space for collaboration and exchange for national and regional authorities to address energy poverty. Some of the tools provided are:

- EPAH-ATLAS, an online database of all projects and measures taken around the world that address energy poverty.
- Technical assistance to directly assist local governments to launch actions to address energy poverty. [15]

1.3.4. The Italian context

As seen in paragraph 1.3.3 the European Union encourages Member States to monitor energy poverty in their country and address it by including within their national plan measures to combat it.

In the case of Italy, within PNIEC there are disposes to the problem. The heterogeneity in the interventions reflects what has been analyzed so far: the causes of energy poverty are various and often very different from each other, so it is necessary to work on different fronts. These interventions can be divided into three categories: income support actions, energy expenditure reduction actions, and home energy efficiency actions. The first two types are “protection” policies and are short-term, they aim to provide relief to households, while the last is a “promotion” policy, which is long-term and aims at a structural improvement in the condition of fragile individuals.

As the analysis in section 1.3.2 shows, income poverty is strongly associated with energy poverty, consequently, income support actions can help to counter it. Among the most important actions are direct subsidies, provided to those with incomes below a certain threshold. This intervention by its nature is a tool for combating poverty in general, in fact, it provides additional resources for all consumption, including energy consumption. The risk is that the household benefiting from it will increase its expenses and consequently its energy consumption, thus not incentivizing virtuous behavior.

More focused instead on energy poverty are social tariffs and bonus payments. This type of policy aims to reduce energy spending alone by increasing the ability to spend on other goods and services, they will also not be encouraged to increase their consumption.

Gas and electricity bonuses originated in Italy in 2009 as the economic crisis deepened and energy tariffs rose due to higher oil prices. These measures provide a subsidy to be deducted directly from the bill for those who have an ISEE not exceeding 7500 euros (20000 for families with more than 3 children). Their value depends on family size and, in the case of gas, also on the climatic zone of the municipality of residence and corresponds to approximately between one and two monthly payments. Over the years the bonus has been updated by changing the ISEE threshold, in 2023 by 15000 euros, and simplifying the access procedure, since 2021 it is, in fact, automatic for all those who apply for the Dichiarazione Sostitutiva Unica (DSU) [6].

However, statistics from Banca d'Italia [21] show that these measures have had limited effectiveness in 2012; in fact, 83% of the families benefiting from the bonus are not PE families and only 13% of the families in energy poverty have benefited from the bonus. The limitations of social tariffs as a tool to combat PE could be due to two different factors: the limited scope of the bonus and the exclusiveness of the use of ISEE. The bonus, as it is currently structured, limits the payback to users connected to the gas grid, thus excluding all those households without a heating system and using a different source such as oil, wood, or biomass. Moreover, income alone cannot capture specific aspects of PE. In the future, therefore, it is not excluded that the requirements for access to subsidies will be modified perhaps through the use of an index specific to energy poverty.

Other types of discounts in energy consumption expenditures are represented by the elimination of interest for late bill payments, applied to users experiencing temporary vulnerable situations. This type of help is usually handled by the individual companies offering this type of service [22].

Analyzing long-term policies instead, one can find the ECOBONUS and the SUPER BONUS, incentives aimed at the energy requalification of homes. As seen in section 1.3.2 there is a strong link between individuals in energy poverty and low efficiency of residential buildings, the latter mainly due to their construction dated in the period before the first energy saving law (Law 373/76).

The ECOBONUS originated in 2006 with Law No. 296/2006 L. and provided a deduction from the gross tax of a share equal to 55 percent for energy upgrades in buildings and the installation of solar panels for hot water production. It then evolved going through several stages until 2019 to a 90% gross tax deduction for renovations of opaque vertical structures of exterior facades, and in 2020 the SUPER BONUS was introduced. It provides a 110% deduction of expenses incurred for the implementation of specific interventions aimed at energy efficiency and static consolidation or reduction of seismic risk of buildings. Facilitated interventions also include the installation of photovoltaic systems and infrastructure for charging electric vehicles [26]. Building efficiency could be a very important tool to alleviate energy poverty, especially if we look at public housing and cooperatives; however, the results of the effectiveness of this measure will be visible only in a few years.

Finally, it is pointed out that many users in PE reside in rented dwellings, and incentivizing their efficiency poses a great difficulty. The landlord in fact may collect insufficient rent to justify the investment in improvements, and at the same time, the tenant may anticipate a limited period of residence in the dwelling such that he or she may not bear the expense.

1.3.5. Mapping the risk of energy poverty

In the section 1.3.2 it was discussed that the factors influencing energy poverty are multiple: economic, demographic, geographic, and social. The absence of the development of a standard index to be able to measure it has driven to several studies adopting different strategies thus raising a problem of comparability. One of the possible uses of this index is the identification, within a territory, of the areas most at risk, so that it can be useful for politicians and legislators to have a real vision of their region and act consequently. In Italy, some universities and research groups have express an interest in the problem.

A study by Camboni, Corsini, Miniaci, and Valbonesi (2020) [10] reported in the latest OIPE report, proposed a method to be able to map the risk of energy poverty at the municipal level. Specifically, the proposed method combines socio-demographic and income information of households, obtained from ISTAT's SILC survey, with the Energy Performance Certificates (EPCs) of buildings in the municipality. These certificates characterize each dwelling by assessing their energy efficiency and allow the theoretical requirement needed to maintain the temperature inside the buildings that the legislature deems appropriate to be derived. From the theoretical demand, this then leads to the theoretical expenditure for each household.

The use of theoretical expenditure instead of actual expenditure has two major advantages, the first being that it does not fit into the individual preferences of households and it manages to highlight the problem of hidden energy poverty, when people voluntarily decide to lower their consumption to spend less [23].

Household energy certificates have been mandatory since 2009 for buying, selling, or renting property. They are a very useful tool for estimating heat demand because they contain information on the age of the building and the operating limit of domestic heating systems. In addition, they are collected consistently across all member states of the European Union.

Unfortunately, there is no single database containing all certificates of buildings in the Italian territory, and the information that can be collected is fragmented. Therefore, such an approach is applicable only to specific municipalities/provinces and not on a national scale. To overcome this problem, a research group of the Department of Energy at the Politecnico di Milano is proposing some possible solutions.

Initial work has been done as technical support for the Piano Regionale Energia Ambiente e Clima (PREAC) [40], a document approved by the Lombardy Regional Council in 2022 that indicates the path the region must follow to get to the 2050 European targets. The coefficient of risk to energy poverty that was developed is composed of three different coefficients multiplied by each other:

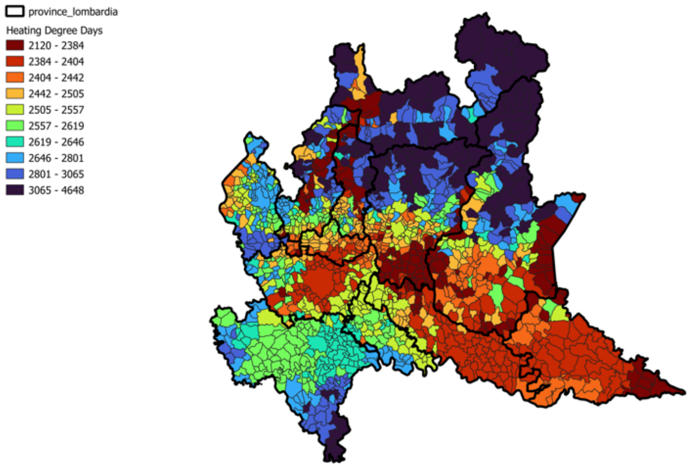
- Thermal coefficient is given by the ratio of municipal and regional thermal energy needs for both heating and cooling
- Economic coefficient obtained from the ratio of average municipal income to household spending on durable goods at the provincial level
- Internal areas coefficient (1.5 if internal area otherwise 0)

This index was constructed taking into account the data available for Lombardy, which is greater than for other Italian regions. For this reason, starting from the work done for Lombardy, the research group is currently developing a new indicator capable of mapping the entire Italian territory at the municipal level. The difficulty is to find a coefficient that uses data available on a national scale but with municipal precision. Therefore, the data used for this index were obtained from reworkings of the IRPEF, ISTAT, and ARERA databases.

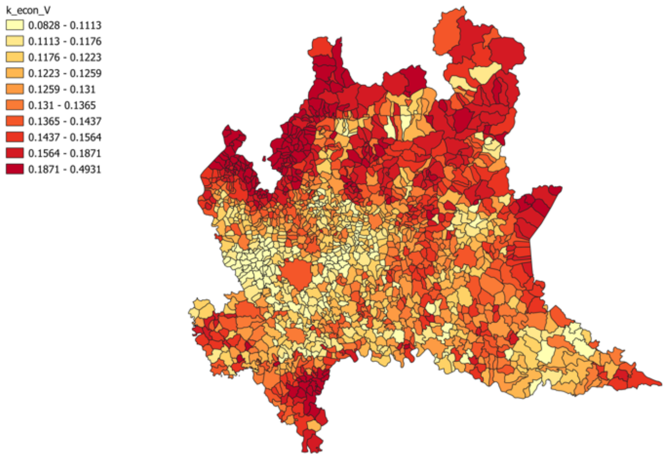
The new energy poverty risk coefficient is composed of:

- A thermal coefficient that depends on the heating degree days in the municipality
- An economic coefficient is given by the ratio of the percentage of individuals in poverty multiplied by the average expenditure on durable goods on a provincial scale and the average income of individuals in poverty

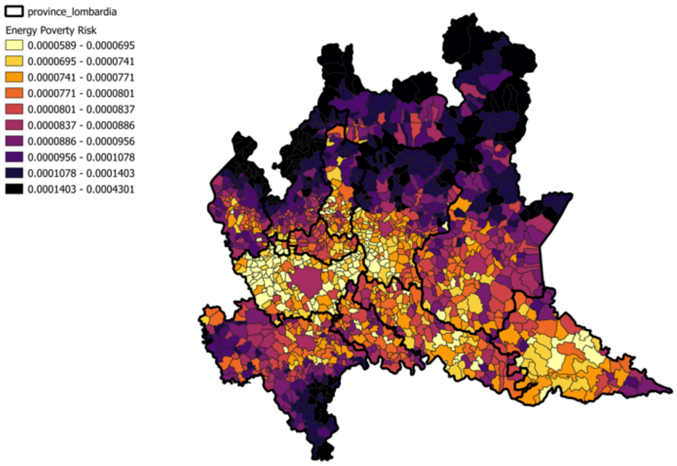
Below are the initial results, tested on Lombardy, using GIS software. The areas that are most at risk are mountainous areas with harsher climate and large cities with a higher cost of living.



(a) Heating Degree Days in Lombardy.



(b) Economic Coefficient in Lombardy

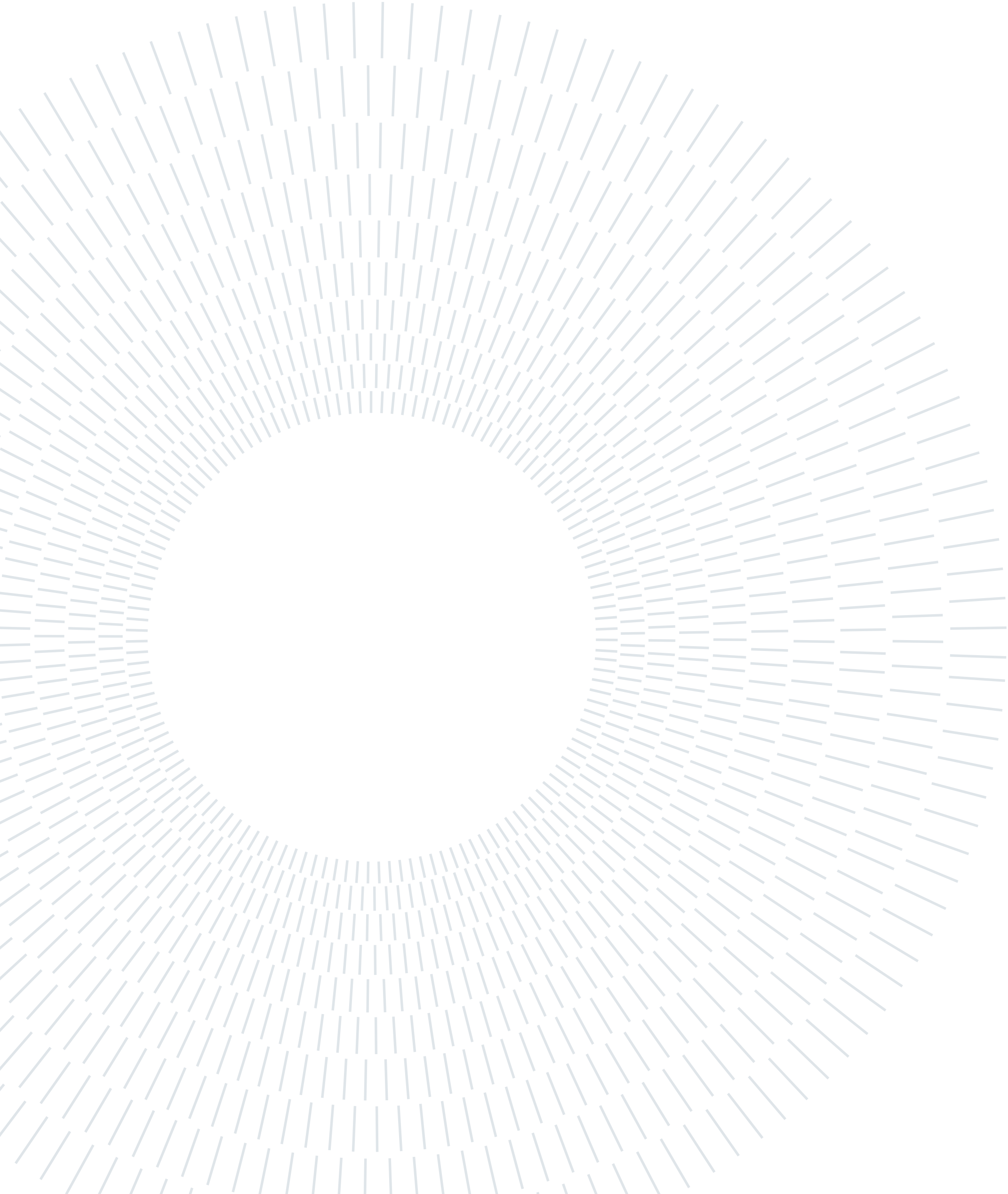


(c) Energy Poverty coefficient in Lombardy

Figure 1.14: Results of the energy poverty risk coefficient on Lombardy developed by Politecnico di Milano

The goal of the work is to determine which municipalities are most at risk of energy poverty to outline planning and prioritization of potential incentives and funds available. These incentives would go toward helping those municipalities considered to be at the greatest risk. One of the possible initiatives that could be implemented is the creation of Energy Communities, led by the municipality, involving individuals in energy poverty. These individuals would have the opportunity to use renewable energy without taking on the investment of the plant themselves and would achieve a reduction in energy bills, as seen in Section 1.1.3.

This approach can therefore be a useful energy poverty mitigation tool for the legislature, an alternative approach is instead to act internally to the Energy Community. In the following sections, a different scenario will be analyzed: the possibility of mitigating energy poverty within energy communities through the allocation of ministerial incentives provided to all RECs.



2 | Proposed methodology

2.1. Energy and economic flow calculation

In order to quantify the community's economic flows, being this the central topic of this thesis, it is necessary to calculate the energy flows and the main economic returns from which the community would benefit.

For this step, the goal was to adopt a general approach and thus easily adaptable to different Community configurations. Three inputs are needed to simulate the Energy Community: production profiles, load profiles, and generic REC characteristics. For such a goal, a Python tool has been developed, fed by Excel input files, so that they are easily compiled.

Energy production in Energy Communities can come from different renewable sources, wind, solar, and hydroelectric; in this analysis, only photovoltaic plants will be considered, which will most likely constitute the majority of plants in Energy Communities that will be created in Italy in the coming years nevertheless the proposed procedure could be adopted also for the other renewable sources. The photovoltaic production profiles are the same for all plants and are expressed per unit. An hourly production profile has been created for 6 different typical days, and each is associated with a frequency in terms of days in a year:

Day Type	Frequency	Period of the reference year 2021-2022
Winter work day (1)	65 days	29/11/2021 - 27/02/2022
Winter weekend (4)	26 days	
Summer work day (2)	65 days	30/05/2022 - 28/08/2022
Summer weekend (5)	26 days	
Mid seasons work day (3)	130 days	28/02/2022 - 29/05/2022 and 30/08/2021 - 28/11/2021
Mid seasons weekend (6)	52 days	

Table 2.1: Days type and their frequency.

The production is independent of the typical day, working or not, it only depends on the seasonality, the profiles are in fact two by two equal, summer, winter, and mid-season profiles. The difference between the profiles is due to the difference in irradiance in the respective seasons. The solar source is intermittent and non-programmable, therefore the use of only three possible profiles in a year is a considerable simplification that overestimates the production of electrical energy. In fact, cloudy, partly cloudy, or rainy days are frequent, especially during the winter and mid-season; on these days, the production decrease and in some cases drops to zero.

For this reason, it was decided to use a reductive coefficient that varies according to the Italian area where the REC is located. The factor is multiplied by the profile values, thus shifting the maximum value from 1. In this way, 6 simple production profiles are maintained and at the same time values close to reality are obtained in terms of annual production. The correction factors are shown in Table 2.2.

Italian zone	Reductive coefficient
North	0.7
Centre	0.8
South	0.9

Table 2.2: Reduction coefficient for the FV production profiles.

Figure 2.1 shows the profiles for northern Italy, which were later used for the case study.

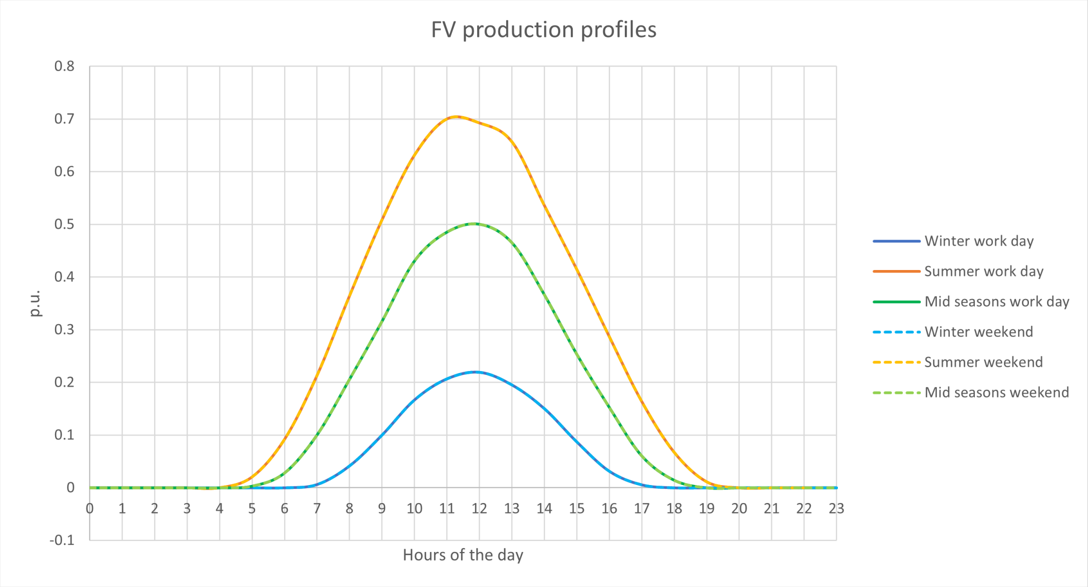


Figure 2.1: Photovoltaic production profiles for northern Italy.

According to production, the corresponding typical days are also present on the load side, but in this case, there will be more or less evident differences between the holiday and weekday profiles. Also for consumption, the profiles are expressed per unit.

In addition to the type of day, loads also vary according to their category; in fact, 6 different categories have been created so that each final user can be associated. The categories are:

- Old couple
- Young couple
- Family
- Office or School
- Small and medium-sized enterprise in the industrial sector
- Small and medium-sized enterprise in the tertiary sector

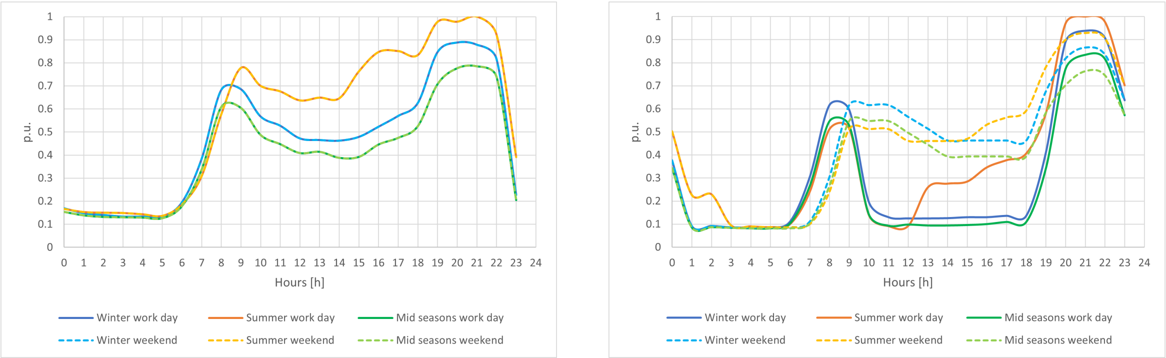
Profiles were constructed for each category through a reformulation of the profiles used in an earlier study by the Politecnico di Milano [44], to reproduce the frequent habits of that particular user. From Figure 2.2a, we can see that the old couple has few fluctuations during the day as they tend to spend most of their day at home, starting very early and ending it around 10-11 pm in the evening. It also does not vary its habits between the week and the weekend, and therefore the profiles overlap.

For the young couple, instead, it was assumed that they both worked outside the home, so there is a peak in consumption in the morning and then it almost goes to zero during the middle hours of the day to rise again in the evening after 6 p.m, Figure 2.2b. In this case the profiles between working day and weekend are very different, at the weekend consumption will most likely start later, remain more constant during the day and continue into the late evening.

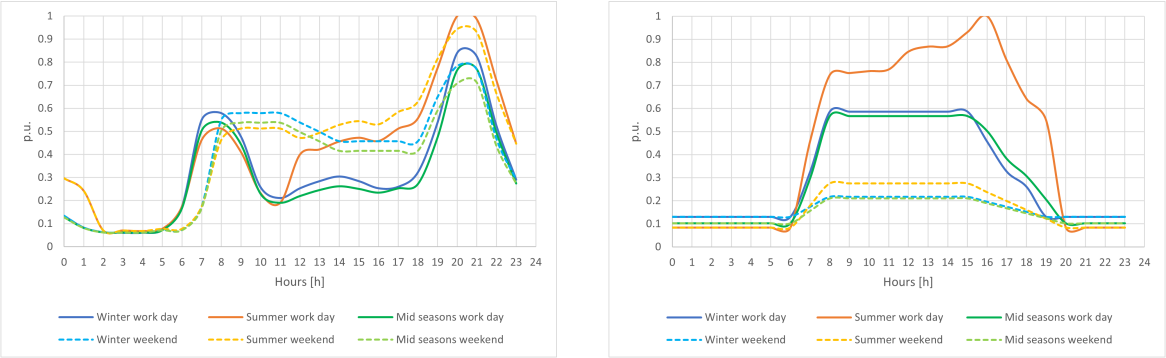
Regarding the family category, from Figure 2.2c, it has a profile somewhere between the two previously seen, there is a peak in the morning and a downward ramp after 8-9 a.m. as in the case of the young couple, but the load then rises again after lunch when some family members come home.

The non-residential profiles, on the other hand, include offices and SMEs. The office has a very constant profile growing very fast in the morning and decreasing more gradually in the second afternoon, Figure 2.2d. In contrast, the SME profiles are less constant. Two different cases were considered, the small industry and the shop or commercial activity, based on previous elaborations carried out by the Politecnico di Milano, Figures 2.2e and 2.2f. In both cases, the weekend load was lowered to approximately one-fifth of the working days.

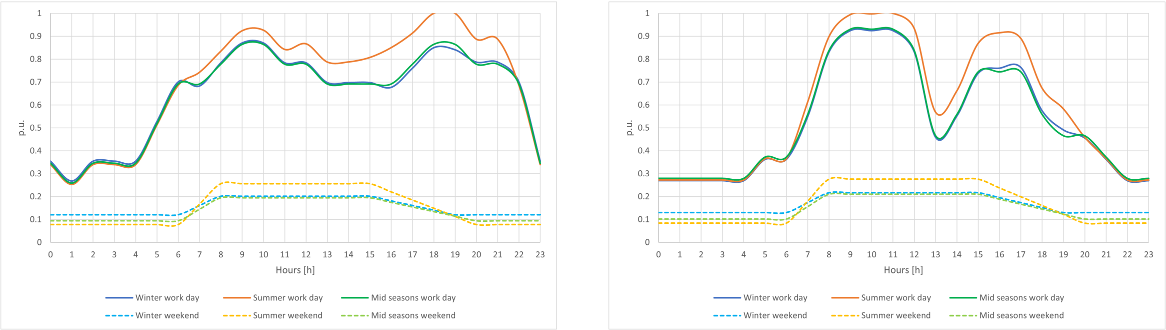
In all categories, both residential and non-residential, the load is higher in the summer period, reaching a peak value of 1, due to the use of cooling systems.



(a) Old couple load profiles (b) Young couple load profiles



(c) Family load profiles (d) Office and school load profiles



(e) Small and medium-sized enterprise in the industrial sector load profiles (f) Small and medium-sized enterprise in the tertiary sector

Figure 2.2: Load profiles for different categories of final users in different day types.

The last information needed for the calculation of energy flows is the Energy Community specification. The following information is included in the main file:

- REC contracted peak power [kW]
- Total peak power of photovoltaic plants [kW]
- Number of plants with direct connection to the grid: this type of system could be located on the ground or on a roof but not under a consumer
- Total peak power of plants with direct grid connection [kW].

For each user category, it is also possible to specify:

- Percentage which the category represents in relation to the total load
- Number of users
- Peak power per user [kW]
- Peak power of the photovoltaic plant under a specific user [kW]
- Capacity and power of the battery under a specific user [kW]

The information that can be entered is varied and thus allows different configurations to be analyzed, such as the presence or absence of batteries and the possibility of including plants not connected to a load.

A first distinction can be made between the types of installations. Self-consumption on site is zero for plants that have their own grid connection, all the energy produced is therefore fed into the grid. In contrast, in the case of plants connected to a single POD with a load, the first step is the self-consumption and then eventually feed-in.

A further difference is made between the configuration of a plant integrated with a battery and a plant without one.

Where there is no battery, the calculation which is made hour by hour, h, on each typical day, d, for each final user, i, is as follows:

$$Self\ Cons_{i,d,h} = \min(Load_{i,d,h}; Prod_{i,d,h}) \tag{2.1}$$

$$En\ Surplus_{i,d,h} = Prod_{i,d,h} - Self\ Cons_{i,d,h} \tag{2.2}$$

When a storage system is present, there are two possible modes of operation, the charging phase and the discharging phase of the battery. The charging phase occurs when the energy required by the load is less than the production, the available energy, *En available*, that can be used to charge the battery is therefore:

$$Self\ Cons_{i,d,h} = Load_{i,d,h} \tag{2.3}$$

$$En\ available_{i,d,h} = Prod_{i,d,h} - Load_{i,d,h} \tag{2.4}$$

However, the battery has limits given by the maximum power ($P\ max$), or equivalently the energy that can be exchanged in one hour, $En\ max$. The energy that will be effectively transferred to the battery, *En actual*, will therefore be:

$$En\ max = P\ max * 1\ h \tag{2.5}$$

$$En\ actual_{i,d,h} = \min(En\ max; En\ available_{i,d,h}) \tag{2.6}$$

The energy content of the battery is usually tracked by the state of charge expressed in terms of percentage, an increase in energy will lead to an increase in the state of charge:

$$SOC_{i,d,h+1} = \min(1; SOC_{i,d,h} + \frac{En\ actual_{i,d,h}}{En\ nom} \cdot \eta_{charge}) \tag{2.7}$$

As Equation 2.7 shows, a maximum SOC of 1 is imposed, which corresponds to 100%, the battery is therefore charged to the maximum and cannot contain any more energy. The energy content that will flow to the battery will be less than what was entered due to the efficiency η.

The efficiency of a battery depends on many factors: power, energy, temperature, humidity, current, voltage, and state of charge are some of the parameters. Only the most influential variables have been taken into account here: SOC and power. Efficiency is therefore calculated using Table 2.3 taken from previous studies [38]. A function was created that takes as input the initial state of charge and the power to be transferred, the closest efficiency value is returned from the table.

		SOC [%]				
		0	0.15	0.5	0.85	1
PgridAC [p.u.]	0	0.54	0.54	0.55	0.48	0.48
	0.05	0.54	0.54	0.55	0.48	0.48
	0.09	0.842	0.842	0.842	0.787	0.787
	0.18	0.818	0.818	0.931	0.896	0.896
	0.36	0.926	0.926	0.947	0.917	0.917
	0.54	0.895	0.895	0.931	0.927	0.927
	0.72	0.868	0.868	0.922	0.908	0.908
	0.9	0.861	0.861	0.896	0.859	0.859
	1	0.861	0.861	0.896	0.859	0.859

Table 2.3: Battery efficiency lookup table.

The surplus energy that is fed into the grid and made available to the community is finally:

$$En\ surplus_{i,d,h} = En\ available_{i,d,h} - (SOC_{i,d,h+1} - SOC_{i,d,h}) \cdot \frac{En\ nom}{\eta_{charge}} \tag{2.8}$$

In the discharge phase, on the other hand, the electrical energy required by the load is greater than the production, and therefore the battery acts if possible to cover this shortfall, the energy needed (*En needed*) to cover the entire load is:

$$En\ needed_{i,d,h} = Load_{i,d,h} - Prod_{i,d,h} \tag{2.9}$$

$$En\ actual_{i,d,h} = \max(En\ max; En\ needed_{i,d,h}) \tag{2.10}$$

$$SOC_{i,d,h+1} = \max(0; SOC_{i,d,h} - \frac{En\ actual_{i,d,h}}{En\ nom * \eta_{discharge}}) \tag{2.11}$$

In this case, a minimum SOC is imposed instead, the battery may not discharge beyond 0%. The self-consumption will be calculated as the sum of the production and the battery contribution as in Equation 2.12, and the energy surplus will be 0.

$$Self\ Cons_{i,d,h} = Prod_{i,d,h} + (SOC_{i,d,h} - SOC_{i,d,h+1}) \cdot En\ nom \cdot \eta_{discharge} \tag{2.12}$$

After analyzing each plant within the community, directly connected or not to the grid, the total energy fed into the grid annually ($En\ fed_{TOT}$) can be calculated, considering the frequency of typical days in Table 2.1, and analogously also the annual energy withdrawn from the grid ($En\ withdrawn_{TOT}$) and the energy shared ($En\ shared_{TOT}$):

$$En\ withdrawn_{TOT} = \sum_{i=1}^{n_{users}} \sum_{d=1}^{6} \left(\sum_{h=0}^{23} (Load_{i,d,h} - Self\ Cons_{i,d,h}) \right) \cdot Day\ freq_d \tag{2.13}$$

$$En\ fed_{TOT} = \sum_{i=1}^{n_{users}} \sum_{d=1}^{6} \left(\sum_{h=0}^{23} (En\ surplus_{i,d,h}) \right) \cdot Day\ freq_d + Direct\ Prod \tag{2.14}$$

$$En\ shared_{TOT} = \min(En\ fed_{TOT}; En\ withdrawn_{TOT}) \tag{2.15}$$

The initial state of charge of the typical day is iteratively derived to obtain a value approximately equal to the final value, corresponding to the last hour of the day. Any small differences between these two values are added to the calculation of annual energy flows. The approach used is summarised in the Figure.

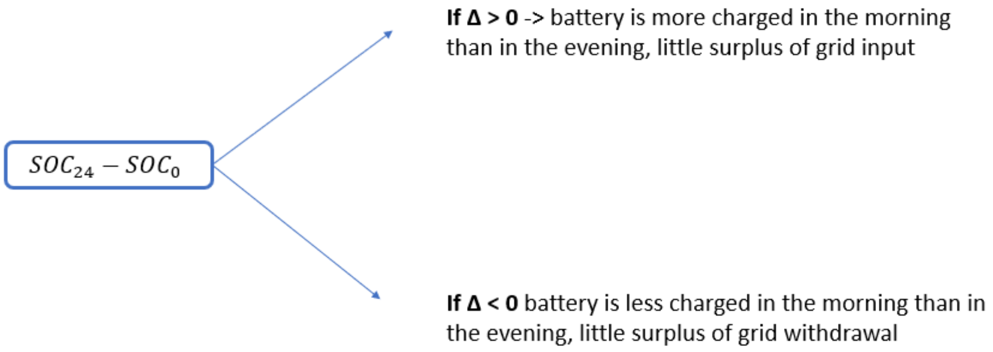


Figure 2.3: Difference in state of charge in a day between initial and final values.

In case of a positive difference, there will therefore be an increase in energy withdrawn from the grid, while on the contrary, if the difference is negative, there will be an increase in energy fed into the grid.

Once the values of the total annual energy flows of the REC are known, it is also possible to determine the economic flows. There are three main economic benefits:

1. Revenues due to the feeding into the grid of the energy produced by photovoltaic plants. In the draft ministerial decree, there are no explicit indications on the valorization of the energy produced, for this reason, it was decided to use the document

of the previous consultation indeed, published in November 2022[32]. There is a distinction between shared energy and the remaining part of the energy fed into the grid as follows. A price cap has also been set as indicated by the European Union. The Commission in EU 2022/1854, adopted on 6 October 2022, proposes to set the cap for those "inframarginal" producers to €180/MWh[11].

- If the fraction of shared energy on the energy produced is greater than 70%:

$$Rev\ Inj = En\ fed \cdot \min(PCap; Pz) \tag{2.16}$$

  where Pz is the zonal price.

- If the fraction of shared energy on the energy produced is lower than 70%:

$$Rev\ Inj = (En\ fed - En\ shared) \cdot \min(PCap; Pz) + En\ shared \cdot Pz \tag{2.17}$$

2. Revenues due to the energy shared between users as part of the community under the same primary cabin. This assessment was made considering the latest available documents, the draft MASE for the incentive in Table 1.1 and the DCO of ARERA for the reimbursement:

$$Total\ Incentive = MASE\ Incentive + ARERA\ reimbursement \tag{2.18}$$

$$Rev\ Sharing = Energy\ shared \cdot Total\ Incentive \tag{2.19}$$

3. Avoided costs due to physical self-consumption. Thanks to self-consumption on-site at certain hours of the day, part or the entire load will be covered by photovoltaic production, which translates into a reduction in the electricity bill. This saving will be greater the more the load is synchronized with production. To evaluate this benefit, the following formula was used:

$$Avoided\ Costs = \sum_{i=1}^{nusers} (Self\ Cons_i \cdot Bill\ Cost_i) \tag{2.20}$$

2.2. The energy poverty index: LIHC

In Section 1.3.1, the principal indices used to measure the risk of energy poverty were analyzed. Each of them has its own validity and analyses one or more aspects of the phenomenon requiring more or fewer data for calculation. In this thesis, the objective is to find an index that is compatible with the context of the energy community. It is, therefore, necessary for the chosen index to require easily available data, and also to have a simple formulation so that it is verifiable by everyone. For this reason, the LIHC index was chosen using the following formulation:

$$LIHC = I\left\{[s_{e,i} > P50(s_{e,i})] \cup \left[\frac{(y_i - s_{e,i})}{Nind_{income}} < y^*\right]\right\} \tag{2.21}$$

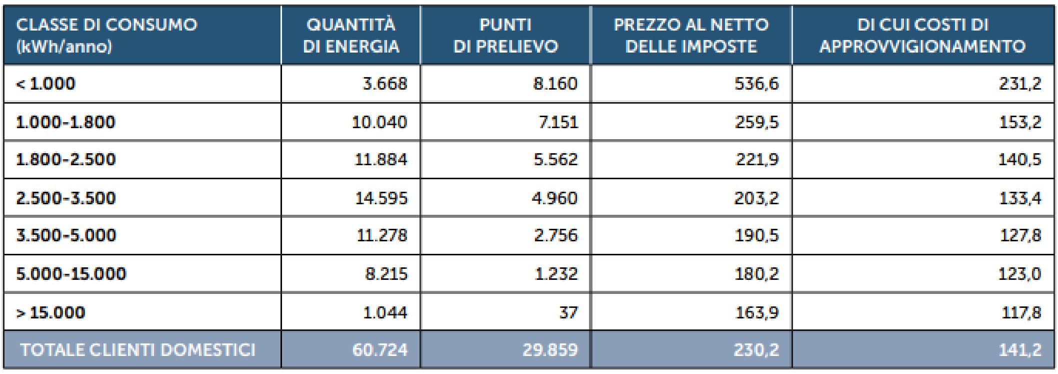
where $s_{e,i}$ is the sum of the annual energy expenditure, $P50(s_{e,i})$ is the median value of the reference sample, y_i is the total annual income of the household, $Nind_{income}$ is the number of individuals in the household who benefit or should benefit from a salary and y^* is the income threshold that identifies a family at risk of poverty.

This index places a family at risk of energy poverty if two situations occur simultaneously, a low salary and high energy expenditure. Let will now look in more detail at the terms of comparison considered.

2.2.1. Calculation of the reference value

The first term in Equation 2.21 checks the household's energy expenditure and whether it is higher than the national median value. The $P50(s_{e,i})$ term will consist of two different expenditures, the electricity expenditure and the heating expenditure. For simplicity, it was assumed that the latter comes from the gas bill and no other sources for heating were considered.

These two energy bills were estimated using ARERA's Annual Report on the state of Services in 2021 [5]. For electricity expenditure, the table in Figure 2.4 was analyzed, in particular the consumption class and withdrawal points.



CLASSE DI CONSUMO (kWh/anno)	QUANTITÀ DI ENERGIA	PUNTI DI PRELIEVO	PREZZO AL NETTO DELLE IMPOSTE	DI CUI COSTI DI APPROVVIGIONAMENTO
< 1.000	3.668	8.160	536,6	231,2
1.000-1.800	10.040	7.151	259,5	153,2
1.800-2.500	11.884	5.562	221,9	140,5
2.500-3.500	14.595	4.960	203,2	133,4
3.500-5.000	11.278	2.756	190,5	127,8
5.000-15.000	8.215	1.232	180,2	123,0
> 15.000	1.044	37	163,9	117,8
TOTALE CLIENTI DOMESTICI	60.724	29.859	230,2	141,2

Figure 2.4: Final average prices to domestic customers in 2021 by consumption class [5].

The median value of the withdrawal points is approximately 14930 which corresponds to 1755 kWh/year.

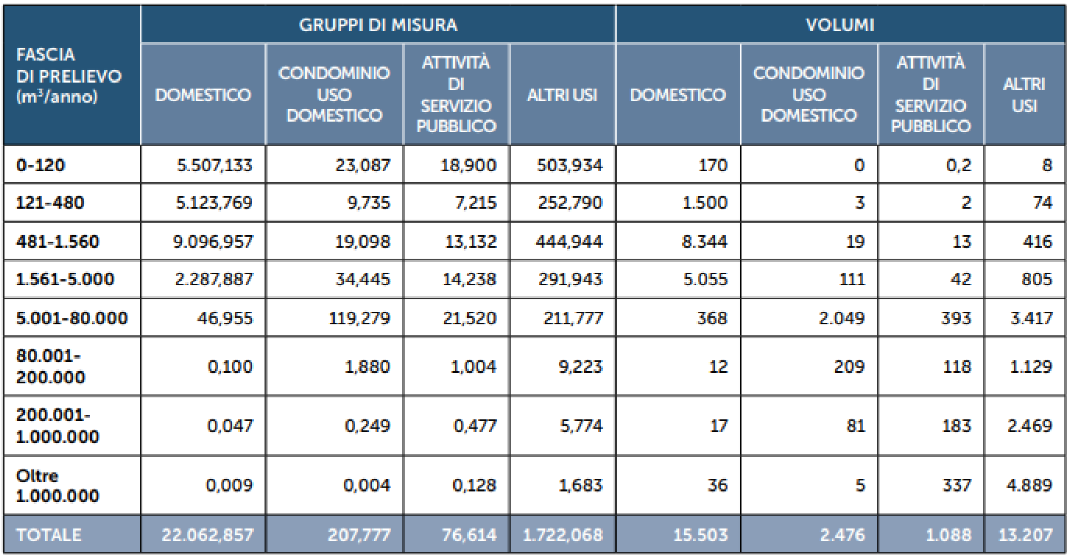
Electricity bill costs vary depending on the price, for this analysis, the costs estimated by ARERA for December 2022 shown in Table 2.4 were considered. Through interpolation, a median energy expenditure for electricity of 749.22 €/year is obtained.

Annual consumption [kWh]	Type profile [€]
1500	659.51
2200	905.77
2700	1081.67
3200	1257.57

Table 2.4: Estimated annual expenditure, excluding taxes, for the supply of electricity in December 2022 [2].

Electricity consumption is not considered to be geographically dependent and therefore the value is on a national scale. In fact, it is a reasonable approximation to assume that lighting and appliance use depends on the habits of individual households and not on climate zones.

For the gas bill, the same logic was applied, using consumption bands and withdrawal points, as shown in Figure 2.5.



FASCIA DI PRELIEVO (m^3/anno)	GRUPPI DI MISURA				VOLUMI			
	DOMESTICO	CONDOMINIO USO DOMESTICO	ATTIVITÀ DI SERVIZIO PUBBLICO	ALTRI USI	DOMESTICO	CONDOMINIO USO DOMESTICO	ATTIVITÀ DI SERVIZIO PUBBLICO	ALTRI USI
0-120	5.507,133	23,087	18,900	503,934	170	0	0,2	8
121-480	5.123,769	9,735	7,215	252,790	1.500	3	2	74
481-1.560	9.096,957	19,098	13,132	444,944	8.344	19	13	416
1.561-5.000	2.287,887	34,445	14,238	291,943	5.055	111	42	805
5.001-80.000	46,955	119,279	21,520	211,777	368	2.049	393	3.417
80.001-200.000	0,100	1,880	1,004	9,223	12	209	118	1.129
200.001-1.000.000	0,047	0,249	0,477	5,774	17	81	183	2.469
Oltre 1.000.000	0,009	0,004	0,128	1,683	36	5	337	4.889
TOTALE	22.062,857	207,777	76,614	1.722,068	15.503	2.476	1.088	13.207

Figure 2.5: Breakdown of distribution customers and withdrawals by withdrawal band and use (redelivery points and metering groups as of 31 December 2021 in thousands and withdrawn volumes in M(m^3))[5].

Considering half of the total domestic metering groups, the result is 11031 which corresponds, within the 121-480 withdrawal band, to approximately 500 m^3 per year. The costs corresponding to this consumption are also taken from ARERA's estimates for December 2022, Table 2.5, but in this case, there is a distinction by macro-zone within the Italian territory, since the expenses related to heating depend on the climatic zone. In the case of Lombardy, the North-East zone is considered, the estimated expenditure is therefore 664.3 €/year.

Annual consumption [Smc]	Tariff area					
	North West	Eastern North	Central	South-Central East	South-Central Western	Southern
120	234.61	224.68	229.33	224.46	241.53	252.43
480	660.57	643.56	656.25	658.84	689.73	715.94
700	892.82	871.85	889.04	917.17	951.48	990.56
1400	1680.76	1647.20	1678.68	1741.46	1796.05	1866.70
2000	2353.98	2309.59	2353.37	2445.87	2517.92	2615.69
5000	5716.15	5617.56	5722.9	5964.11	6123.55	6357.06

Table 2.5: Estimated annual expenditure, excluding taxes, for the supply of natural gas in December 2022 (values in euro) [2].

The second term in Equation 2.21, on the other hand, considers the household's annual income net of energy expenditure with respect to the y^* term. It is the income threshold that identifies a family at risk of poverty, equal to 60% of the median equivalent income by Eurostat, as defined in Lavecchia and Faiellea's report[21]. In the Eurostat study "Living conditions in Europe - income distribution and income inequality" there are Median equivalised disposable incomes of all European countries in 2020 [20], as shown in Figure 2.6.

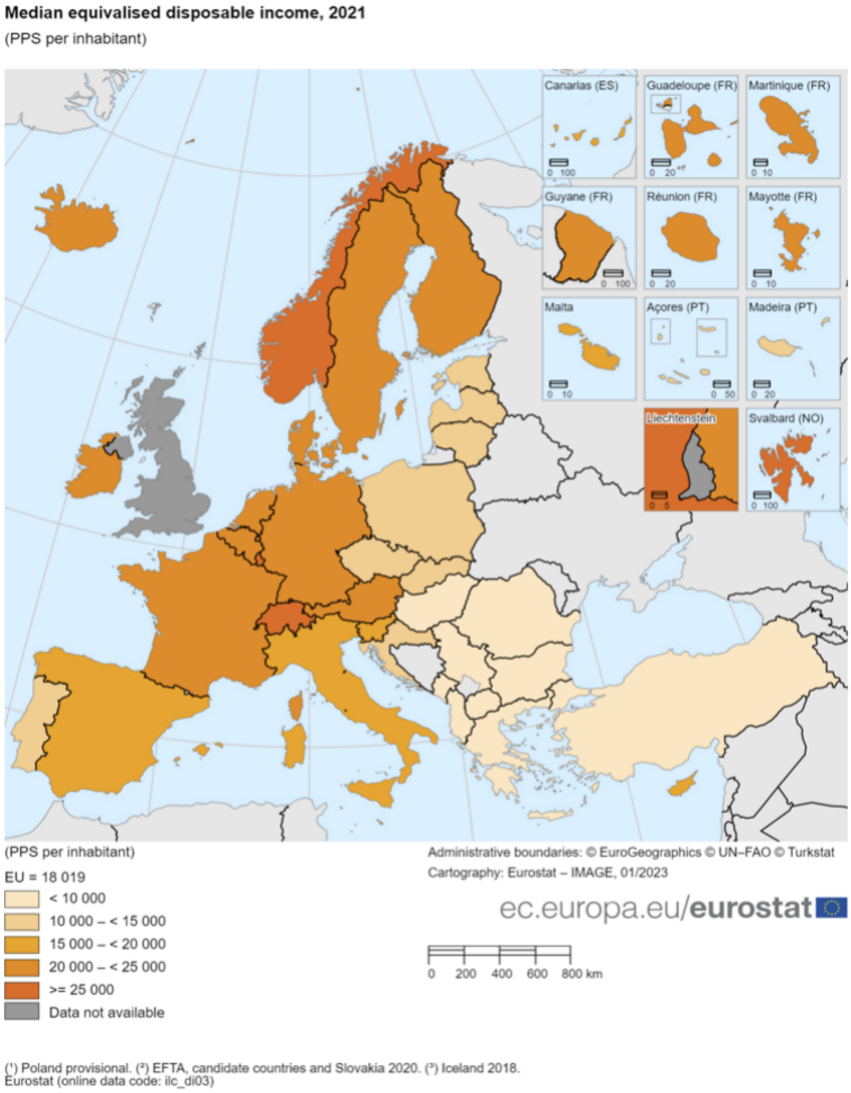


Figure 2.6: Median equivalised disposal income, 2021 [20].

Italy is in the intermediate range and more precisely has a median income value of 17764 PPS (Purchasing Power Standard), very close to the European average. The PPS is an artificial currency unit used by Eurostat as a common currency. Price differences across borders mean that different amounts of national currency units are needed for the same goods and services depending on the country. Theoretically, one PPS can buy the same amount of goods and services in each country.

To translate this value into euros, the conversion factor was derived from the GDP per capita, which is present in both currencies. In 2021 the GDP per capita in Italy was 30600 PPS and 30150 €, the conversion factor is therefore 0.985 €/PPS. This gives a median equivalent income value of 17503 €/year. The term y^* corresponds to 60% of it as defined, it is, therefore, equal to 10502 €/year per inhabitant.

2.2.2. Boolean and continuous poverty risk index

Once the terms of comparison have been defined, it is possible to create the algorithm that determines whether the household is at risk of energy poverty. It is necessary to have information about the household and in particular the index requires the following information:

- Total annual energy expenditure, composed by the sum of electricity and heating bills;
- total annual income of the household;
- number of individuals having or expected to have an income.

The conditions are then checked and if both are verified the algorithm will return the value True otherwise False as in the Equation 2.21, thus establishing the most vulnerable households.

However, the index does not give any indication of how close the household is to the threshold or not, and therefore no information is given on how high the risk is. For this reason, it was decided to transform the Boolean output of the algorithm into a continuous output. The new algorithm, therefore, returns a value of 1 if the family is not at risk and a value between 0 and 1 if the conditions are met. The further the value deviates from 1, the greater the probability of vulnerability. The new index is calculated using the following formula:

$$Mean\left\{\left[\frac{P50(s_{e,i}}{s_{e,i}})\right];\left[\frac{(y_i - s_{e,i})}{Nind_{income} \cdot y^*}\right]\right\} \tag{2.22}$$

2.3. Sharing indices for Energy Communities

In the following paragraphs, several community economic benefit-sharing methods are analyzed. As will be seen later, they present very different characteristics and each of them focuses on one or more aspects related to Energy Communities. The main aspects that have been identified are three:

- the ownership of the plants;
- the "virtuosity" of the members of the Energy Community;
- the energy poverty risk of the members of the Energy Community.

These three different perspectives were analyzed in order to create indices measuring them quantitatively, to characterize the sharing methods but also to characterize the individual participants in the community.

The first KPI takes into account the economic aspect, in fact an initial investment was required for the installation of the production plants. This investment could be made by an entity outside the community, ESCO, or internally. In fact, it is possible that some or all members of the community participated in the investment and thus have a percentage of ownership on the plants. The indicator is then defined as the percentage that the individual user has paid for the initial investment, as shown in the Equation 2.23.

$$Owner\ KPI_i = \frac{Contribution_i}{Overall\ investment} \tag{2.23}$$

where i is a member of the community.

The second KPI characterizes the user according to how virtuous their behavior is concerning electricity consumption. In fact, production comes from an intermittent and non-programmable source, so it is up to the consumers to coordinate with production in order to increase self-consumption and sharing of the energy produced. In order to assess the virtuosity of the users, it has been referred to paragraph 1.2 and in particular the self-sufficiency index.

The index is constructed with a Python algorithm using the same inputs analyzed in Section 2.1 and is based on the following equations:

$$Sharing\ KPI_{i,d} = \frac{\sum_{h=0}^{23} \min(Load_{i,h}; CER\ Prod_h)}{\sum_{h=0}^{23} Load_{i,h} + \sum_{h=0}^{23} \min(Load_{i,h}; CER\ Prod_h)} \tag{2.24}$$

$$Sharing\ KPI_i = Mean(KPI_{i,d}) \tag{2.25}$$

The value obtained will be between 1 and 0, the higher the index the greater the user's ability to synchronize with production, this being because the index calculates the fraction of the individual user's self-consumption of the energy produced by all the installations in the community compared to their total consumption.

The last index concerns a social aspect, the risk of energy poverty of the users. For this aspect, the continuous LIHC was used as index, analyzed in the previous section 2.2.

2.4. Sharing Methods

Section 1.1.1 and 1.1.2 analyzed the regulations in place at both European and Italian levels and the technical and economic rules that characterize an energy community: maximum power, geographical limits, and sharing incentives. One of the positive peculiarities of Energy Communities, emphasized in these documents, is their autonomy in internal organization, each one can therefore create its statute and outline its own allocation rules as it thinks best, considering its specific needs. The distribution system operator (DSO) will then measure the energy flows and provide the corresponding incentives. These revenues will reach the community manager who will distribute them as internally determined to the members of the community.

The MASE decree and the ARERA resolution, therefore, do not outline any mandatory rules on this subject, but at the same time do not even set out guidelines or suggestions on how the benefits generated by self-generated energy can be shared. This lack of guidelines could create confusion and not allow a large-scale implementation of this new instrument. In addition, considering that REC is a relatively recent topic of discussion, the literature so far has focused more on the technical aspects, leaving out the economic and more practical side of the issue.

For this reason, it was decided to explore possible sharing mechanisms by which users can share in the collective self-generation of electricity and to analyze how much they may impact different categories of users. The intention is therefore not to find a perfect method applicable to every reality but to provide alternatives.

The algorithms constructed are partly reworkings of existing algorithms and partly new algorithms. They are very different from one another in several aspects: the amount of data required, communication effectiveness and simplicity, computational cost, and aspects considered.

With respect to the latter, in section 2.3 KPIs have been developed based on three main aspects, the different algorithms implemented can be characterized according to them, meaning whether they are taken into account or not. In particular, Table 2.6 presents all the algorithms that will be analyzed in the following sections, and for each one, it shows how many and which aspects are taken into account among: ownership of the facilities, diligence of the community members, and risk of energy poverty.

	Ownership	Sharing	Energy poverty
Owners	yes	no	no
Proportional	no	yes	no
Packets	no	yes	no
Shapley	no	yes	no
Owners + Proportional	yes	yes	no
Energy Poverty + Proportional	no	yes	yes
Energy Poverty + Owners	yes	no	yes
Energy Poverty + Proportional + Owners	yes	yes	yes

Table 2.6: Aspects considered in the different sharing mechanisms.

A further issue not examined in depth in the documentation is which of the economic flows analyzed in paragraph 2.1 can and/or should be shared among the community. In principle, therefore, the community can decide whether to share one or more of the benefits: sharing, feed-in, and self-consumption. In order to consider this variable all algorithms that have been constructed in this thesis take generic economic quantities as input and then allocate them, they can therefore be used independently of the individual community's choice.

2.4.1. Owners algorithm

The first algorithm is the simplest of those analyzed; it only considers plant ownership. This allocation system was implemented by the Politecnico di Torino[35] and considers each member's ownership share of the generation power plant. It is, therefore, necessary to add this information to the general information of the community. A column is then added to the Excel file where the percentage of each member's investment in relation to the total investment is shown. The principle here is that the community is based on the production of renewable electricity and this would not exist without the initial investment of the plants. Those who have contributed the most will get the most benefit.

The economic benefits are then calculated for each typical day and for each hour and then distributed according to the Ow factor that corresponds to the $Owner\ KPI_i$ given in Equation 2.23. Once it has been obtained how much each member is entitled to hour by hour, the annual revenue is calculated by multiplying it by the frequency of each typical day. The algorithm is given below in a block diagram.

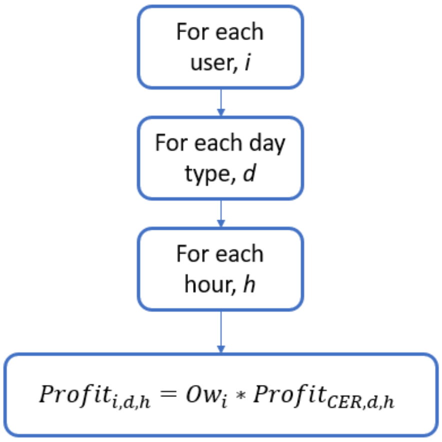


Figure 2.7: Block diagram for Owners algorithm.

This algorithm is very simple both in terms of communicative effectiveness and computational cost, the Python code in fact calculates the final allocation in a few seconds. Furthermore, the concept of ownership is separated from that of plant location. In fact, a plant can also be located under the PODs of users who have not contributed to the investment, thus favoring the choice of the best location for the plant by considering where space is available and where there is better exposure. The point remains, however, that if it is decided to share only the revenues due to sharing, the benefits of feed-in and self-consumption will go to the person who physically has the plant.

This type of allocation does not make sense to be used when the investment is made by an external entity or by only one member of the community such as the municipality, the other participants would get no economic return and would therefore have no incentive to be part of the community.

2.4.2. Proportional algorithm

Besides the percentage of ownership, another important aspect is the synchronism between consumption and production. When these two are synchronized, the economic benefits increase. Therefore, an allocation criteria could be rewarding and thus remunerating more those users who are considered to be more virtuous. The ways to recognize the most virtuous users can be different, in this thesis three different methods were analyzed: a method called Proportional, one called Packets, and one using the Shapley value.

With the first method, benefits are allocated through a proportional factor defined as the fraction of the individual user's load compared to the total load. This factor is calculated not only for each user, as was the case with the Owners algorithm, but also for each hour of each typical day. The block diagram is shown in Figure 2.8.

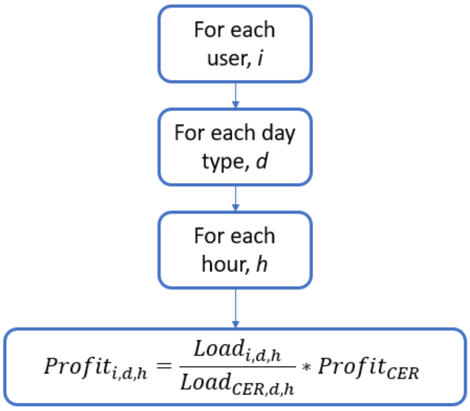


Figure 2.8: Block diagram for Proportional algorithm.

The proportional factor, being calculated hour by hour, is able to take into account the synchronism between load and production and to incentivize users to consume when they actually have generation. During the night, for example, the production of solar panels will be zero, the self-consumption, feed-in, and sharing will be zero, and consequently also the economic return linked to them. Consuming when there is no production, therefore, does not earn the user any revenue. On the contrary, the greatest revenue will be in the middle hours of the day when there is peak electricity production; consuming during these hours will benefit the user.

The data required for this algorithm are less simple to obtain than for the previous algorithm, it is in fact necessary to know the consumption of all the users of the Energy Community at each hour of the day. Submetering systems will therefore be required, that are able not only to measure consumption but also to collect it in order to make it available to the REC operator.

With this algorithm, larger energy users, i.e. those that account for a large percentage of the community's total load, will be advantaged. The risk is therefore that, in the case of a community made up of loads of very different sizes, users with low consumption will be poorly remunerated and will therefore have no incentive to synchronise with the grid.

2.4.3. Packets algorithm

The second algorithm that takes into account the diligence of the users was developed by Politecnico di Torino[35] as an allocation method for shared energy only. Shared energy is 'virtually' self-consumed, so it is not possible to explicitly identify the contribution of each user in the community. For this reason, an iterative allocation system was developed that allocates individual packets of shared energy to each user in each iterative cycle until exhaustion. The developed algorithm is illustrated in Figure 2.10 by means of a block diagram.

The single iterative cycle is based on two main variables which are updated from time to time and specific for a certain hour in a certain day type. The first variable is L, a vector that keeps track of the user's consumption still to be covered, initially it is formed by the energy demand. The other variable is $SE\ to\ be\ allocated$, which keeps track of how much shared energy still has to be allocated, at the first iterative cycle it is all the shared energy. The packet of energy that is distributed to the users in the iteration is given by the minimum of the vector L, in total, therefore, $Partial\ SE$ will be allocated given by the multiplication of the number of users and the energy packet. L_{min} is then distributed to those who still have uncovered consumption, i.e. a value of L other than zero. L is subsequently updated as the previous value subtracted from L_{min}. The energy allocated to each user SE_i will be that allocated to the previous iterative cycles plus the energy package L_{min}. The last iterative cycle occurs when the energy remaining to be allocated is less than the energy that should be allocated in that iterative cycle, $Partial\ SE \geq SE\ to\ be\ allocated$, this remaining part is divided among the remaining users. In Figure 2.9 shows an example graph, the REC members are sorted in ascending order and each color represents the single energy packet allocated in an iteration.

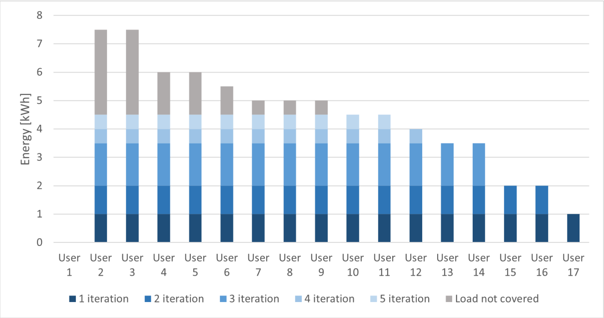


Figure 2.9: Packets algorithm example

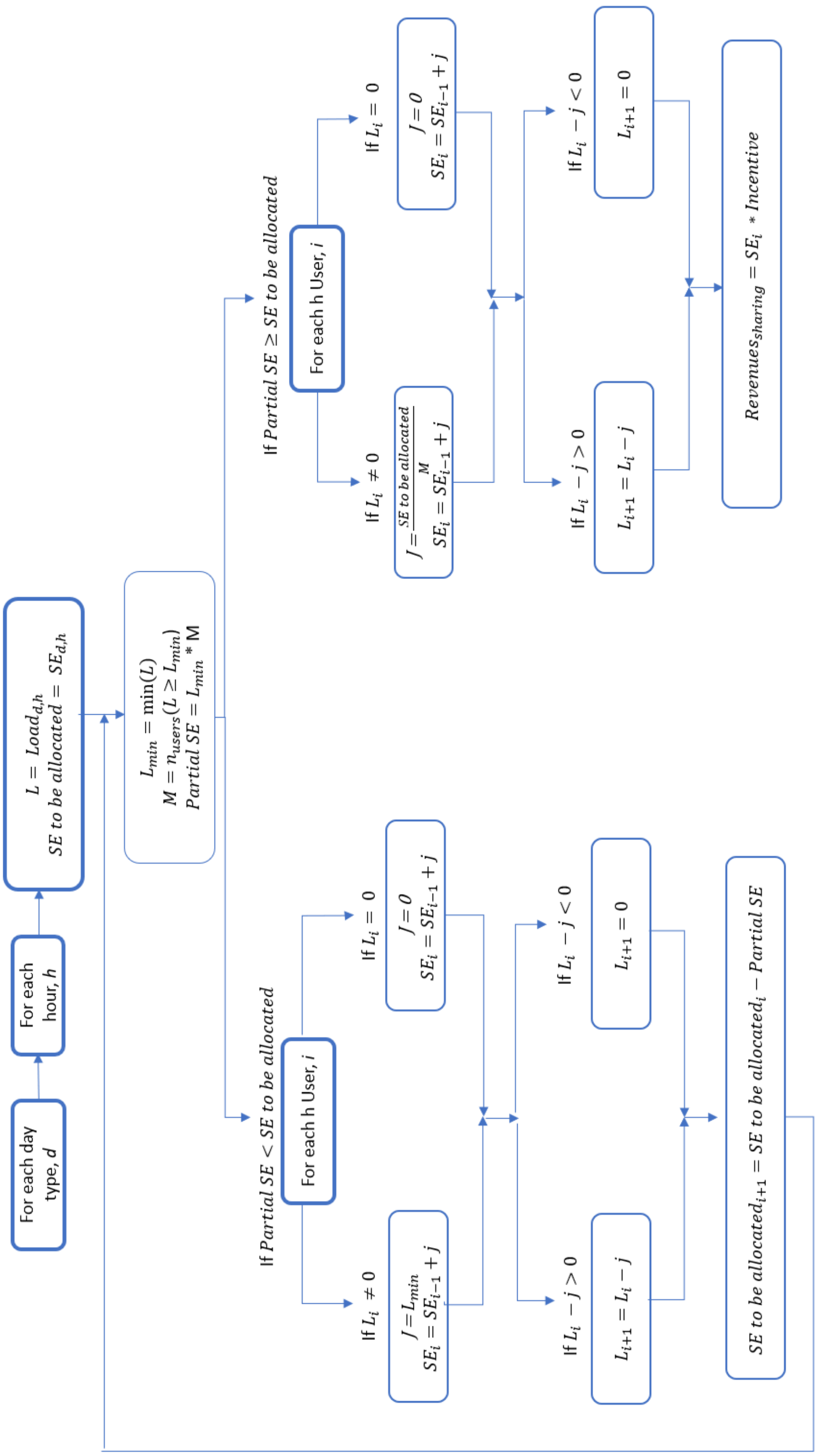


Figure 2.10: Block diagram for Packets algorithm.

Compared to the Proportional method, energy is not simply distributed with respect to the load of individual users, but they are sorted in ascending order according to their demand, so users with high consumption are not favored.

The algorithm was created taking into account only the distribution of shared energy, in fact, it is talking about energy packages and not economic packages. For this reason, the algorithm must be modified so that it can also be applied in the case where energy fed into the grid and self-consumed is shared.

It is not possible to generalize the algorithm analyzed above due to its intrinsic structure, in fact, there is the condition that the shared energy to be distributed is always less than or equal to the sum of the loads, by its own definition, as seen in Equation 2.15. If, on the other hand, it is desired to share also the self-consumed or fed-in energy, this condition is no longer respected in every hour, in summer in the central hours of the day it may happen that the production of energy is greater than the demand of the REC. A generic function has therefore been created which receives as input a DataFrame containing energy values, it will share according to the algorithm in Figure 2.10, what is not distributed is allocated to the users who own the plants according to the Owners method.

Despite the higher degree of complexity compared to the other algorithms, the Packets method has a computational cost of a few seconds. The data required is the same as for the Proportional algorithm: consumption of each user every hour and the value of energy produced; while shared, fed-in, and self-consumption can be calculated accordingly.

2.4.4. Shapley value algorithm

The third method that is analyzed, is a complex method, and as will be seen, it is not easy to implement and subsequently use in real applications. However, it has been considered as a reference against all the other algorithms created because it is currently one of the best algorithms available in the literature for a fair distribution of incentives.

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.

With this idea, the Politecnico di Milano team developed a method in charge of distributing the revenues of the REC in an equal manner, taking into account the interactive nature of energy sharing, using the Game Theory [36]. The Game Theory originated with Von Neumann with the aim of defining in mathematical terms how individuals behave when they are in a situation that may lead to sharing or winning something and making decisions that affect each other's welfare.

The Game Theory 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, on the other hand, individuals are independent and no constraints are required. In this case, therefore, each player will try to maximize their own benefits and minimize their costs by not communicating with the others, so there will be no coalition formation.

The Energy Community can be seen as a grand coalition and therefore the dynamics that are created can be represented through a cooperative game where the players are all the participants: producers, consumers, and prosumers. They, in fact, cooperate and communicate with each other in order to improve their earnings. The set of actors in the community or players is therefore called N, and $v(S)$ the value of the coalition, where $S \in N$. The payoff of each player x_i, with $i \in S$, is determined by a fair allocation criterion that disadvantages no one. To allocate the value of the coalition among the players in an equal manner, the Shapley value is used. This index is calculated according to the definition in Equation 2.26 and considers the added value that each player brings to the coalition, i.e. their marginal contribution.

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n - |S| - 1)!}{n!}(v(S \cup \{i\}) - v(S)) \tag{2.26}$$

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.

It can be seen that 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 in accordance with a factorial function, so there is a maximum limit of players that can be considered, approximately 10-12 players. 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. Clustering means bringing together under one entity, several players who consider themselves to be similar, e.g. they are all passive consumers, and downstream distributing the payoff received among the players in the subgroup, in a proportional way. A further limitation of this method is the fact that it assumes that those who have a plant under their POD also own it. To overcome the problem, two different users should be created, one virtual and one physical.

The algorithm used as a starting point was applied in a paper published by the research group of Politecnico di Milano, in which a methodology was proposed for the design and management of an energy community[44]. After an optimization problem, the Shapley value algorithm was used to calculate the earnings due to the individual members of the community. The case study examined consisted of an apartment building with 9 users with different load profiles. The users are all passive and there is only one system under the 'condominium' user. The work that has therefore been done is to generalize this case study and adapt it to the inputs analyzed in Section 2.1.

Compared to the original algorithm where players were either producers or consumers, this new version also considered the possibility that users could occupy both positions and thus be prosumers. Further integration was made by including batteries within the function that calculates energy flows.

The block diagram describing the algorithm is shown in Figure 2.11. For each participant in the Energy Community and for each value from 0 to the total number of members, all possible coalitions that can be formed with n players and the multiplication factor expressed in the Equation 2.26 are 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.

In contrast to the Packets method, this algorithm is constructed in such a way that a sum of money, and not a quantity of energy, is distributed, so it is easy to extend the algorithm to distribute not only the gains from shared energy but also the other economic benefits that have been highlighted.

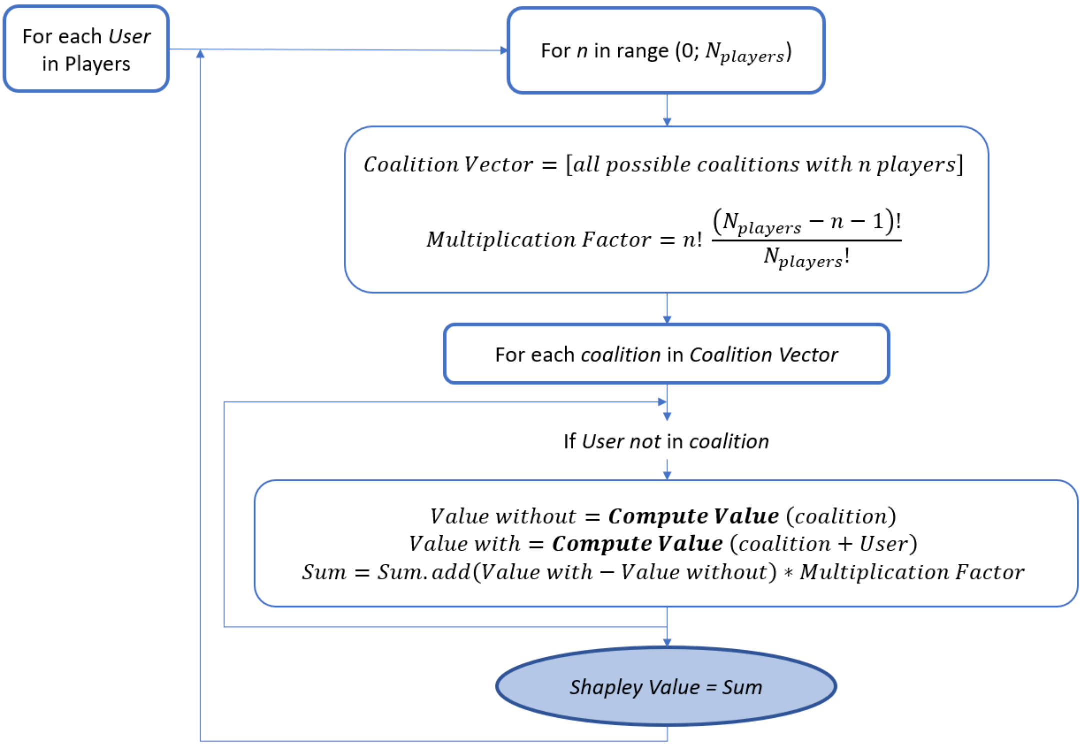


Figure 2.11: Block diagram for Shapley value algorithm.

2.5. Bi-level algorithm

In the previous sections, several allocation methods were analyzed, each focusing only on one aspect of energy communities. In this section and in Section 2.6, instead, the methods will be combined, forming algorithms that allocate the economic benefits of the community across two or three different levels. For each level, a portion of them will be distributed using a different sharing method.

2.5.1. Diligence and owners

The first bi-level algorithm analyzed was created with the intention of coming close to the results obtained with the Shapley value, which is considered to be the fairest of all, while at the same time overcoming its limitations. The limitations of the Shapley value as analyzed in Section 2.4.4 are mainly two: the very high computational effort and the link between plant placement and ownership. For this reason, it was decided to use in combination the algorithm that takes ownership into account, the Owners method, and an algorithm that takes energy flows and user diligence into account, the Proportional method. The first part of the economic benefits is distributed according to the Proportional algorithm, while the remaining part is distributed at the second level among those who contributed to the initial investment.

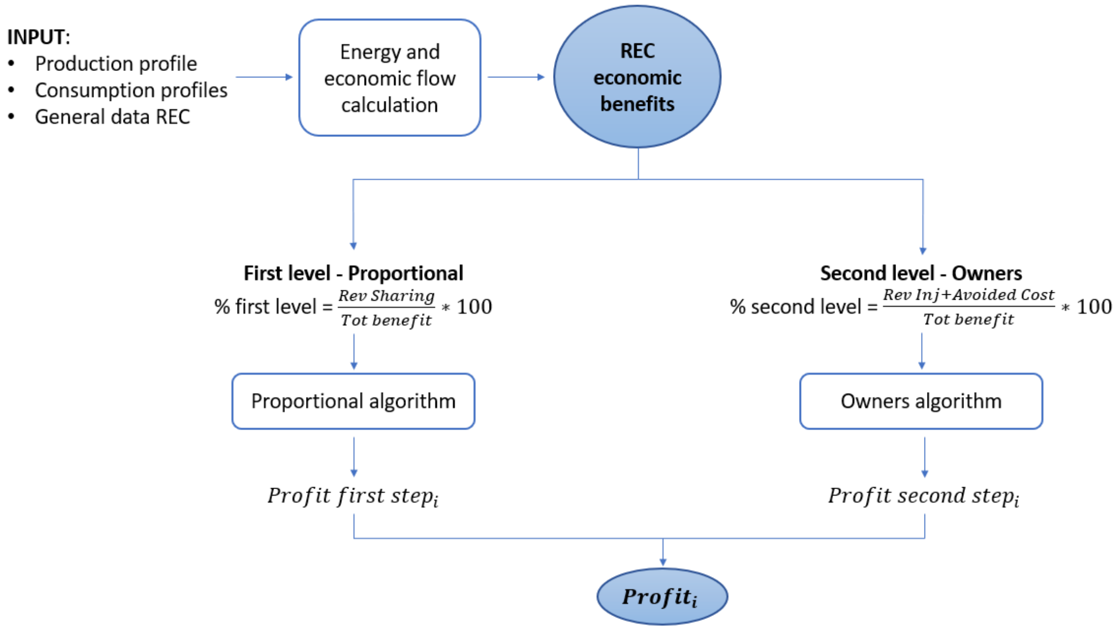


Figure 2.12: Block diagram for the bi-level algorithm, Proportional and Owners methods.

The percentage allocated to the first level is the fraction of the annual revenue due to sharing compared to the total, this is because sharing is from both production and load so everyone has contributed to it. On the other hand, earnings due to feed-in and self-consumption are closely linked to production and less to load, which is why they are allocated to the second level. Once the profits of each member are derived from the first and second tier, the final profit will be the sum of the two contributions.

2.5.2. Energy poverty algorithms

Until now, the social aspect has not been considered in the distribution of the economic benefits of Energy Communities, in this paragraph, it will take up what was seen in Section 2.2 and integrate the LIHC index into the algorithms.

In paragraph 1.1 it was seen how legislation places a particular focus on Energy Communities as a useful tool for mitigating the phenomenon of energy poverty and more generally for helping economically weaker individuals. These households will most probably not have the financial possibilities to afford their own photovoltaic system, but thanks to this new tool they will be able to benefit and use ‘clean’ energy produced by renewable plants without necessarily contributing in terms of money. It will therefore be possible to have users who have invested zero in installations but who provide their own load, some of whom are presumably in a state of vulnerability and at risk of energy poverty.

With the methods analyzed so far, the Energy Community as a tool for energy poverty mitigation may not be sufficient. If economic benefits are shared out through the Owners method, vulnerable people would risk getting no economic return since they did not contribute to the purchase of the installations. With the Diligence methods, on the other hand, they might get a return, but a minimal one, considering that their consumption is much lower than that of the entire community. This fact will lead to a low payoff, especially using the Proportional and Shapley methods. Therefore, it is not enough to consider the economic and diligence aspects, some energy communities may also consider the social aspect. These are most likely to be carried out by municipalities that are interested not only in the economic return but also in contributing to the welfare of their community and would therefore give up part of their profits to help energy-poor households.

Therefore, two bi-level algorithms were constructed, both considering energy poverty at the first level while at the second level, one considers ownership of the plants, Figure 2.13, and the other user diligence through the Proportional method, Figure 2.14.

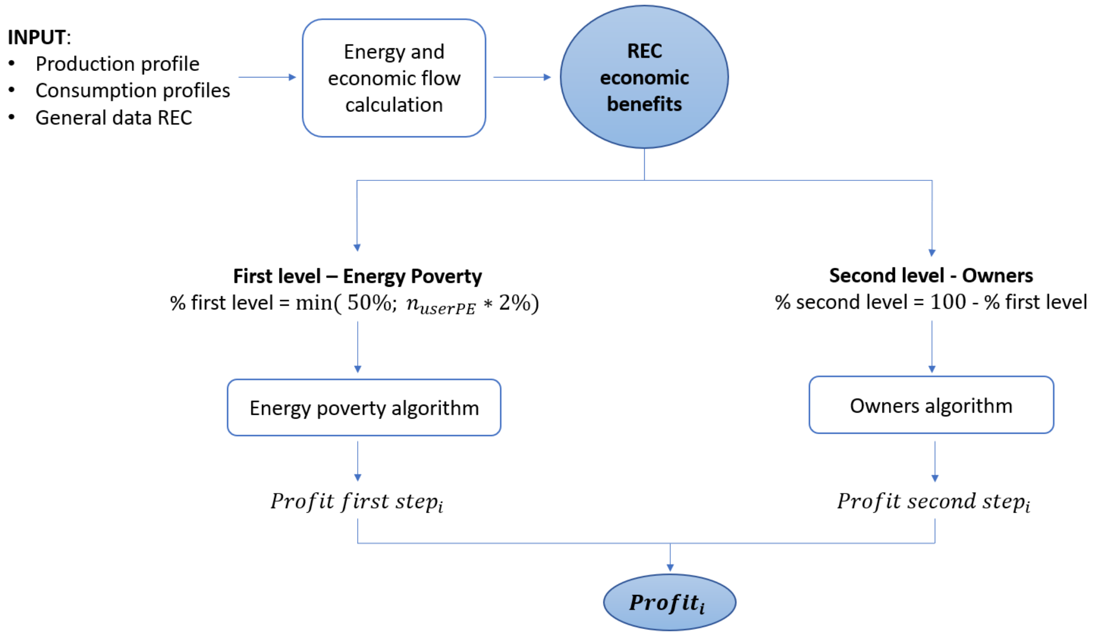


Figure 2.13: Block diagram for the bi-level algorithm, Energy poverty and Owners methods.

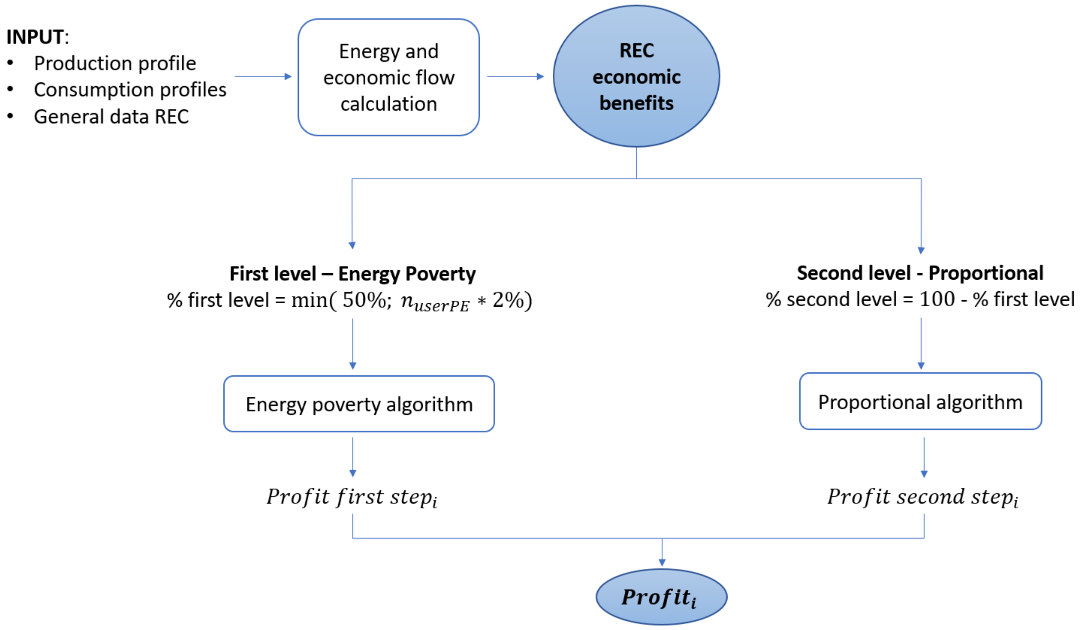


Figure 2.14: Block diagram for the bi-level algorithm, Energy poverty and Proportional methods.

In the first step, therefore, a fraction of the REC's earnings are distributed only among the users in poverty, the households thus having obtained a LIHC value different from 1. Each household will be paid according to how high the risk is, thus using the LIHC index in the continuous version. The lower the index, the higher the risk of energy poverty and thus the greater the share of profits allocated to that household.

The balance between the percentage distributed in the first step and the percentage distributed in the second step is crucial. If users in poverty are over-advantaged, there is a risk of not incentivizing other households to join the REC because they are paid too little. On the contrary, considering the social condition less would make the algorithm useless and the economic condition of the users would not improve significantly. It was then proceeded by iteration, checking the results as they came in, in order to obtain methods that were acceptable to both parties. The distribution shown in Figures 2.13 and 2.14 was finally obtained. In the first step, a percentage of the earnings equal to 2% is distributed for each user in poverty up to a maximum of 50%.

In addition to the problem that not all REC users might accept to give up part of their earnings in favor of weak users, a further complication could be due to the collection of data needed to implement these algorithms. The necessary data, in fact, that each community member has to provide to the operator are the annual energy bills, the annual income of the household, and the number of beneficiaries. This information might not only be difficult to find but for privacy issues, not all users might be willing to share it.

2.6. Tri-level algorithm

To complete the picture, a final algorithm was constructed. It consists of three levels and considers social, economic and energy aspects. In some Energy Communities, a very diverse situation could arise, where there are users in poverty, disparities in investment contributions and also very different load profiles from one another. In these cases, the method shown in Figure 2.15 could be applied.

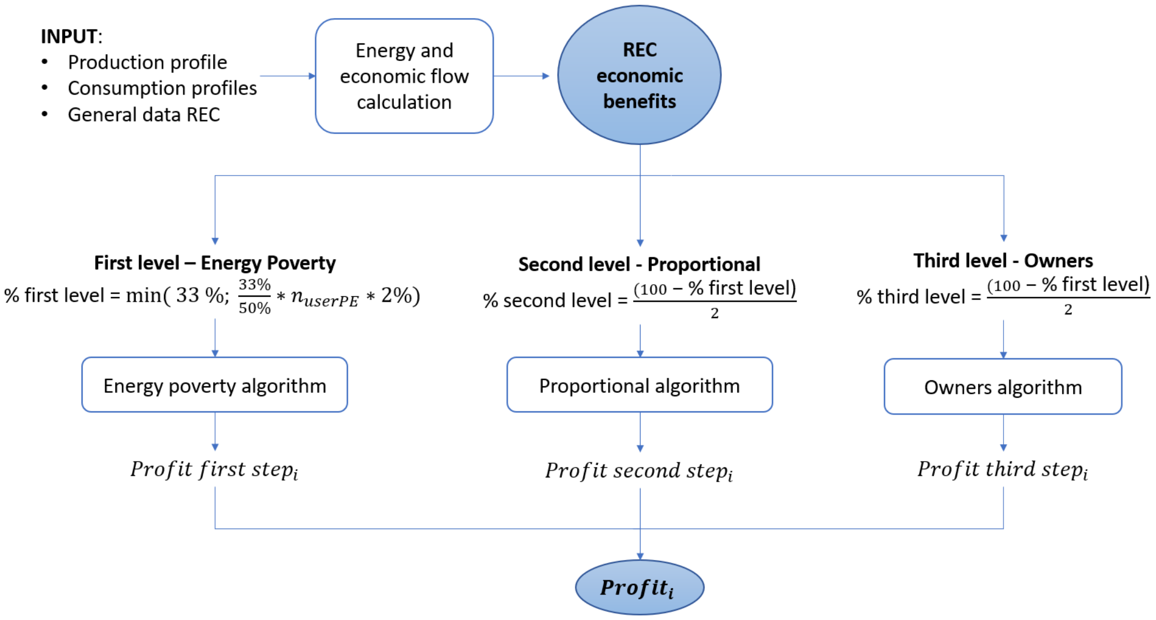
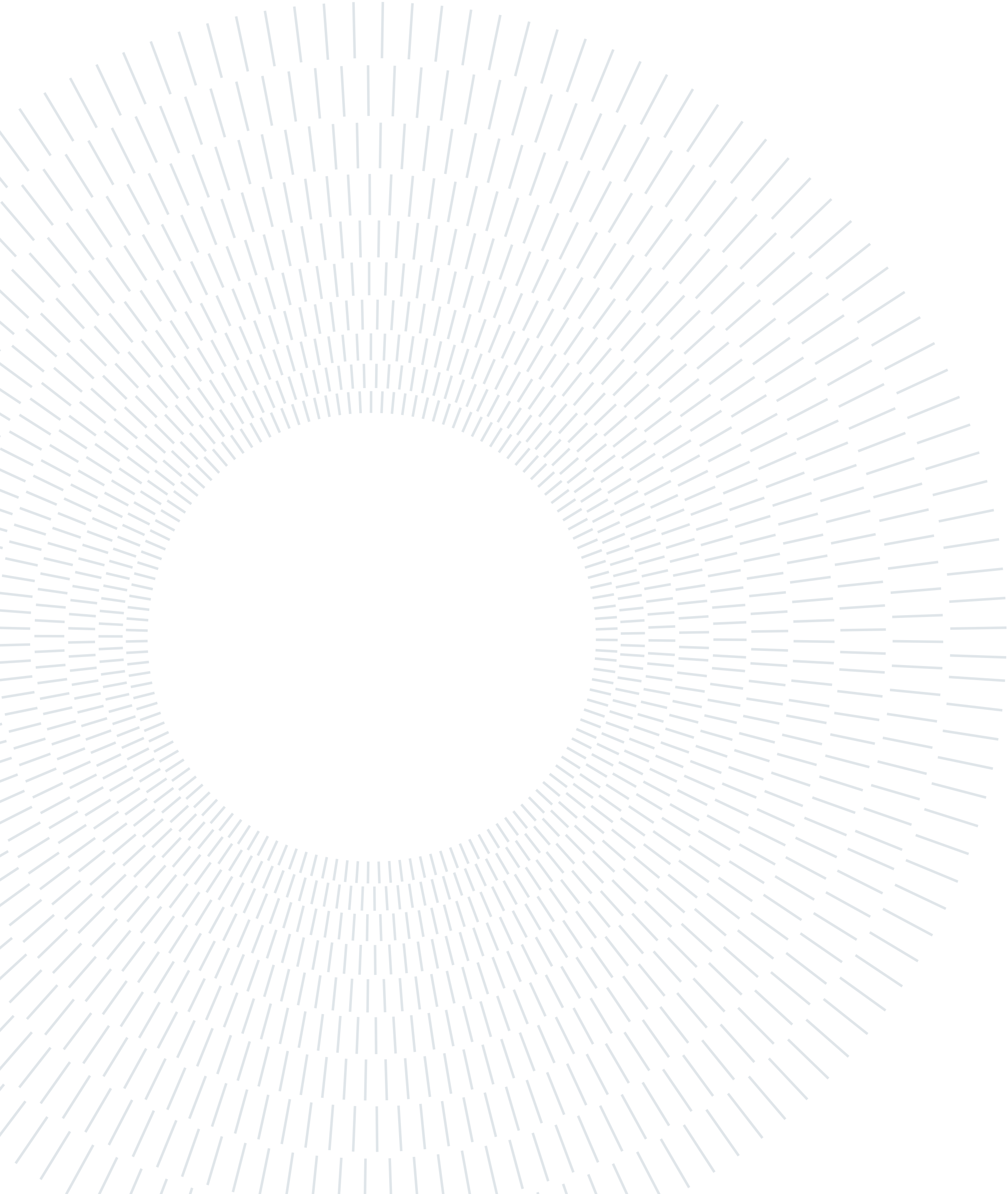


Figure 2.15: Block diagram for the tri-level algorithm, Energy poverty, Proportional and Owners methods.

The distribution between the three allocation levels was done in a similar way as in the bilevel methods, with the difference that the cap is set at 33% and the second and third levels distribute the same percentage, thus having the same weight. The latter algorithm requires a lot of data to be applied, both with respect to the economic conditions of the users and to their hour-by-hour consumption. However, its computational burden is very low, in the order of seconds, unlike Shapley's method.

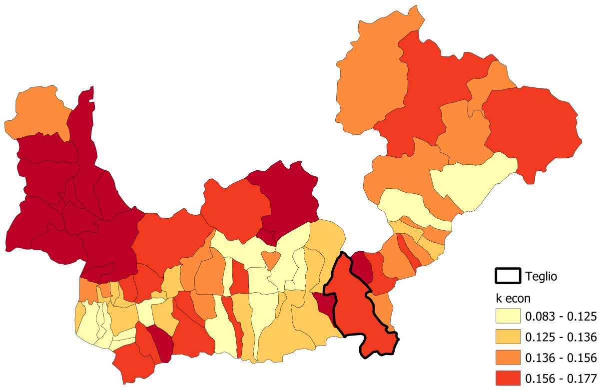


3 | Case study: the REC of Teglio

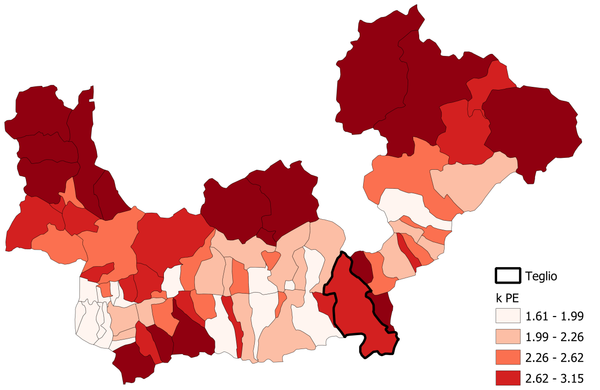
In this chapter, a real case will be applied in order to test and validate what was developed in the previous chapter. In particular, the municipality of Teglio, in Valtellina, was chosen to develop an Energy Community. The current configuration and possible improvements that could be adopted to optimize the community will be analyzed and the algorithms developed will be applied to analyze the different social impacts. The case study was built from real data provided by the municipality thanks to the collaboration with the Politecnico di Milano.

The municipality of Teglio is located in the middle of Valtellina, in the province of Sondrio, and it had 4410 inhabitants in 2021, according to Istat. It is located in a mountainous area and is therefore characterized by a harsh climate in winter and a mild one in summer. According to the climatic classification, Teglio is in zone F with 3278 degree days, a medium-high value compared to the other municipalities in Valtellina. Energy expenses due to heating, therefore, could have a considerable impact on resident households.

Using the maps developed by the research group of the energy department in Politecnico, as mentioned in paragraph 1.3.5, it is possible to analyze the economic condition and energy poverty risk of the municipality by comparing it to other municipalities in the same province. From the maps shown in Figures 3.1a and 3.1b it is evident that Teglio is a municipality in the medium-high range for both indicators. The economic indicator highlights that, compared to other municipalities in Valtellina, there is a high percentage of taxpayers in poverty and at the same time a low average salary for these individuals. The critical economic situation together with the harsh climate and therefore high energy expenses put the population of Teglio at risk of energy poverty. the municipality will therefore have to find solutions to mitigate and prevent this phenomenon. One of the solutions to which it has focused its attention is the formation of an Energy Community also driven by Manifestazione d'interesse for the presentation of REC projects, published by Regione Lombardia in July 2022 [39].



(a) Graphical representation of the economic coefficient for the province of Sondrio.



(b) Graphical representation of the energy poverty risk coefficient for the province of Sondrio.

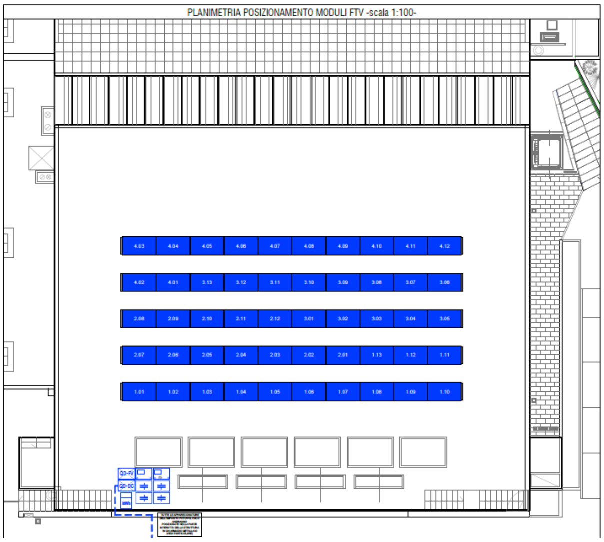
Figure 3.1: Energy poverty risk map of Sondrio province by municipality developed by the energy department of Politecnico di Milano.

3.1. FV plants in Teglio

In Teglio there are three main photovoltaic installations, which were realized during the summer of 2022. These three plants are connected to three PODs of the municipality: the middle school in Teglio, the primary and middle school in Tresenda, and the sports arena. The municipality itself did the financing.

The installation plans are shown in Figure 3.2, in all three cases, the installations are located on the roof of the utility. The sizes of them are different, and as will be analyzed later, this is due to the different consumption. The type of panels chosen is the same for all, the model is Q.PEAK DUO ML-G9+ of the manufacturer Q cell. The contract that has been established is the "scambio sul posto".

(a) Photovoltaic system plan of Teglio school. (b) Photovoltaic system plan of Tresenda school.



(c) Photovoltaic system plan of sports Arena in Teglio.

Figure 3.2: Installations currently existing in Teglio.

All PV systems are also equipped with a storage system consisting of a lithium-ion battery. The nominal storage capacity, the maximum power output and the number of life cycles, together with the installed capacity of the PV system and the annual production are given in Table 3.1. The nominal depth of discharge is set at 100%.

	Peak Power FV [kW]	EE annual production [kWh/year]	Battery capacity [kWh]	Maximum battery power [kW]	Number of life cycles
Teglio School	5.93	7 194.66	15	6	3650
Tresenda School	18.96	23 003.49	40	20	3650
Sports Arena	18.96	23 003.49	40	20	3650

Table 3.1: Technical specifications on existing plants in Teglio.

The theoretical energy produced by these plants was calculated using the profile shown in Figure 2.1 obtaining a total value of 53201.6 kWh/year which corresponds to 1213 equivalent hours, consistent with other plants located in the northern part of Italy.

The costs for the installations were not provided, therefore they were estimated. A Fraunhofer study from 2021, reports the capital expenditure (CAPEX) and operating expenditure (OPEX) of some renewable technologies in order to estimate their LCOE [31]. For photovoltaic technology, a distinction is made between different costs depending on the size of the plant, reporting a lower and an upper limit as shown in Table 3.2. For this thesis, it was decided to use the most conservative values and thus the highest costs. For storage systems, on the other hand, a value of 1200 €/kWh of capacity was considered, an average value for lithium batteries for "Turnkey" systems in 2022-2023. The final estimates of the investment and maintenance cost of each Teglio plants are shown in Table 3.3.

CAPEX [€/kW]	PV rooftop small ($\leq$ 30 kWp)	PV rooftop large (>30 kWp)	PV utility-scale (1MWp)
low	1000	750	530
high	1600	1400	800
OPEX [€/kWh]	PV rooftop small ($\leq$ 30 kWp)	PV rooftop large (>30 kWp)	PV utility-scale (1MWp)
mean	26	21.5	13.3

Table 3.2: Specific CAPEX and OPEX for current plants in 2021 according to Fraunhofer [31].

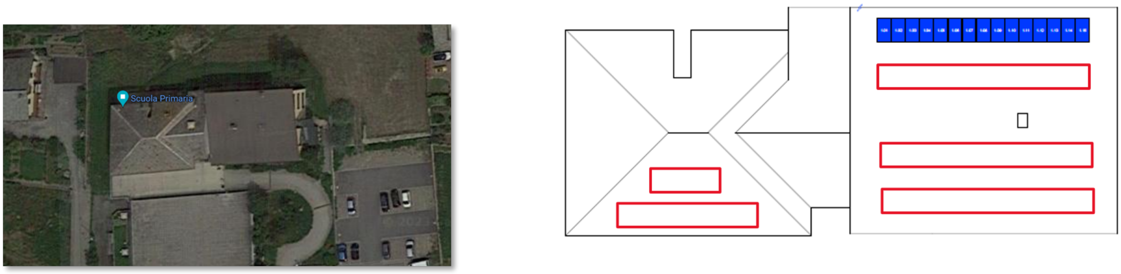
	Total Investment costs [€]	Operating cost [€/year]
Teglio School	27 488	154.18
Tresenda School	78 336	492.96
Sports Arena	78 336	492.96

Table 3.3: Total investment and operating costs for the existing plants in Teglio.

The plants analyzed are primarily designed to cover the load of the utility for which they are installed and not with the intention of developing an Energy Community, so it can be assumed that the energy surplus is very limited and consequently also the energy shared. This point will be analysed in more detail later on, however, the photovoltaic potential is reported in this chapter. The three plants as seen from the plans do not cover the entire roofs, there is additional space that can be used to increase the existing plants, the maximum installable power is therefore analyzed.

3.1.1. Additional PV potential estimation

The Teglio school has an installed power of 5.93 kW. From Figure 3.2a it can be seen that the actual number of panels is 15 which means an output of 0.395 kW/per panel. A further three rows can be added on the same portion of the roof and another 15 panels can be placed on the roof next to it, distributed over two rows. Thus, 60 panels can potentially be added, and a final output of 29.65 kW would be achieved.



(a)

(b)

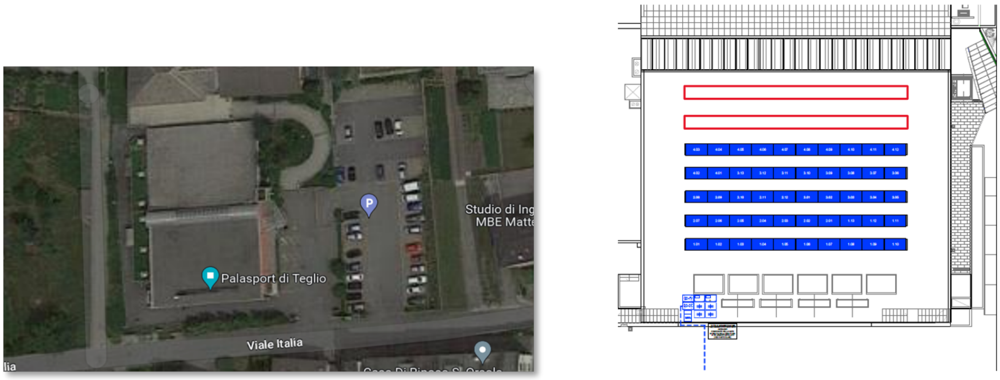
Figure 3.3: Satellite image and photovoltaic installation potential of the Teglio school.

The school in Tresenda has an installed power of 18.96 kW, distributed over two rows of 25 panels. The roof has a lot of unused space, the potential of the roof is therefore very high. In addition to the 25 panels, another 22 panels can be placed horizontally. By adding a further 4 rows, 3 above those already installed and one below, it is possible to install a further 232 panels in the transverse area and 40 in the vertical area, as shown in Figure 3.4b. The theoretical system output would then reach 122.10 kW.

(a) (b)

Figure 3.4: Satellite image and photovoltaic installation potential of the Tresenda school.

The roof of the sports arena, on the other hand, is already exploited; it has an installed power of 18.96 kW distributed among 50 panels. However, two more rows could be added for a total of 70 panels. From the satellite images shown in Figure 3.5b, it can be seen that the plans involve only the roof to the south. It is assumed that the roof above it could also be exploited. The two roofs have approximately the same dimensions, so the potential of the sports hall is 140 panels, which corresponds to an output of 53.09 kW.



(a) (b)

Figure 3.5: Satellite image and photovoltaic installation potential of the sports arena in Teglio.

A final consideration should be made about another utility, which is included in the data provided by the municipality, the nursing home. It does not currently have any installations but has reported that it would be interested in installing one on its roof. It is therefore reasonable to consider the space for the Energy Community's evaluation of installed capacity. Unfortunately, no floor plans were provided, and no 3D images are available, an estimate of the available space was therefore made from the satellite image shown in Figure 3.6. The south-facing part of the roof consists of two parts, the one on the left is about 200 m^2, and the one on the right is about 100 m^2. Considering that the average surface area of a panel is 1.7 m^2 and that the roof does not have a regular area available, the maximum power that can be installed is approximately 80 kW.

Figure 3.6: Satellite image of the nursing home in Teglio.

3.2. The Energy Community users

Once the possible production side of the Energy Community has been analyzed, the next step is to analyze and construct the load side. The energy community considered is made up of real existing users, obtained from real data provided by the municipality of Teglio, and fictitious domestic users, constructed so as to obtain a representative sample of the territory's population.

The load profile data provided by the municipality of Teglio involved four users: the two schools, the sports arena, and the nursing home. For the latter two, hourly consumption for the period from 30/08/2021 to 28/08/2022 was collected. In order to extrapolate the six consumption profiles representing the six typical days, hour-by-hour values were averaged over the period that includes the typical day, as expressed in Table 2.1. These two utilities do not correspond to any of the categories considered, so the profiles obtained were added manually within the Excel file with the load's profiles.

The nursing home profile is shown in Figure 3.7. The occupation of a healthcare facility is continuous and does not vary from day to day, in fact, it can be seen, that the weekend profiles overlap with the weekly profiles. It can also be remarked that the load increases around meal times due to the use of the kitchen. The profile with the highest loads is the winter one and not the summer one, air conditioning in summer is probably not used, being a mountain area.

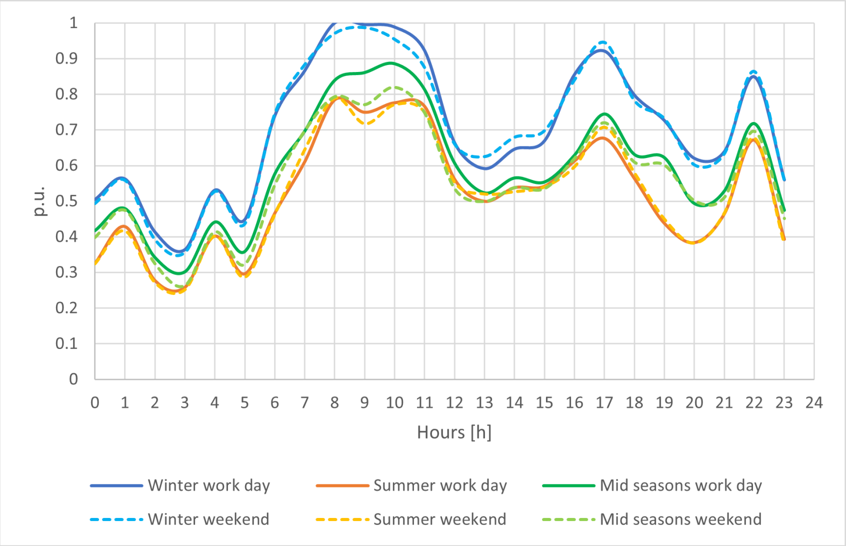


Figure 3.7: Load profiles for Teglio nursing home.

In contrast, the sports hall profiles show many differences both between seasons and between work and weekend trends. In particular, it can be noted from Figure 3.8 that the weekend profiles present a single peak in the afternoon due to sports matches. During the week, on the other hand, there are two peaks, one in the morning and one in the afternoon, which are therefore the two periods of sports courses. Winter and mid-season consumption are higher than in summer, in fact, many weeks in this season had no or very low consumption due to the summer holidays, which then lowered the profile.

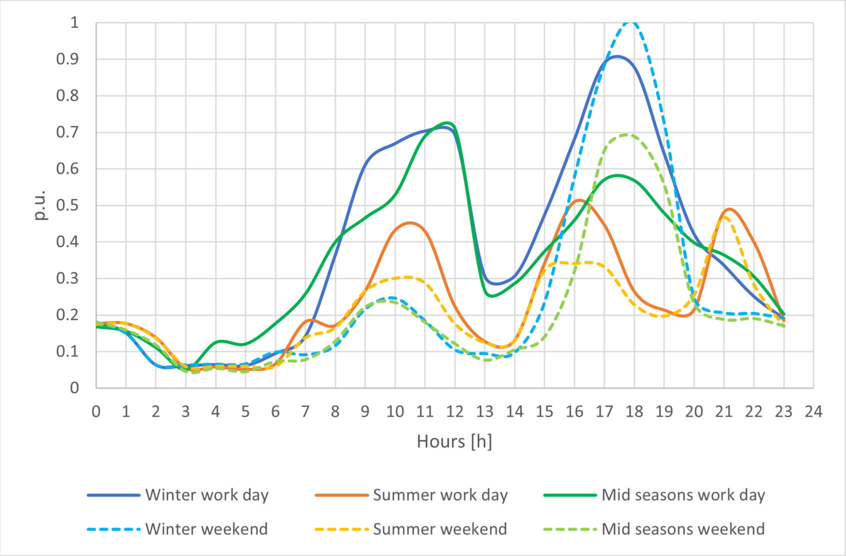


Figure 3.8: Load profiles for Teglio sports arena.

The data available for the two schools are the consumption per band each month: F1, F2, and F3. This type of data does not make it possible to obtain a time profile, but it can be assumed that they follow the profile of one of the constructed categories, the "Office/school" category. It was therefore only necessary to calculate the peak consumption to obtain the hourly profiles of the six typical days. To obtain the peak consumption, the energy intensity of the category was used, calculated according to this formula:

$$Energy\ Intensity = \frac{\sum_{d=1}^{6} \left(Day\ freq_d \cdot \left(\sum_{h=0}^{23} Load_{p.u.}\right)\right)}{1}\ [kWh/kW] \tag{3.1}$$

$$Peak\ load\ Power = \frac{F1\ Load_{user} + F2\ Load_{user} + F3\ Load_{user}}{Energy\ Intensity}\ [kW] \tag{3.2}$$

The energy intensity represents how much energy per year is consumed considering 1 kW as the peak power. A value of 2555.58 kWh/kW was obtained for the "Office/school" category. The sum of the consumption of the three bands was then divided by the energy intensity value to obtain the respective consumption peaks of the two schools. For the school in Teglio, this gives 18.32 kW while for the school in Tresenda 16.45 kW.

The Energy Community is not only made up of these four customers, it was decided to add a further 12 domestic customers in order to explore the social impact of the REC on certain categories of the population.

In order to allocate users between categories, the population of the municipality of Teglio was analyzed using Istat databases. Istat indeed makes available the population census for each municipality, which makes it possible to know their demographic structure. The data considered are in particular the number of people for each age group from 0 to 100 years old that are residents in the municipality [30]. These data were then grouped into 4 groups and the percentage that the group represents of the entire population was calculated. This information had to match the three categories created: "old couple", "young couple" and "family". The 20-34 bracket was then associated with the young couple, the 60-100 with the old couple and the remaining two 0-19 and 35-59 correspond to the family category. The tables below show the percentage of Teglio's population in each age group and the corresponding percentages obtained by considering the final user categories. Distributing this percentage among 12 new users leads to 2 users in the "young couple" category, 4 under the "old couple" category, and 6 families.

Age range	% of the population in the age range
0 - 19 years old	15.76 %
20 - 34 years old	13.22 %
35 - 59 years old	34.83 %
60 - 100 years old	36.19 %

Table 3.4: Percentage of Teglio's population in different age ranges from Istat data [30].

Categories	% of the population corresponding to the category
Young Couple	13.22 %
Old Couple	50.59 %
Family	36.19 %

Table 3.5: Percentage of domestic final consumers in the Energy Community

Once the number of users in each category was obtained, further data had to be entered for each of them: the peak power, the cost of the electricity bill, the annual energy expenditure, and the total annual income of the household.

The peak consumption of each user was set so that the annual consumption of the individual was a realistic value. Electricity consumption depends mainly on the number of people in the household, consumption for two people is approximately 1600 kWh/year, for three people 2100 kWh/year, and for four people 2100 kWh/year. The power values were derived accordingly knowing that old and young couples are composed of only two individuals while families, four are composed of three people and two of four people.

The cost of the electricity bill is expressed in €/kWh and depends on the contract each user has made. In general, however, it deviates from the zonal price in the range of (+0.1; +0.2) €/kWh for households and in the range of (+0.075; +0.1) €/kWh for others. Random values respecting these conditions were then extracted and subsequently put in order so that those with the highest consumption have a lower specific electricity bill cost. The zonal price was set at 150 €/MWh, a value estimated from the forward market by GME (Gestore dei mercati energetici).

The annual energy bill, as analyzed above, is composed of two different terms, the electricity bill, and the heating bill. The first is calculated by simply multiplying the bill cost just mentioned by the user's annual consumption. The costs for heating in this area can be very different from user to user due to the different types of sources used, many households use oil or biomass as a source. Due to a lack of available data, a simplification was therefore made, assuming that all households use gas as their heating source. The cost incurred was estimated starting from the per capita gas consumption for the province of Sondrio: 904.01 m^3 [1]. This value differs greatly from the national average since a mountainous region is being analyzed where the climate is harsh in winter, heating-related expenses will therefore be an important weight on the energy expenses. Starting from the per capita value and following the trend in electricity consumption, gas consumption values were derived for households of 2, 3, and 4 individuals, and the gas price is set at 1.3 €/m^3.

The last information needed is household income. There are no data available on average salaries per age group at the municipal level, so the national average salaries estimated by Istat were used [29], shown in Table 3.6. The three middle age groups were grouped together into one value by taking the average.

Istat age range	Average annual household income [€]
<35 years old	26 033
35 - 44 years old	32 535
45 - 54 years old	34 245
55 - 65 years old	35 998
>65 years old	23 577

Table 3.6: Average annual net household income by age group of the main earner according to Istat data.

For each category, the corresponding average values were varied in a range of ±10% in order to have a more generic scenario. All the data just analyzed are shown in Table 3.7. For non-domestic users, data on electricity consumption are given, which are useful for calculating the savings in the bill due to self-consumption. Other data have not been calculated as the energy poverty index does not make sense to calculate for non-domestic users.

	Annual electricity consumption [kWh]	Electricity bill cost [€/kWh]	Natural gas consumption [m3]	Total energy expenditure [€/year]	Family annual income [€]
Old Couple 1	1490.16	0.35	1481	2446.86	25934.7
Old Couple 2	1530.44	0.341	1481	2447.18	24755.85
Old Couple 3	1570.71	0.32	1481	2427.93	22398.15
Old Couple 4	1610.99	0.307	1481	2419.87	21219.3
Young Couple 1	1533.97	0.331	1481	2433.04	28636.3
Young Couple 2	1592.97	0.319	1481	2433.46	23429.7
Family 1	2090.99	0.303	2058	3308.97	37685.27
Family 2	2121.3	0.292	2058	3294.82	36543.06
Family 3	2151.60	0.282	2058	3282.15	35401.20
Family 4	2181.91	0.278	2058	3281.97	33117.47
Family 5	2787.99	0.269	2635	4175.47	31975.61
Family 6	2878.91	0.252	2635	4150.99	30833.4
Teglio School	46818.17	0.27	-	-	-
Tresenda School	42831.47	0.262	-	-	-
Nursing Home	165058.78	0.25	-	-	-
Sport arena	24407.54	0.295	-	-	-

Table 3.7: Detailed input data regarding members of the Energy Community.

3.3. Sharing indices application

Having defined the community on both the production and load side, it is possible to better characterize the users that constitute Teglio's Energy Community through the KPIs presented in Section 2.3.

	Ownership KPI	Sharing KPI	Energy poverty KPI
OldCouple1	0.000	0.378	1.000
OldCouple2	0.000	0.378	1.000
OldCouple3	0.000	0.378	0.766
OldCouple4	0.000	0.378	0.740
YoungCouple1	0.000	0.320	1.000
YoungCouple2	0.000	0.320	0.790
Family1	0.000	0.369	1.000
Family2	0.000	0.369	1.000
Family3	0.000	0.369	1.000
Family4	0.000	0.369	1.000
Family5	0.000	0.368	1.000
Family6	0.000	0.368	1.000
Office_School1	15.447	0.419	-
Office_School2	63.612	0.420	-
NursingHome	0.000	0.329	-
SportsArena	20.941	0.358	-

Table 3.8: KPIs to describe Energy Comunity members.

It was said that the investment in the installations was made totally and exclusively by the municipality, it is, however, composed of three different users: Teglio school ("Office School 1"), Tresenda school ("Office school 2) and the sports arena. It was decided to allocate a percentage to each as if they had participated individually and not as a single entity, in particular it was assumed that the investment would be proportional to the installed power.

The sharing index, on the other hand, evaluates how well-aligned a final consumer is with photovoltaic production, from the table the two schools are the most remarkable. The consumption profile of a school or office is very compatible with photovoltaic systems, as the facilities have the highest load during the day and almost no load in the evening and at night. On the other hand, young couples are considered worse, they have the highest load in the evening and the lowest load during the day.

Analyzing the energy poverty index instead, three members of the REC are considered to be at risk. All have very high energy expenses due to the climate zone, those with below-average income are at risk, for the older couple 5 and 10% lower respectively, and for the younger couple 10%. Remember that the second energy poverty index check is made on income net of energy expenses so both values weigh. For non-domestic households, the calculation does not make sense

3.4. What profits should be shared?

It was mentioned in Section 2.4 that there are no indications or proposals in the decrees and ARERA 's resolutions as to which method can be used to share out the benefits among the members of the Energy Community. Another open question not clarified in the documentation is what is shared out. This point is also left open, so it is up to the community to decide what is to be shared, just one, two, or all three of the economic benefits described in Section 2.1.

Since it is not known in advance what the statute of the individual community will provide, all algorithms developed in the methodology section are general. They take as input an amount of money and allocate it, the algorithm is therefore suitable for all cases regardless of the choice made.

The choice of what to distribute among members depends on the different possible configurations a community can adopt and on individual choices. Two examples of communities are given to analyze what the choice might be depending on the configuration.

The first case is a community created from a single large plant owned by an industry. This industry has financed its plant by placing it on top of its industrial hall. Citizens living close to this industry consume the energy produced that is not self-consumed by the warehouse. The industry has no social purpose but is usually driven by profit motives. This community will most likely only share the incentive on the shared energy among the members, input, and self-consumption will remain with the owner of the plant.

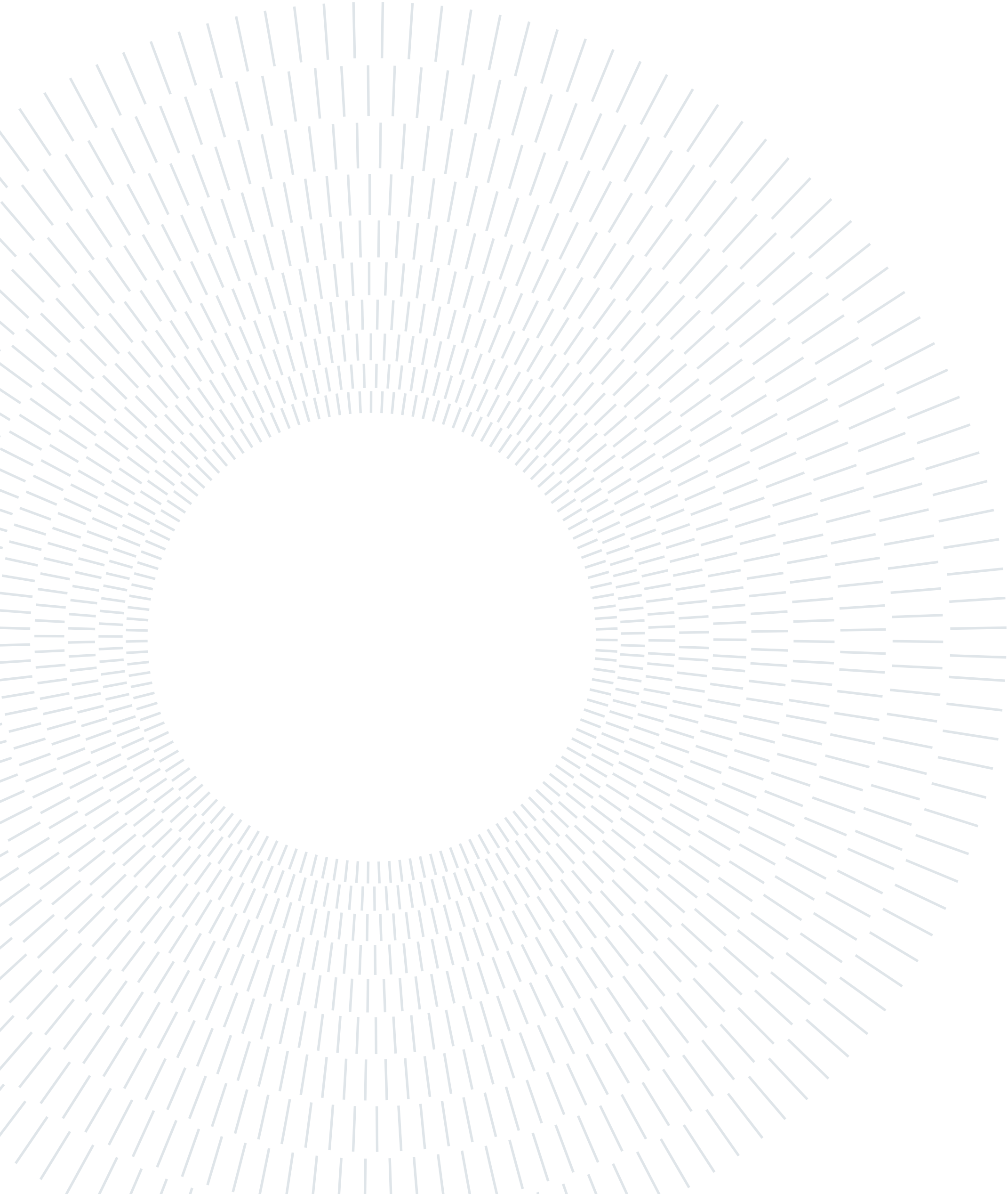
The second case, on the other hand, is a community created by the common agreement of many citizens; it consists of several distributed installations. All members contributed to the financing of the installations and they were placed on the roofs considered best, with sufficient space and good exposure. The users who have the installations placed on their roofs take advantage of self-consumption and feed-in without having contributed more than the others. In a community such as this, it might be fairer to share all three economic benefits among all members of the REC.

In addition to the distinction between different types of configuration, one must also take into account the simplicity of the distribution of each of the economic flows, as they are not all equal. The incentive for sharing will be paid to the community by the GSE, so it is an explicit flow that is easy to find since it goes directly to the community manager. Revenues from feed-in, depending on the contract made or the type of connection, for example if connected to the grid directly or to a consumer utility, may be more or less easy to find but in any case represent an explicit flow. More complex, on the other hand, is the bill saving due to self-consumption. To obtain this figure, it is necessary to have the user's hourly consumption and production data and to estimate the savings using either the cost of the individual user's bill or an average value compared to the zonal price. The lost cost due to self-consumption is an implicit flow.

Focusing on the specific case of the Teglio Energy Community, this is a community created thanks to the investment of a single entity: the municipality. Compared to industry, the municipality also follows the social purpose, the community was created as a tool to mitigate energy poverty, thus wanting to leave more benefits to individual citizens. Part of the funds also might come from the legislature, so profit is put on the back burner. Despite this, sharing all three economic benefits is complex and unrealistic, so it was decided that only the explicit flows, the incentive on sharing, and the revenue from the sale of energy fed into the grid will be shared in this case study. The benefit of the bill savings from self-consumption is kept by those who physically own the plant.

Energy flow	Cash flow	Original owner	How to compute	Should be shared in the REC?
Shared energy	REC incentives	REC	Computed by GSE and transferred to the REC.	Yes, always.
Injected energy	Electricity market price	PV owner	The PV owner receives it in its injection contract. This can be directly registered to the REC or transferred from the owner to the REC.	Yes in case the plants are collectively bought, or the REC is a social REC.
Self-consumed energy	Avoided cost (=bill cost)	PV owner (or prosumer if different)	Should be estimated from the prosumers bill and transferred to the REC.	Could be shared, only in case the plant is collectively bought and there is no interest in valorizing the self-consumption effort of the prosumer.

Table 3.9: What profits should be shared in a Energy Comunity.



4 | Results

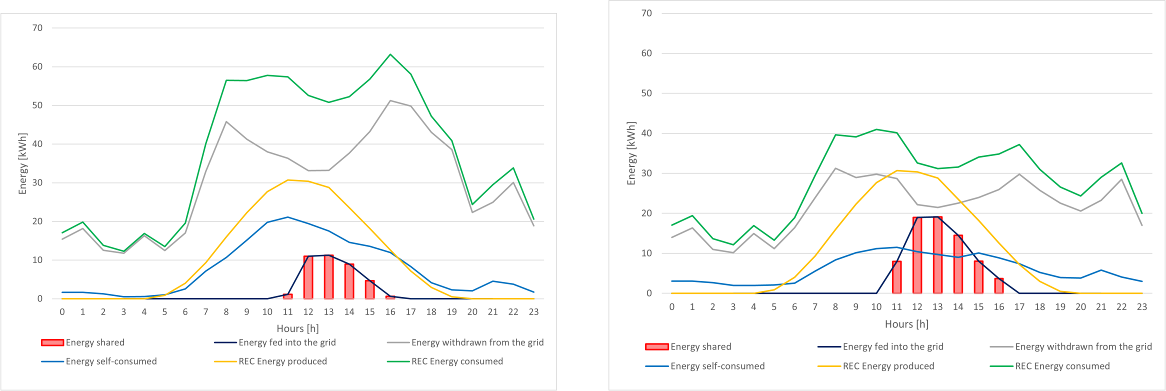
4.1. Analysis of the actual scenario: energy flow and economic analysis

The starting point for this analysis is the simulation of the current scenario in Teglio, so what would be the energy and economic flows if an Energy Community was formed with the already installed systems analysed in Section 3.1.

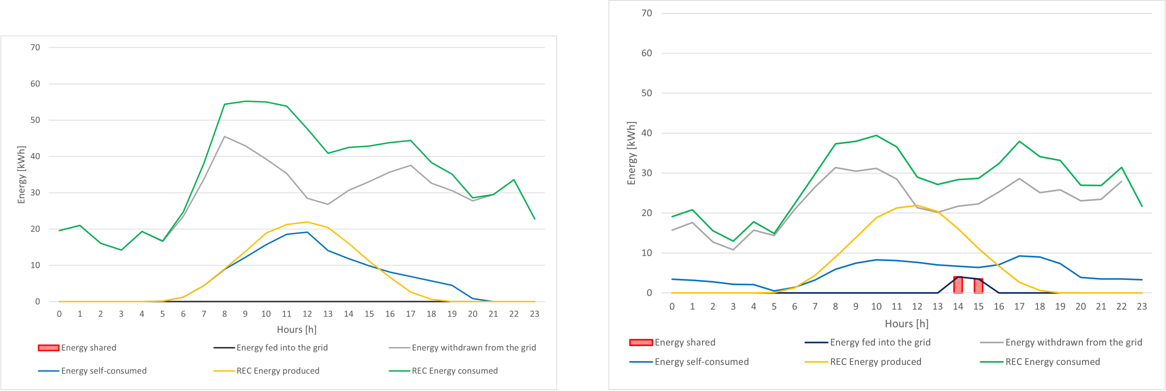
The graphs below show the energy trends on 6 typical days, in particular, the energy fed into and withdrawn from the grid, the energy self-consumed and shared, and finally the energy consumed and produced by the community.

Analyzing the graphs, it can be seen that the load profile is greater during the week than at the weekend. In fact, although the consumption of domestic users increases at the weekend, the greater loads on the other hand decrease, in particular, the sports arena consumes only in the afternoon and the two schools are closed, therefore they have minimal consumption. The maximum load is on the ‘winter work day’, the day when production is lowest.

(a) Winter work day energy profiles (b) Winter weekend energy profiles



(c) Summer work day energy profiles (d) Summer weekend energy profiles



(e) Mid seasons work day energy profiles (f) Mid seasons weekend energy profiles

Figure 4.1: Trend during six typical days of energy inject into the grid, withdrawn, self-consumed, shared, produced, and consumed in the reference case.

The feed-in of excess energy produced and not self-consumed is very low, in winter and mid-season it is zero. All the energy that is produced therefore is used to supply the load connected to the same POD of the photovoltaic system. If a more specific analysis of the individual plants is made, from Table 4.1, a large imbalance between energy produced and consumed can be seen. In the case of Teglio school, the energy produced is only 15% of the load.

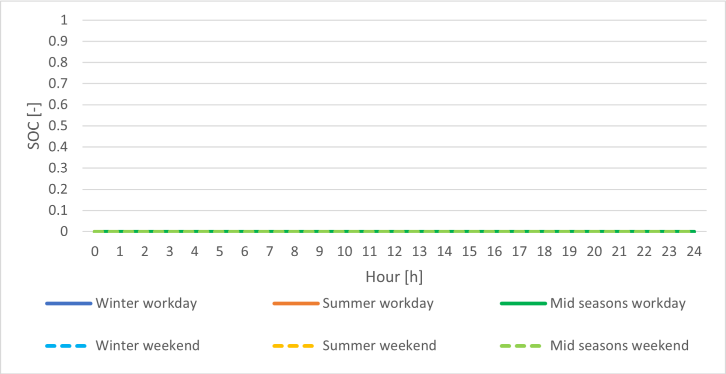
Prosumer	EE produced [kWh/year]	EE consumed [kWh/year]
Teglio school	46818.2	7194.7
Tresenda school	42831.5	23003.5
Sports arena	24407.5	23003.5

Table 4.1: Energy consumed and produced annually by prosumers in the reference case.

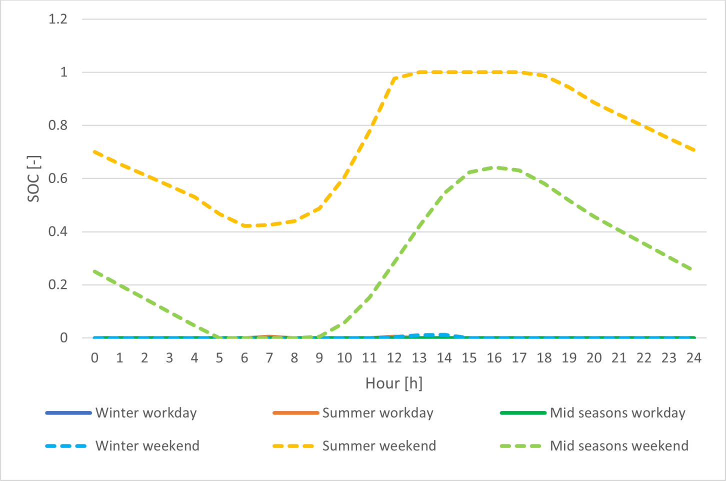
One of the most frequently used rules for an initial dimensioning of a PV system is that the energy produced annually is approximately equal to the energy consumed. This rule is respected in the case of the sports arena but not for the two schools, the installed power is too low compared to the energy demand. This fact leads to no energy surplus and therefore the energy fed into the grid is zero. In the case of a private installation this would be a limited problem, the user would still save money on the bill due to self-consumption but would not get any revenue from the sale of the energy.

In the case of a REC, however, this also affects the shared energy, it is in fact calculated as the minimum between the energy fed in and withdrawn from the grid, Equation 2.15, zero feed-in means zero sharing. The two profiles are in fact overlapped on all six typical days, the energy fed in coincides with the energy shared. The community's revenues will therefore be low for two of the three items that were analyzed above, the sale of excess energy and the incentive on shared.

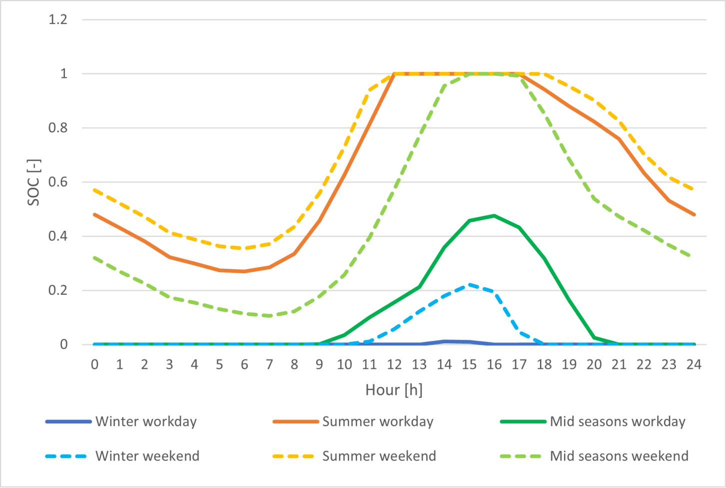
Finally, it can be pointed out that the self-consumption profile is not always behind the production profile, but in some cases continues for a few hours after the sun has set and therefore there is no more production. This 'delayed' self-consumption is due to the batteries. In order to better understand how the batteries are used, the trends of the state of charge of the three batteries integrated with the photovoltaic systems are shown below.



(a) Battery SOC for the Teglio school plant



(b) Battery SOC for the Tresenda school plant



(c) Battery SOC for the Sports arena plant

Figure 4.2: Trends of battery state of charge in the reference case.

It is immediately evident that the trend in the state of charge of the Teglio school battery is flat, fixed for each day at zero, the battery therefore never has the opportunity to charge. The imbalance between load and production just analyzed not only means that there is no surplus energy downstream of self-consumption, but that there is never any excess production to charge the battery.

Even in the case of the second school there is low battery utilization, in this case the battery is charged during the summer and mid-season weekends. On these days the photovoltaic production is considerable and the load is minimal, one-fifth of the working day, the battery can be charged. Despite this, it should be remembered that electrochemical batteries are storage systems suitable for daily, not seasonal, storage. In the case of photovoltaic systems, the batteries store the excess production that occurs in the middle hours of the day for use during the evening and night of the same day or, if necessary, later days. So even though the battery of the Tresenda school system is charged on two of the six profile days, it is not very useful since the load at night for the school is zero.

The third prosumer is the sports arena, where the battery is well utilized due to the fact that the plant is sized correctly with its load. The system during the middle hours of the day produces more than the load needs, and therefore the battery has the opportunity to charge. Figure 4.3 shows the trend during the mid-day in the week, the day with the highest annual frequency value. Thanks to the battery, the load is almost completely covered even in the hours outside the production range.

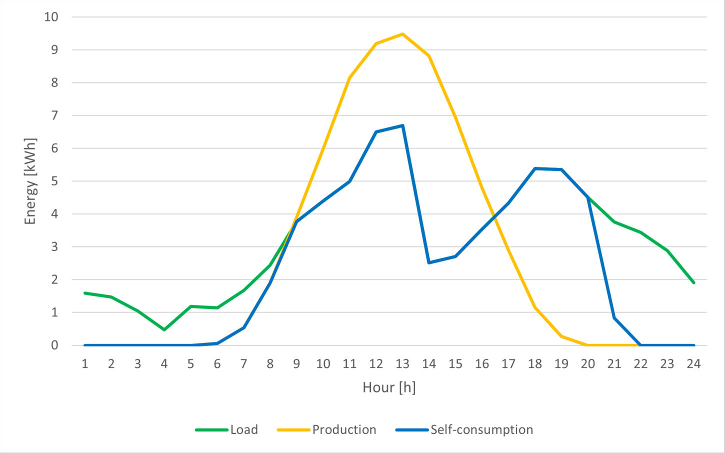


Figure 4.3: Produced, consumed, and self-consumed energy trends of the sports arena in the reference case.

The imbalance between production and load is also visible by analyzing the annual quantities in Figure 4.4. Annual shared energy and fed-in energy have very low values, and being equal on all typical days, their ratio is 1.

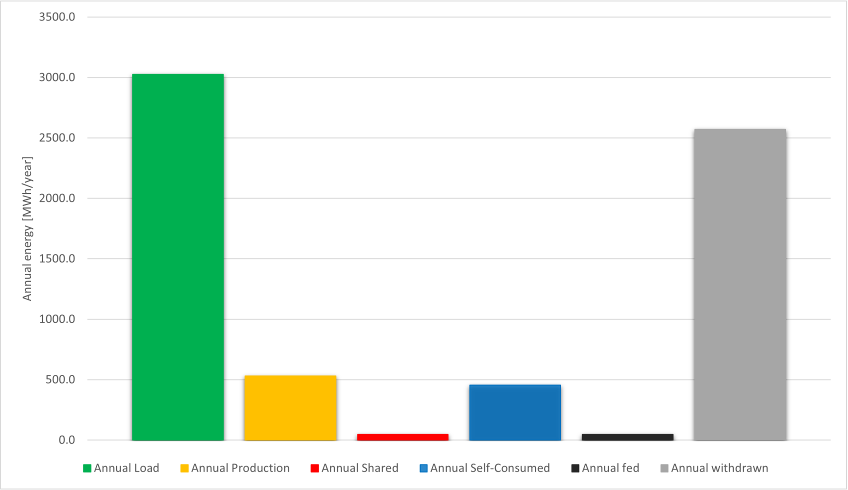


Figure 4.4: Annual energy quantities for the reference case.

The economic analysis of this current configuration of the Energy Community is then carried out. The investment costs were analyzed in section 3.1 and consist of the costs of the photovoltaic system and batteries. The economic variables used throughout the analysis are shown in Table 4.2.

The ARERA reimbursement is made up of two terms as stated in TIAD document in section 1.1.2, the avoided use of the transmission grid and the avoided grid losses of the shared energy, in fact, it remains under the same primary substation. For simplicity, this value has been set at the value shown in Table 4.2. The calculation of the MASE incentive was done using the formula provided in the draft decree. The area under analysis is in Lombardy so the correction to the tariff of + 10 €/MWh was also added.

A discount tax of 50% on the initial investment was considered, distributed equally over the first 10 years. Finally, after 15 years, the batteries are replaced at a cost of approximately 70% of the original battery price.

Average Zonal Price	0.15 €/kWh
MASE incentive	0.12 €/kWh
ARERA reimbursment	0.0113 €/kWh
GSE fixed contribution	50 €/year
GSE variable contribution	2 €/kW
Price cap	0.18 €/kWh
Inflaction rate	6 %
Tax discount	50 %

Table 4.2: Economical variable for the economic analysis.

Table 4.3 shows the economic benefits for the community. As expected due to the small surplus of energy, the gains from the incentive and the sale of energy are very low, the greatest benefit being the avoided costs on the electricity bill.

Revenues from grid feed-in	708.02 €/year
Revenues from sharing	619.76 €/year
Avoided cost for self-consumption	12 530.79€/year

Table 4.3: Annual economic benefits in the reference case .

Revenues costs and tax discounts were added together and the cash flow for each year up to 20 years, the lifetime of the photovoltaic systems, was then found. The cash flows were then discounted considering an inflation rate of 6%. Figure 4.5 shows the actualized and accumulated cash flow.

The cumulative cash flow remains negative even at the end of 20 years, the net present value (NPV) is in fact - 10 527 €. The payback time of the investment is 24 years. The municipality will therefore not pay back the investment made, the main cause being the batteries. They represent a large cost for the municipality, more than half of the initial investment cost. Furthermore, as has been analyzed, they are not exploited and therefore do not provide any economic benefit, the installations integrated with them are too small.

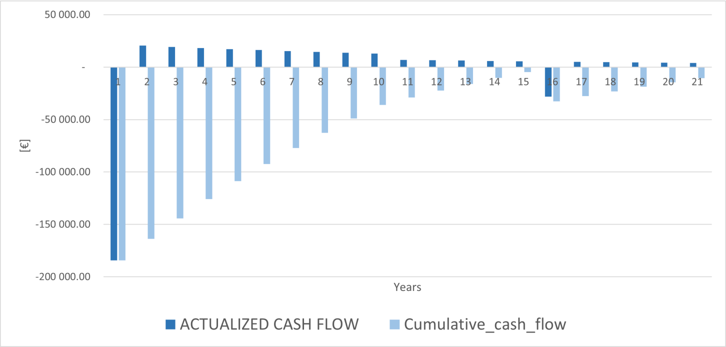


Figure 4.5: Economic analysis for the reference case.

The investment of these plants from an economic point of view is therefore not cost-effective and furthermore the configuration is not suitable for shared self-consumption, the installed power is not sufficient to cover the demand. For this reason, it was decided to increase it and find an optimum for the emerging Energy Community in Teglio.

4.2. Sizing the generation portfolio

The previous section mentioned that an annual energy production approximately equal to annual energy consumption is generally considered a dimensioning rule for photovoltaic systems. The ratio between the two quantities, which is called the balance factor in this discussion, should therefore be approximately equal to 1.

Considering the Energy Community in the same way, adding up all the loads of the members of the community and summing up the energy produced by all the plants, in the reference case a ratio of 17% is obtained. It was therefore decided to increase this ratio to 25, 50, 75, 100, 125, and 150% to find an optimum point.

The annual energy consumed remains unchanged in the different scenarios, what changes is the energy produced needed to obtain an effective value for the balance factor. This produced energy will correspond to the required installed power. Once the power to be installed in excess of the reference case was obtained, assumptions had to be made on how to distribute it, the procedure adopted is reported:

- The increase in power starts with the existing plants up to the maximum potential, as analyzed in Section 4.1. The starting point was the smallest plants, which had the greatest imbalance between production and consumption, the school in Teglio (scenario 25%), and then the second school (scenario 50% and 75 %), and the sports arena (scenario 75% and 100%).

- Once the maximum potential of the main utilities was reached, the nursing home was involved, inserting a maximum system size of 80 kW as analyzed in Section 3.1(scenario 100 and 125%).
- Finally, domestic users were involved. There was no data available on free space for these consumers, so a maximum installable of 10 kW per roof was assumed. Starting with the users with the highest loads and then going downwards.
- No batteries were added or changed.

The power and energy configurations are shown in Table 4.4.

	REF CASE	25%	50%	75%	100%	125%	150%
Annual load [MWh/year]	302.7	302.7	302.7	302.7	302.7	302.7	302.7
Annual prod. needed [MWh/year]	-	756.6	151.3	227.0	302.7	378.3	454.0
Power needed [kW]	-	64	128	192	256	320	384

OldCouple1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OldCouple 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OldCouple 3	0.0	0.0	0.0	0.0	0.0	0.0	10.0
OldCouple 4	0.0	0.0	0.0	0.0	0.0	0.0	10.0
Young Couple 1	0.0	0.0	0.0	0.0	0.0	0.0	10.0
Young Couple 2	0.0	0.0	0.0	0.0	0.0	0.0	10.0
Family 1	0.0	0.0	0.0	0.0	0.0	0.0	10.0
Family 2	0.0	0.0	0.0	0.0	0.0	0.0	10.0
Family 3	0.0	0.0	0.0	0.0	0.0	6.0	10.0
Family 4	0.0	0.0	0.0	0.0	0.0	10.0	10.0
Family 5	0.0	0.0	0.0	0.0	0.0	10.0	10.0
Family 6	0.0	0.0	0.0	0.0	0.0	10.0	10.0
Office_ School 1	5.9	26.1	29.7	29.7	29.7	29.7	29.7
Office_ School 2	19.0	19.0	78.9	122.1	122.1	122.1	122.1
Nursing Home	0.0	0.0	0.0	0.0	52.0	80.0	80.0
Sports Arena	19.0	19.0	19.0	40.2	53.1	53.1	53.1
TOTAL	**43.9**	**64.0**	**127.5**	**191.9**	**256.8**	**320.8**	**384.8**
Real balance factor	**17.1%**	**24.9%**	**49.8%**	**74.9%**	**100.2%**	**125.2%**	**150.2%**

Table 4.4: Configurations for different power installation scenarios.

To find the optimum point, however, it is necessary to make an economic analysis of each case. The economic variables remain the same as those reproduced in Table 4.2, with the exception of the MASE incentive, above 200 kW the formula therefore changes, and 110 €/MWh is obtained. The CAPEX and OPEX also change for plants above 30 kW as in Table 3.2.

Trends of the three different economic benefits of the community are shown in Figure 4.6.

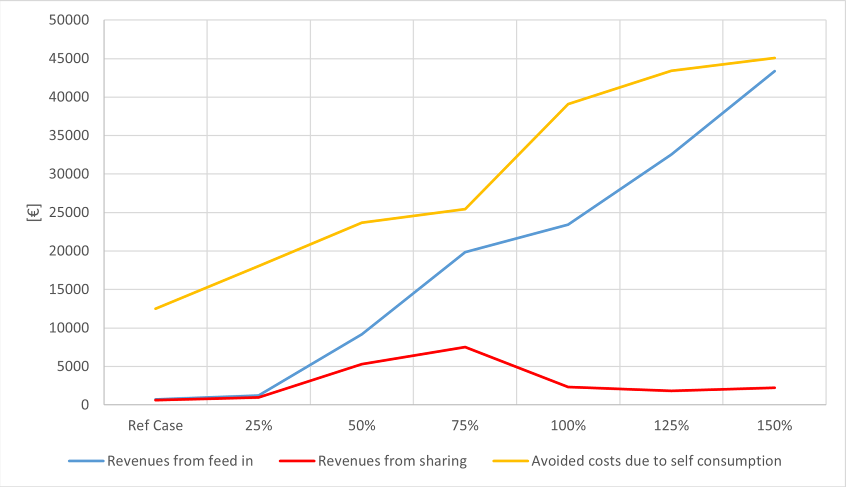


Figure 4.6: Community economic benefits for different scenarios.

In all scenarios, the greatest benefit is always self-consumption, it is much greater than the other two items especially initially, and then gradually flattens out in the later scenarios.

It is evident that two of the three profiles are always increasing, while the profile of shared gains reaches a maximum. In general it can be said that by increasing the installed power not in a single system but by involving more and more users, both the self-consumption and the feed-in will increase but the increase factor is not constant, in the middle, 50-75 and 100% scenarios there are big changes in inclination.

In the 50% scenario, the systems of the two schools, the most critical and undersized systems in the reference case, are saturated, so a great improvement in economic terms is immediately noticeable, especially in terms of self-consumption also due to the greater use of batteries. At 75%, the space of the sports arena is also utilized, self-consumption increases less as the user does not need any more energy, the batteries are charged more, and above all, there is a greater sale of energy and a consequent increase in shared energy. This extra power in fact does not serve the utility under which it is located but serves the community. The 100% case involves another utility, the nursing home, the trends change again. The installation of a system on such an energy-consuming utility increases the avoided costs for self-consumption, the sale of energy grows less than linearly, and the gains from shared power drop a lot.

The NPV and PBT trend as the scenarios change can now be seen in Figure 4.7. The NPV does not have a maximum point, increasing the energy produced will also increase the profitability at the end of 20 years and this is due to the fact that both the savings for self-consumption and the sale of energy always increase. Despite this the trend is less than linear, there is a big increase between scenario 25 and 50% and then this increase decreases. The PBT drops dramatically between the reference case and the first scenario from 24 years to 10. The value then settles at 8 years, the increase in production does not lead to a return on investment sooner.

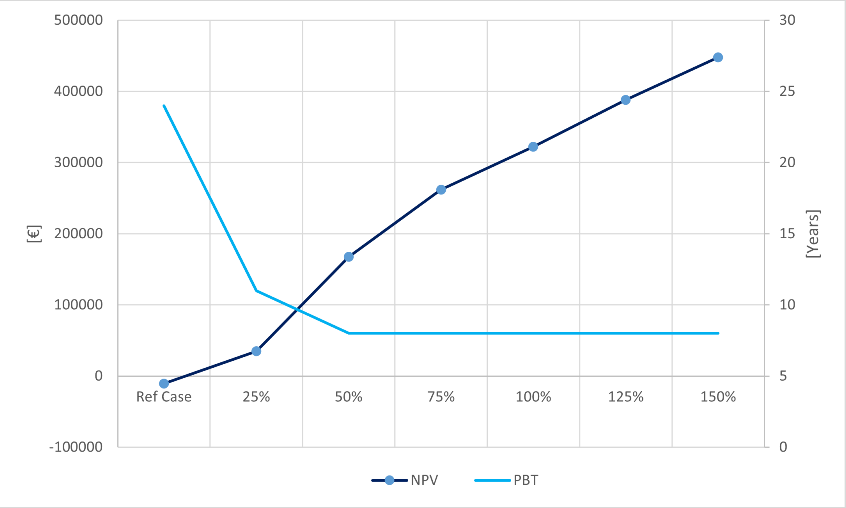
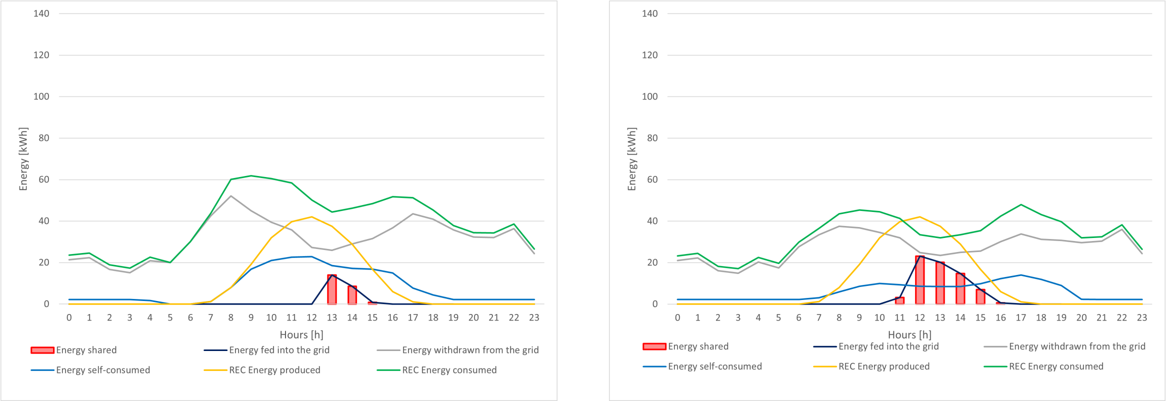


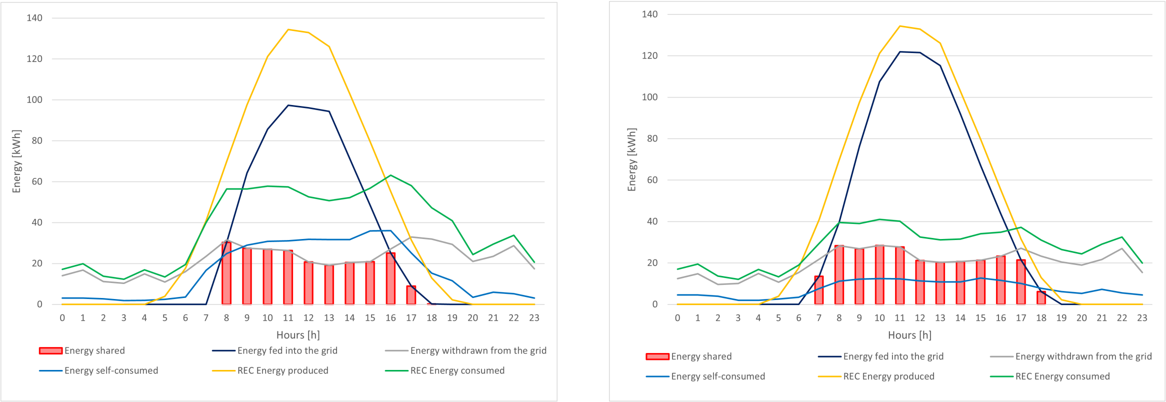
Figure 4.7: Net Present Value and Pay Back Time for different scenarios.

There is therefore no optimum case in terms of the point where profit is maximised, so it is necessary to decide according to other criteria.

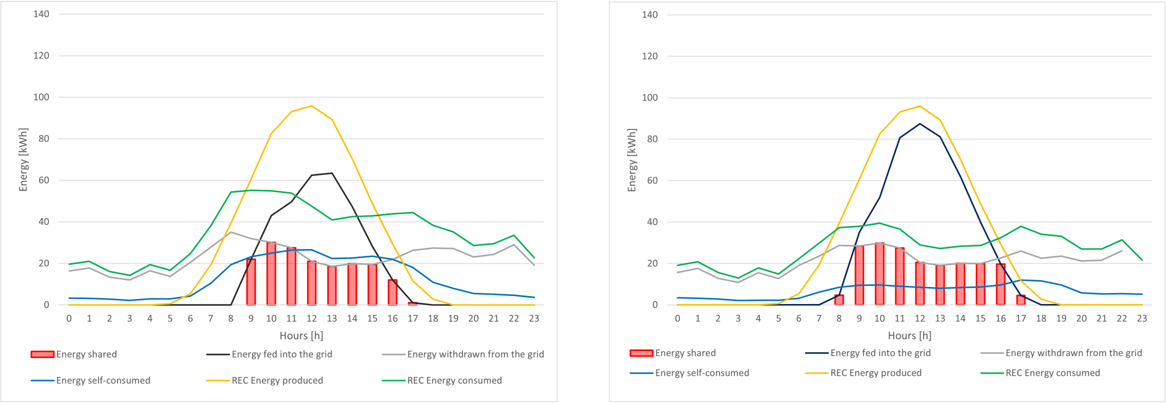
The case considered most interesting is the 75% scenario. In this case, the utilities whose available space is precisely known are fully exploited moreover, it is the optimal point from the point of view of the Energy Community the revenues from sharing are maximized. In the specific case of Teglio in this configuration, the municipality not only finances the installations but also physically owns them, as they are positioned on the roofs of its utilities. The energy flows of different typical days are now analyzed more in detail, Figure 4.8.



(a) Winter work day energy profiles (b) Winter weekend energy profiles



(c) Summer work day energy profiles (d) Summer weekend energy profiles

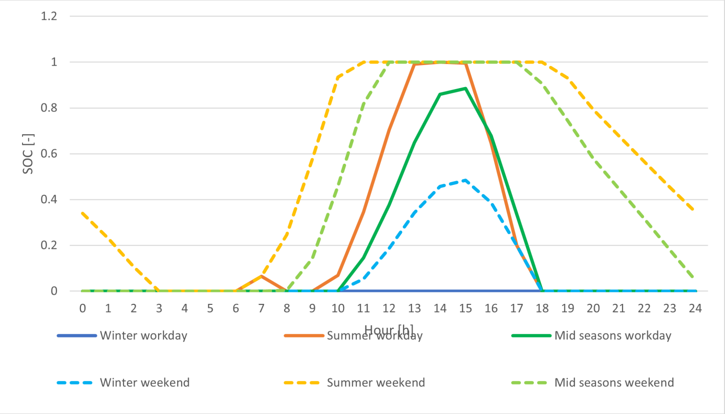


(e) Mid seasons work day energy profiles (f) Mid seasons weekend energy profiles

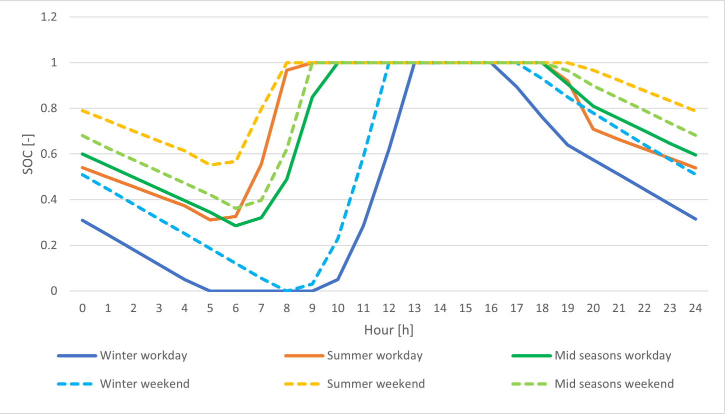
Figure 4.8: Trend during six typical days of energy injected into the grid, withdrawn, self-consumed, shared, produced, and consumed in the optimum case.

The graphs shown are very different from the reference case, in almost all profiles it can be seen that the energy production bell exceeds the community load profile during the daytime hours, therefore there is a surplus of energy. The shared energy no longer always coincides with the energy fed in as before, but during the summer and mid-season profiles, it coincides with the withdrawal from the grid. Furthermore, even in the worst case, the winter working day profile where there is maximum consumption and minimum production, a share of shared energy is obtained thanks to the installation surplus.

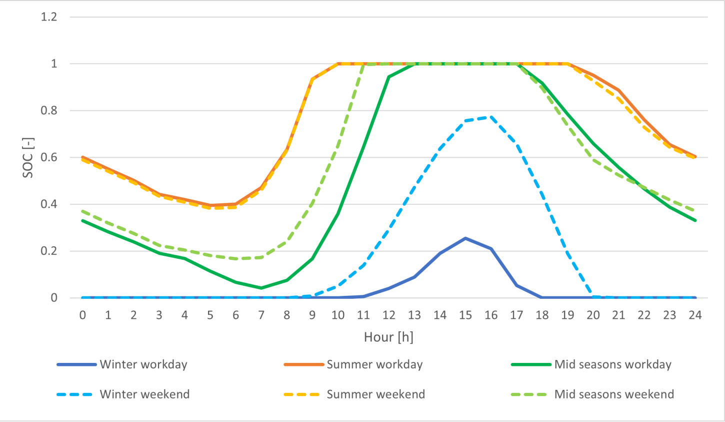
In this configuration all three batteries are utilized, in fact they cover part of the evening load of the users they serve. The school batteries are also used in the winter period, in particular, the school in Tresenda, on all six typical days it in fact performs charge and discharge cycles. With this configuration, the investment, therefore, makes sense.



(a) Battery SOC for the Teglio school plant



(b) Battery SOC for the Tresenda school plant



(c) Battery SOC for the Sports arena plant

Figure 4.9: Trends of battery state of charge in the optimal case.

4.3. Testing the Sharing Methods

The configuration considered optimal in the previous section was adopted as the configuration for all subsequent simulations. In this section, the algorithms analyzed in Section 2.4 will be applied to the case study.

4.3.1. Comparison between the Sharing Methods

Below there is a table summarising the results of all simulations, in particular, how much is given to each member of the REC depending on the algorithm used. Please note that the split earnings are due to the feed-in of the energy produced and the incentive on the shared energy.

	Shapley	Owners	Prop.	Packets	Prop. + Owners	PE + Prop.	PE + Owners	PE + Prop.+ Owners
Old1	34	0	128	161	18	120	0	61
Old2	35	0	131	165	19	124	0	63
Old3	36	0	135	170	19	503	503	430
Old4	37	0	138	174	20	495	495	419
Young1	25	0	103	120	15	97	0	50
Young2	26	0	107	125	15	508	508	428
Family1	44	0	171	204	24	160	0	82
Family2	44	0	173	207	25	163	0	83
Family3	45	0	176	209	25	165	0	84
Family4	46	0	178	212	25	167	0	85
Family5	58	0	227	267	32	214	0	109
Family6	60	0	235	275	33	221	0	113
Off/Sch1	851	4226	5563	6657	4416	5229	3972	4698
Off/Sch2	18079	17402	5089	6422	15650	4784	16358	10796
Nurs.Home	3680	0	13012	7786	1852	12232	0	6246
SportsArena	4255	5729	1790	4201	5168	1682	5385	3609

Table 4.5: Earnings from grid feed-in and shared energy incentive for each member of the REC with different sharing methods.

The starting and reference point is the Shapley value algorithm, it actually represents how important each user is within the community. The simulation was done by clustering, in particular the old couple and young couple and family categories gathered in single load, while the other users, especially those who play both load and producer roles, were left individually. In this way the computational cost of the simulation remained low, about 40 min. From the results of the Shapley algorithm it can be seen that domestic users have a very limited return of about 30 € for smaller loads, 50 € for larger families. The school in Tresenda is the most important member, in fact it has a return of about 67% of the total. This importance is due to the plant, on the Tresenda school a power of 122 kW is in fact installed out of a total of 191 kW, its marginal contribution is therefore very high. The other two installations that are present, school 1 and the sports arena, on the other hand, have less installed power, their role is therefore less important. The nursing home despite being a passive load and not having photovoltaic installations has a considerable gain, it constitutes the main load in the community, 30 kW peak. 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, it is essential that there is load.

The "Owners" method comes very close to the results of Shapley. This is only due to the fact that the installations are placed under those who made the investment, in a different set-up the results would be very different, Shapley, in fact, fails to capture this difference. Obviously with this method those who do not have a percentage of ownership on the plants receive nothing, in the case of Teglio this is an issue as they correspond to passive users. Household users and the nursing home would not participate in the community and would therefore miss a large part of the energy demand.

The methods that evaluate how virtuous users are, "Proportional" method, and "Packets" are visibly different from the reference algorithm. The "Proportional" method considers a lot the size of the load and not just the time at which it is consumed, which is why those who consume a lot like the nursing home get the most benefit. Household users also receive much greater compensation than with the Shapley algorithm, which penalized users with plants. With these algorithms, the production side is not taken into account. The "Packets" method differs slightly, it equalizes all results, and there are fewer differences between users. The two schools having approximately equal loads have the same payback, the size of the installations placed on the roofs is not considered.

In order to get closer to the results of the Shapley value, the "Proportional" method and "Owners" were combined, the computational cost is very low and importance is given to both the load side and the production side. With this algorithm, unlike the Shapley algorithm, importance is given to who made the investment and not where they are located. In the case study, these two things coincide, so a comparison can be made.

Compared to the shapley algorithm the passive household users and the nursing home are heavily penalized, they receive half of what would be expected. The difference between the two schools, as opposed to the "Proportional" method alone, is captured.

The results of the simulations with the algorithms involving the energy poverty index are now analyzed. The bi-level algorithms give very similar results to the implementation of the algorithm without considering energy poverty. Non-poverty users receive an amount similar to the original algorithm. For users in poverty, on the other hand, there is a large increase, about 500 €/year. This means that at the expense of a slight decrease in the income of the non-poverty users there is a lot of support for the poverty users, so it is plausible that people are willing to use algorithms of this type.

The three-level method is the most complete of all those analyzed, the most important aspects of an Energy Community are taken into account, but it deviates from the reference code in that the social aspect is considered, ignored in the Shapley value. The profit of poverty users is about 400€, and between 60 and 100€ for domestic users has no risk. By using the proportional method, the large loads, nursing home and school 1, are valued at the expense of school 2.

It is also interesting to observe the final bill reduction that individual members have. In the bill reduction not only the feed-in and incentive earnings on the shared energy are taken into account, but, for the members who physically own the system, the self-consumption is counted. The results are shown in Table 4.6.

	Shapley	Owners	Prop.	Packets	Prop. + Owners	PE + Prop.	PE + Owners	PE + Prop.+ Owners
Old1	7%	0%	25%	31%	3%	23%	0%	12%
Old2	7%	0%	25%	32%	4%	24%	0%	12%
Old3	7%	0%	27%	34%	4%	100%	100%	86%
Old4	8%	0%	28%	35%	4%	100%	100%	85%
Young1	5%	0%	20%	24%	3%	19%	0%	10%
Young2	5%	0%	21%	25%	3%	100%	100%	84%
Family1	7%	0%	27%	32%	4%	25%	0%	13%
Family2	7%	0%	28%	33%	4%	26%	0%	13%
Family3	7%	0%	29%	35%	4%	27%	0%	14%
Family4	8%	0%	29%	35%	4%	28%	0%	14%
Family5	8%	0%	30%	36%	4%	29%	0%	15%
Family6	8%	0%	32%	38%	5%	30%	0%	16%
Off/Sch1	71%	98%	109%	101%	100%	106%	96%	102%
Off/Sch2	259%	253%	143%	137%	237%	140%	244%	194%
Nurs.Home	9%	0%	32%	19%	4%	30%	0%	15%
SportsArena	146%	167%	112%	117%	159%	110%	162%	137%

Table 4.6: Percentage savings on the electricity bill for each member of the REC with different sharing methods.

Thanks to the addition of self-consumption the municipality's utilities cover the entire electricity bill ($\geq 100\%$) in almost all the algorithms used. With the Shapley value there is a large imbalance on production as shown in the revenue table. School 1 would receive more than double its bill.

In contrast to the municipality, the nursing home, which from the revenue table seemed to get big benefits in many algorithms, has a very limited reduction in its bill, 30% in the best situation. Domestic users on the other hand have a very variable reduction, excluding the "Owners" method where the reduction is 0%, they have a reduction between 3 and 30%.

For all users who did not contribute to the investment, in particular for users in poverty, a maximum bill reduction of 100% was imposed. It was considered unreasonable for the community not only to cover their energy costs but to give them additional income. With the bi-level methods, users in poverty have their entire electricity bill covered, only the heating bill remains. With the three-level algorithm, however, the reduction is a significant, 80%.

4.3.2. The cash fund

The maximum reduction for users in their bills was imposed using the following formula:

$$Final\ Revenues_i = min(Revenues_i,\ El\ Bill + \frac{CAPEX}{Depreciation\ years} \cdot \%Investment_i) \tag{4.1}$$

With this formula, a maximum return of 100% is imposed on users who did not contribute to the investment, and a higher cap on other members, thus leaving the possibility of returning the investment made.

If, according to the distribution of the algorithm used, some users exceed their cap, they are assigned the maximum allocable according to the formula, what remains is 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, due to changes in the price of electricity or the amount of energy produced. Should the fund be substantial, it could be used for improvements to the production facilities.

$$Cash\ fund = \sum (Revenues_i - Final\ Revenues_i) \tag{4.2}$$

The following table shows how much is left in the cash fund after applying the different algorithms and setting the cap. The remainder is zero except in the bi-level poverty methods.

	Shapley	Owners	Prop.	Packets	Prop. + Owners	PE + Prop.	PE + Owners	PE + Prop.+ Owners
Cash Fund	0	0	0	0	0	493.95	136.03	0

Table 4.7: Cash fund in different sharing methods.

4.3.3. Economic implications for the municipality

Once all the developed algorithms have been taken into account, it is also interesting to know what the economic implications are for the municipality, which is the one that supported the investment. An economic analysis was therefore performed for each case considering the point of view of the municipality alone, its gains, costs, and avoided costs, given as the sum of the two schools and the sports arena. Again, the economic variables listed in Section 4.1 were used. The graph shows the two most important indices for evaluating an investment the NPV and the PBT.

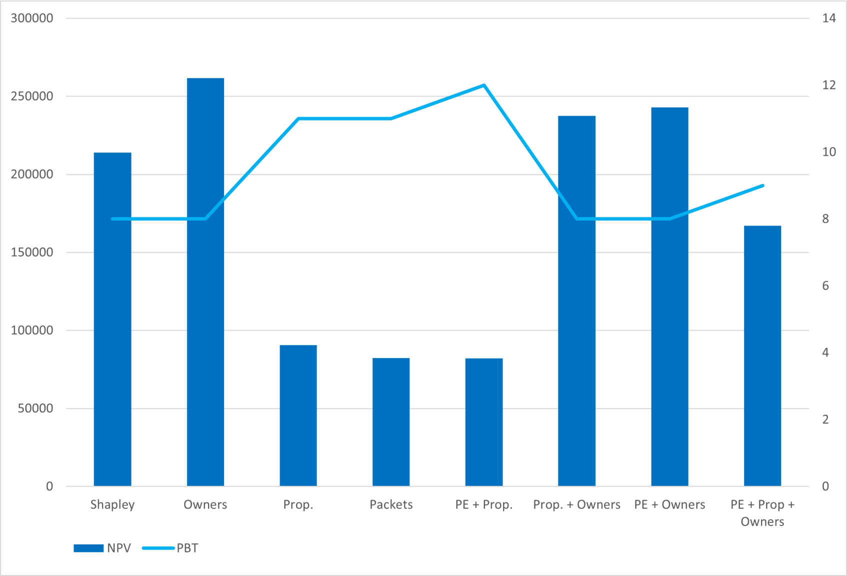


Figure 4.10: NPV and PBT for the municipality's investment in different sharing methods.

The two indicators are complementary, a high NPV corresponds to a low PBT. The lowest PBT is when using the Shapley algorithm, the owners, and the bi-level "Energy Poverty + Owners", in these three cases the highest values of gains for the municipality are obtained. The lowest NPVs are when the sharing KPI, "Proportional", "Packets" method, and "Energy Poverty + Proportional" are considered. A middle way that the municipality could adopt is the three-level system, the payback would be only one year more than in the reference case, the NPV is considerable and considers the social aspect, the members at risk of energy poverty. In all cases, however, there is a PBT of less than 13 years, over a 20-year plant lifetime, and the NPV is always positive, so the investment makes sense in all cases regardless of the method adopted.

4.4. Sensitivity analysis on the energy poverty

In the case study analyzed, the users at risk of energy poverty were three domestic users, two elderly couples, and one young couple. This result is in line with what Istat statistics report as analyzed in paragraph 1.3.2. They, therefore, constitute 25% of the household users belonging to the community.

It is now analyzed what the impact would be if the Energy Community consisted of several energy-poor users, in particular 50% and 100%. It will be analyzed how the economic benefits of energy-poor and non-poor users vary and the economic implications for the municipality of Teglio.

4.4.1. 50% and 100% of users in energy poverty

Each member of the REC is characterized by an electricity expenditure, a heating expenditure, and an annual income. In order to increase the number of energy-poor users, it was decided to change the income, which is more subject to fluctuations and differences between households. It was therefore modified in order to obtain 6 and then 12 users in fuel poverty, a continuous LIHC index of less than 1.

The simulations were then repeated with the new input data, choosing only some of the analyzed algorithms. The results of all three algorithms involving the energy poverty index were chosen and the Shapley value method was used as a reference. Below are two tables, of the two different cases, users in poverty of 50 and 100%. The bill savings for each case are shown according to the algorithm used.

	Shapley	PE + Prop.	PE + Owners	PE +Prop. +Owners
Old1	7%	100%	100%	82%
Old2	7%	100%	100%	80%
Old3	7%	100%	100%	85%
Old4	8%	100%	100%	84%
Young1	5%	100%	100%	82%
Young2	5%	100%	100%	84%
Family1	7%	24%	0%	12%
Family2	7%	25%	0%	13%
Family3	7%	25%	0%	13%
Family4	8%	26%	0%	13%
Family5	8%	27%	0%	14%
Family6	8%	28%	0%	15%
Off/Sch1	71%	103%	94%	100%
Off/Sch2	259%	138%	234%	190%
NursHome	9%	28%	0%	15%
Sport Arena	146%	109%	157%	135%

Table 4.8: Percentage saving on the electricity bill for each member of the REC with 50% of energy poverty.

	Shapley	PE + Prop.	PE + Owners	PE +Prop. +Owners
Old1	7%	100%	100%	87%
Old2	7%	100%	100%	85%
Old3	7%	100%	100%	90%
Old4	8%	100%	100%	89%
Young1	5%	100%	100%	85%
Young2	5%	100%	100%	84%
Family1	7%	100%	86%	69%
Family2	7%	100%	86%	69%
Family3	7%	100%	87%	70%
Family4	8%	100%	87%	70%
Family5	8%	86%	62%	54%
Family6	8%	89%	65%	57%
Off/Sch1	71%	98%	90%	97%
Off/Sch2	259%	132%	216%	182%
NursHome	9%	24%	0%	13%
Sport Arena	146%	106%	147%	131%

Table 4.9: Percentage saving on the electricity bill for each member of the REC with 100% of energy poverty.

Between Table 4.6 in the previous paragraph and Table 4.8 with 50% energy poverty users, there are no significant differences. In fact, all users depicting an energy poverty risk cover their electricity expenses totally using the bi-level algorithms and at about 80% using the tri-level as in the base case. A slight decrease in bill reduction can be seen for users not considered at risk, but it is a very very small decrease. The reason is that the users at risk constitute a very small part of the total load of the community, in the base case they are 2% in terms of percentage load while in this case they are 3%. It is therefore possible to have 6 users in poverty without unbalancing the balance of the REC too much due to the presence of the large loads, nursing home and municipal utilities.

By increasing the users to 100%, more significant changes can be seen,the percentage of consumption they constitute in relation to the total load has increased to 8%. In fact, with no algorithm is it possible to completely cover the electricity expenditure of all users in poverty. The algorithm that is most helpful to the more fragile households is the bilevel method that combines energy poverty and the proportional method, at the disadvantage of a significant decrease for the municipality and the nursing home. The three-level algorithm benefits the municipality the most, but 4 households considered to be at risk of poverty would have a reduction in their bills of less than 70%.

4.4.2. Economic implications for the municipality

As in the previous case, it is important to have some feedback on the economic implications for the municipality as the main promoter of the Energy Community. In this case, it is therefore analyzed how the profits for the municipality will change depending, not only on the variation of the algorithm adopted, but also on the variation of the users considered at risk of energy poverty.

Applying the three algorithms to the two different scenarios, an economic analysis was made considering the different gains the municipality would obtain depending on the algorithm adopted. The table shows the NPV and PBT values.

		Shapley	PE + Prop.	PE + Owners	PE + Prop. + Owners
25%	NPV	213 930 €	82 135 €	242 949 €	167 107 €
	PBT	8	12	8	9
50%	NPV	213 930 €	73 573 €	224 122 €	157 977 €
	PBT	8	12	8	9
100%	NPV	213 930 €	56 449 €	186 469 €	139 718 €
	PBT	8	15	9	10

Table 4.10: Economic analysis for the municipality in different scenarios

By analyzing these results, it is possible to confirm what was said in the previous paragraph. In fact, the PBT is the same in the 25% case and in the 50% case, the NPV is slightly lower. Increasing the percentage of users at risk to 100% the PBT increases, very clearly using the first bi-level algorithm, from 12 years to 15. In the other two cases, it increases by only one year.

In general, however, NPV values are always positive and the PBT remains below 15 years, so the investment is paid back. The municipality with the purpose of decreasing energy poverty in its area can therefore decide to adopt the algorithm that benefits vulnerable households the most while still achieving a final gain. It is also mentioned that 40% of the investment could be covered by the non-repayable grant provided by the PNRR.

4.5. Does the REC mitigate energy poverty? The computation of the LIHC for REC users

Finally, the energy poverty index was recalculated after applying the sharing method analyzed above, the results are shown in Table 4.11.

	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

Table 4.11: LIHC index before and after application of the "Energy Poverty + Proportional" bi-level algorithm.

The improvement is positive in all scenarios, the LIHC index increases and thus gets closer to the threshold value 1. In some cases, the user manages to get out of the risk band thanks to the energy community, but most users still remain below the 1 value.

The factors influencing energy poverty are mainly three, the household's salary, heating expenditure, and electricity expenditure, with the energy community only improving the latter. It is therefore a tool that can help mitigate energy poverty but not solve it.

It is also important to emphasize that these users would only see their condition improve with a signature, they did not participate in the investment of the installations nor did they have to change any habits in the electricity consumption.

5 | Conclusions and Future Developments

The aim of this thesis was to present a complete overview of the RECs' internal revenue-sharing methods and to highlight how the community can use these algorithms to help users considered to be at risk of energy poverty. The community can choose one of these algorithms, taking into account its own configuration and goals, and also decide which of the various economic benefits it wants to share among all members.

Among the algorithms analyzed, the Shapley value method remains the undisputed benchmark, the only method which in fact succeeds in fairly and ideally capturing the importance that each member brings to the Energy Community. Despite this, alternatives have been developed that focus for example on aspects not captured by the Shapley value, such as the social status of its participants, or which attempt to approach it by overcoming the barrier of communication complexity and computational cost.

The impact on non-poverty-prone users of the presence of fragile users was also explored and it was shown through the case study analysis that solutions can be found bringing benefits to vulnerable families without placing too much burden on other members. Solutions of this kind could thus be effectively implemented and accepted by citizens.

A real case study was chosen, it is located in an area relevant to this study. In fact, the municipality of Teglio is a mountain area, the climate is therefore very harsh and energy costs are very high, furthermore, medium salaries are below the national average. In addition to this it is inhabited by fewer than 5,000 people, it could therefore be the object of an Energy Community project financed in part by the PNRR allocation.

However, there are some limitations of the study conducted, that could be the focus of future investigation. The case study is not representative of each Energy Community and is not completely based on real data. It was analyzed from a static point of view, but the Energy Community is dynamic in practice. Both the production side and especially the load side can vary greatly over the years, in particular the number of users is to be expected to change. It would therefore be interesting to analyze how much these results may vary if the number of users increases or decreases.

The energy poverty index chosen as an indicator of at-risk households is the LIHC index; in the experimental phase, attempts were also made to use more complex indicators such as the index proposed by Faiella and Lavecchia. unfortunately, the lack of data made their implementation difficult. It is also emphasized that regardless of which index is used, in a real application, it might be difficult to obtain even the simplest information on the economic status of the household due to privacy issues.

In section 4.5 it was pointed out that the distribution of incentives does not distort the situation of the energy poor. The Energy Community actually works on only one of the aspects that characterize the phenomenon, which is the electricity bill. In the algorithms, a maximum of 100 percent savings on the bill was also imposed, so the maximum that can theoretically be done is full coverage of the electricity bill. The expense of heating, especially for territories with cold climates, is a problem for these households, so the legislator will have to work on several fronts to bring about more noticeable changes. The funds available for Energy Communities could, for example, be used to help the most vulnerable households to electrify their loads, thus shifting gas heating expenses to electricity. Energy Communities are thus not the answer to energy poverty but are one of the tools that will help mitigate it.

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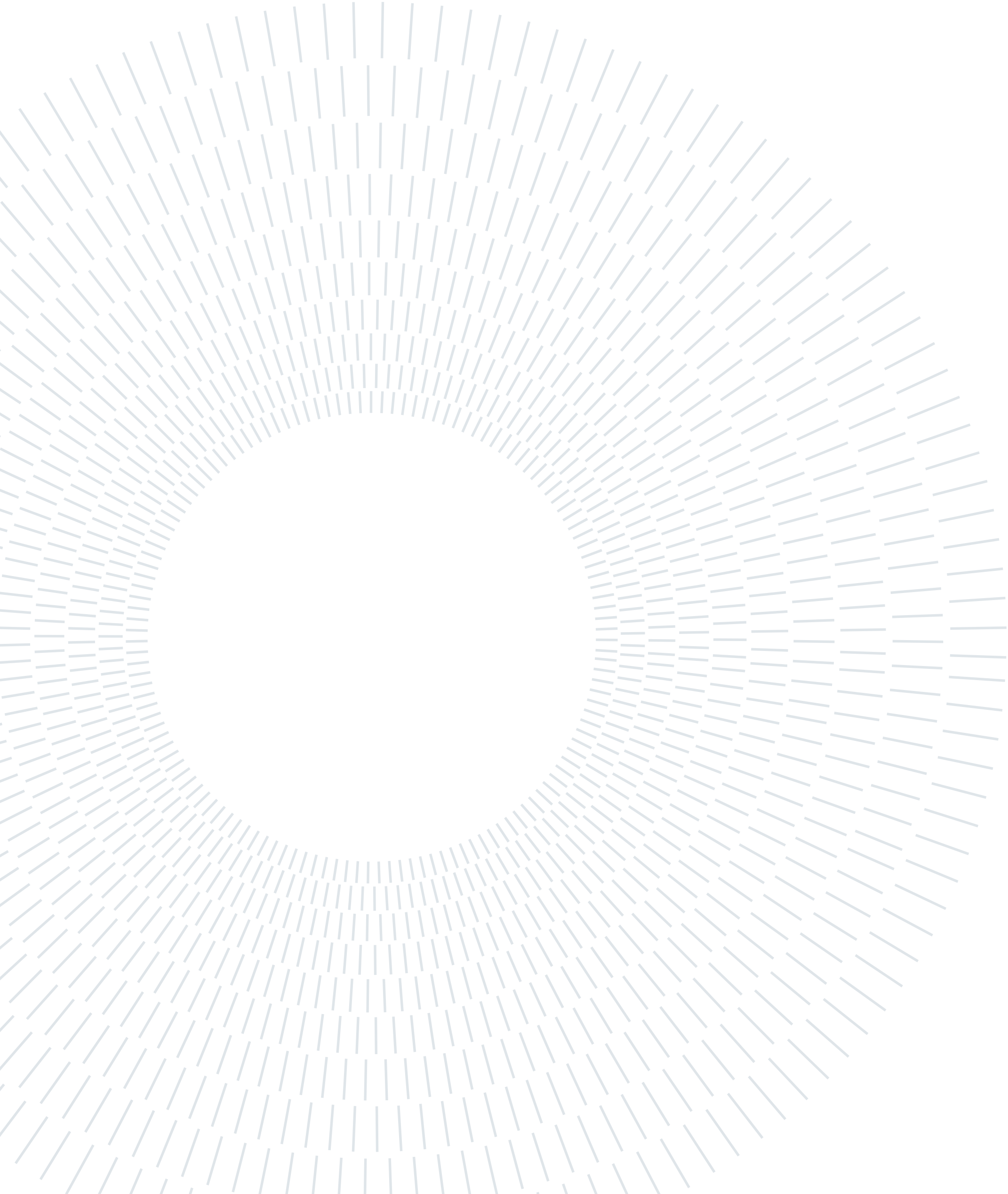

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